Geosci. Model Dev. Discuss.,
https://doi.org/10.5194/gmd-2020-268-AC2, 2020

Geoscientific Model Development Discussions

Interactive comment on "Understanding the development of systematic errors in the Asian Summer Monsoon" *by* Gill M. Martin et al.

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Received and published: 15 December 2020

GMD-2020-268

Response to comments by Anonymous Referee 2.

This article develops a systematic method to detect biases in model simulations to improve the representation of various features of the Asian summer monsoon system in climate models. The study used multiple configurations of the Met Office Unified Model which encompass global climate simulations (fully coupled and atmosphere only), regional climate simulations, and regional nudging simulations. The authors focused on ocean-centric regions such as the Indian Ocean, Maritime Continent, and

the Philippines to demonstrate the growth of regional erroneous atmospheric-ocean circulation over time that can impact the Asian summer monsoon system.

General comments

By providing a multi-layered framework when simulating the Asian monsoon system the authors identified key ocean regions that produce systematic errors and that if corrected will improve how climate and weather models simulate the system. That alone is crucial for the field and although this framework is overall beneficial, the presentation of the text and results could be further improved.

Specific Comments

The title and abstract could use some refocusing - no need to mention Asian monsoon if your main goal is only the EASM. Otherwise, the authors should add some minor additional work to fully represent the title. The authors should restructure the manuscript into EASM, SASM, and Southeast Asia analyses.

We thank the reviewer for this suggestion. However, the aim of this study is to demonstrate the tools and techniques that can be employed in a seamless modelling system to elucidate the source of systematic errors. The ASM is a large system that includes several regional, but interacting, monsoons. Therefore, in demonstrating these tools and techniques, we consider the ASM as a whole but use examples taken from some (not all) of the regional monsoons within this. We would argue that it is not necessary to divide the manuscript into separate analysis of the regional monsoons in order to fulfil the aims of our study. Doing so would both add unnecessarily to the length of the manuscript and potentially lead to confusion as to which parts of the system relate to which regional monsoon (often more than one).

We have, however, reorganised section 3.3 under different sub-headings and separated out the analysis using the NWP hindcasts (which largely focusses the EEIO as an example) into an additional sub-section 3.4. We hope that this will allow the reader to focus on each region within the context of the ASM as a whole.

The RCM simulations only focused on the EASM. If this is not the case then further expand on the Indian monsoon. The regions selected for the RCM simulations have domain cut-offs near high topography regions most likely resulting in erroneous values. Also, it seems like adding china west to China1SE (Figure 4 analysis) would improve the RCM representation of the Indian Monsoon. The same problem occurs in section3.4 the authors switch focus on the Indian monsoon but don't provide any nudged simulations of the EASM.

RCM simulations centred on the Indian Monsoon region were published previously in studies by Karmacharya et al. (2015) and Levine and Martin (2018), hence they are not included here as we wished to limit the number of examples given of the use of this technique. However, we have perhaps not made sufficient reference to these earlier studies nor their findings, particularly on how the inclusion of East Asia in the domain centred over India affects the SASM. Levine and Martin (2018) showed that such an extension made very little difference to the mean state errors over India. We have added more information on this to section 3.2.

The domain cut-offs near high topography regions do result in erroneous values, but this is difficult to avoid without either including or excluding the entire Himalayas and Tibetan Plateau from the domains, which would result in domains covering a huge area or domains only covering E China. The existing domain cut-offs mainly result in erroneous values locally in the boundary regions, and this is far enough away from the area of interest (China in this case).

Extending the RCM domain westwards (and southwards), as in China1W and China1SW, results in a poor simulation of the Indian Monsoon by including within the

RCM areas such as western India, the equatorial Indian Ocean and Arabian Sea that are responsible for a large part for the large Indian Monsoon biases in the GCM. Therefore it is unlikely that the extending China1SE westwards would improve either the Indian Monsoon simulation or the EASM (except perhaps through error compensation).

The simulations where nudging is applied to the Philippines and Indonesia regions directly relate to understanding the errors that affect the EASM. Nudging over the EASM region itself would only provide information about the influence of this region on the other parts of the ASM system. The inclusion of the simulation with nudging over the SASM region is in order to demonstrate that (in contrast to the EASM region) much of the error pattern in the SASM region develops locally and that it also influences the wider ASM system. We have now clarified the reasons behind the choice of nudging regions at the start of section 3.5.1.

The authors used multiple model configurations with varying model resolutions and configurations. It seems important for the authors to note that increasing model resolutions can impact the regional circulation. This is particularly important when looking at a region that is strongly influenced by the regional topography. Add a section talking about the improvements and errors when increasing model resolution.

There are several studies (e.g. Johnson et al., 2016) which demonstrate that the robust systematic errors in monsoon simulations are largely unaffected by model resolution, despite some small impacts on the regional detail. Analysis of the NWP hindcasts also shows similar the error evolution to that seen in GloSea5 despite their significant increase in horizontal resolution. We have separated the latter analysis into a separate sub-section 3.4.1, and we have added some addition detail on this at the end of the Summary.

Lastly, the results incorporate many discussion points. For clarification, either add a separate discussion section or change the section to Results and Discussion as the title for section 3.

We have altered the title for section 3 as suggested, and separated the summary and conclusions into separate sections with more detail in the former, in order to bring things together.

Technical corrections

Line 12 seamless modeling approach is vague. Perhaps adding a table of all the models, reanalysis, and observation used could help the readers.

A table of configurations has now been added (Table 1).

Please be clear when using an abbreviation in the text. NWP or CPLDNWP should be stated in the text as coupled (CPLD) or uncoupled (UNCPLD) Northwest Pacific (NWP).

NWP is Numerical Weather Prediction, as defined in section 2. We have made changes throughout the revised manuscript to clarify the abbreviations.

Consider adding a regular climatology figure for either GC2 or obs with some added labels/information of what the readers should focus on e.g. Indian and East Asian monsoon regions.

The ASM region is well-known to modellers, and we would prefer not to increase the already-large number of figures in our manuscript. Instead, we have referenced key publications relating to ASM errors in the introduction, to help locate the readers.

It seems like errors in GC2 are remedied in GloSea5. Perhaps the color bar needs to be adjusted since it would suggest that there are biases everywhere. The authors can also add a pattern correlation to clarify.

We feel it is essential to use the same colour bar for both, in order to demonstrate that the error patterns are not that different, although the magnitudes are slightly reduced

in GloSea5, as we mentioned in the manuscript. We have used very faint colours for the values between -2.5 – 2.5 mm/day. These could be replaced with no colour, but we prefer to retain the slight distinction between positive and negative values. Pattern correlations have been added to the text. With the exception of June (where the errors in GC2 are larger and somewhat altered, due to the development of SST errors over longer timescales, as discussed) these are above 0.8 for rainfall, and between 0.6 and 0.7 for SST.

Paragraph 166 Is red warm SST bias and blue is cold bias? The text says Cold errors in the Arabian sea when I see red across the Somalia Jet region. Again a climatological figure or a description would help the readers. The same notation is used in the following paragraph.

The cold bias (blue) is evident in the northern Arabian Sea, whereas the warm bias (red) further south is part of the broader western Indian Ocean warm bias. We have clarified that we are referring to the northern Arabian Sea in the text.

Line 201 winter errors need a citation?

This refers to the discussion in previous paragraphs, in which citations have already been provided. We have noted that in this line of the revised manuscript.

Line 215 consider the impact of changing model resolution over mountainous regions, citations such as Curio et al., 2015, Acosta and Huber 2017, Anand et al., 2018

As noted above, several previous studies have demonstrated that the systematic errors in monsoon simulations using this model are largely unaffected by model resolution, despite some small impacts on the regional detail. We now mention this explicitly in new sub-section 3.4.1.

Figure 4 top panels are units the same as figure 1?

Figures 4 and 5 have been redrawn with a colour scale and wind vector that matches Figure 1.

Figures 6 and 8 expand the region westward similarly to figure 7. Enhancement of warm SST anomalies over Somalia is cooccurring with the westward expansion of the EEIO cold anomalies should be noted.

We have expanded this region to the west in Figures 6 and 8 (now Fig. 10), but also reduced the eastward extent of Figures 8 and 9 (now figures 10 and 11) in order to focus on the Indian Ocean.

The development of warm SST anomalies in the western Indian Ocean as the cold anomalies develop and expand from the east was mentioned in the initial discussion of Figure 7 but is now reiterated in subsection 3.3.3 which discusses the equatorial Indian Ocean specifically.

Figure 9 add a caption for the red dashed box. Line 348 is the red dashed box in figure 9 northern EEIO?

This has been clarified.

Figure 13 and Line 350, should the readers focus on FOAM or OISSTV2 as the better model? Please state in the text why one would use FOAM. Why not show HadISST like the rest of the analysis.

We include FOAM SSTs in Fig. 13 because these analyses are used to initialise the CPLDNWP hindcasts. They differ from the OISSTv2 SSTs because they are analyses rather than observations. All of the other Figures except Fig. 2 used OISSTv2 (Reynolds) so we have now replaced Figure 2 with differences against OISSTv2 for consistency.

The comparison between CPLD and UNCPLD is interesting, the disparity in radiative fluxes during pre-monsoon should be further teased out.

We agree, but this is beyond the scope of the current study, which seeks to demonstrate the use of these techniques rather than to understand fully all of the details. We have already noted in the text that this is partly related to the near-surface wind error and

excessive surface latent heat flux, and that further work is required to understand these coupled feedbacks. This may involve the use of targeted sensitivity tests in order to separate the different components. We have added the latter point to the revised text.

Line 385 add a small explanation to identify the purpose of the selected regions.

We have added an explanation to the text at the start of section 3.5.1.

Line 448 is vague and fully lets the ocean model off the hook. It should be further elaborated on and point out that an imbalance in net radiation fluxes leads to weak surface wind errors and is exacerbated by the inaccurate representation of the ocean mixed layer. Several studies have extensively studied the role of ocean heat transport and the authors should also note the role of land-ocean interaction which is not touched upon by the current study. See Chen and Bordoni 2014, and Park et al 2015 for EASM, and Lutsko et al 2019 for the Indian monsoon.

We agree that we have not worded this very fairly, and we thank the reviewer for the additional references. We have reworded and expanded this point in the revised text.

Line 452 again oceanic regions will not benefit from increased horizontal resolution however, many sections of the ASM region are over topography which will improve as you change model resolution.

There is minimal evidence that increasing the model resolution improves the ASM region over topography substantially. Johnson et al (2016) showed that, while there are a number of small, beneficial impacts from increasing resolution in the MetUM, it does not solve the many monsoon biases. We have added a reference to this work in this line, and also noted more explicitly in section 3.4.1 the evidence for this statement from the current study.

Line 464 it should be noted that several similar works on the CMIP models have been done. See Sabeerali et al 2014, Anand et al 2018, Prasanna et al 2020, and Pathak et al 2019.

While there have been several works that examine systematic errors in the Asian summer monsoon in CMIP models (including those that you reference here), and some which use initialized modelling frameworks to diagnose the origins of such errors (such as those referenced in the Introduction), the use of a range of techniques such as those described here within a seamless modelling system that includes both coupled and atmosphere-only configurations and regional modelling to analyse the development and sources of particular errors on a range of timescales has not, to our knowledge, been demonstrated.