In the following, the texts with italic font are the reviewer's original comments, and the texts with normal font are authors' response. The revised parts of the manuscript are marked by red.

Review comments:

Reviewer #1: A. Kerkweg

Dear authors,

In agreement with the CMIP6 panel members, the Executive editors of GMD would like to establish a common naming convention for the titles of the CMIP6 experiment description papers.

The title of CMIP6 papers should include both the acronym of the MIP, and CMIP6, so that it is clear this is a CMIP6-Endorsed MIP.

Additionally, we strongly recommend adding a version number to the MIP description. The reason for the version numbers is so that the MIP protocol can be updated later, normally in a second short paper outlining the changes. See, for example: Printer-friendly version Discussion paper

http://www.geosci-model-dev.net/special_issue11.html,

Good formats for the title include:

'XYZMIP (v1.0) contribution to CMIP6: Name of project' or *'Name of Project (XYZMIP v1.0) contribution to CMIP6'*

If you want to include a more descriptive title, the format could be along the lines of, 'XYZMIP (v1.0) contribution to CMIP6: Name of project - descriptive title' or 'Name of Project (XYZMIP v1.0) contribution to CMIP6: descriptive title.'

When you revise your manuscript, please correct the title of your manuscript accordingly.

Yours,

Astrid Kerkweg

Response:

Thanks for your suggestion. We have revised the title as “GMMIP (v1.0) Contribution to CMIP6: Overview of the Global Monsoons Model Inter-comparison Project” **(P1, L1-2)**

Reviewer #2: W. R. Boos (Referee)

This paper presents a high-level overview of outstanding issues in monsoon variability, then proposes a series of climate model integrations that might be used to better understand the causes of monsoon variability. The introduction is well-written and concise, and does a particularly nice job of quickly summarizing what is known and not known about the coupling between regional and global-scale variations in monsoon circulations. The idea of a model intercomparison focusing on monsoons is well-motivated and compelling, and I am sure that new understanding will be generated by this work.

But some aspects of the experimental design should be clarified and perhaps modified. The "orographic perturbation" experiments do not seem designed to address scientific questions for which there remains considerable uncertainty, and there is some lack of clarity in the associated methodology. The possibility that model bias may interfere with the ability to draw conclusions should be given more consideration. I list more details on these major issues below, along with some minor technical details.

Major scientific issues:

1. Most of the proposed "orographic perturbation" experiments are not appropriately designed to test any hypotheses for which there exists considerable uncertainty. There are several key issues here:

a. It is widely agreed that eliminating all elevated topography from climate models results in a dramatic weakening and southward shift of South Asian monsoon rainfall; this was shown in Hahn and Manabe (1975), Prell and Kutzbach (1992), Boos and Kuang (2010), Wu et al. (2012), and others, with no disagreement amongst those papers. So it seems strange to devote simulations by such a large number of modeling groups to verifying this well-accepted result.

Response:

Thanks for the comments. While the large-scale response of eliminating all elevated topography from climate models is almost the same among the published papers, regional scale features are different. The aim of the "orographic perturbation" experiment is to quantitatively understand the regional response to the orographic perturbation from both the thermal and dynamical perspectives. Because the model dynamics and physics are different among the CMIP6 models, the response in each model may be different across temporal and spatial scales. The results will be very helpful to quantitatively understand the topography effect on the atmosphere and associated physical processes, such as the distribution, intensity, and frequency changes in the precipitation over wide monsoon regions. In addition, the“orographic perturbation” experiments are listed as Tier-3 experiments, viz. the lowest priority, although we wish a large number of modeling groups would do the experiments, the experiments probably will be done only in several modeling centers majored in monsoon research.

b. The manuscript overstates the controversy concerning ways in which Asian orography affects the monsoon. I would agree that there is a widespread belief that controversy exists, but if one actually reads the recent literature one will find little actual disagreement. Wu et al. (2012) clearly state that elevated orographic heating is primarily important for a “northern branch” of the South Asian monsoon that exists north of 20N and lies “along the southern margin of the Iranian Plateau-Tibetan Plateau in the subtropics.” That view is very consistent with Boos and Kuang (2010), who showed that Tibetan Plateau surface enthalpy fluxes indeed produced a large fraction of summer rainfall along the plateau’s southern margin, but made negligible contribution to the interhemispheric monsoon circulation and the main rainfall maxima, both of which lie south of 20N. Boos (2013, CLIVAR Exchanges) reviewed the agreement between Wu et al. 2012 and Boos and Kuang 2010, and discussed the lack of disagreement in recent literature concerning the influence of topography on the South Asian monsoon. So while it would be interesting to see results from the proposed orographic perturbation experiments, I think the authors should seriously consider whether it is desirable to use such a large amount of modeling and computational resources to examine something that is not fundamentally controversial when one reads the literature closely.

Response:

Thanks. In the revised version, we replaced the statement of “the relative roles of the two effects remain controversial” with “the relative roles of the two effects deserve further investigation” **(P4, L2)**. The statement in section 5.4 of “remains debatable” is replaced with “needs further study” **(P10, L25)**. In addition, the model resolutions in most old GCMs (100km or so) are not high enough to resolve the complex topography over south slope of TP and we hope the higher resolution models of CMIP6 could better resolve these effects. Recent progress indicates that the surface entropy over northern India is quite sensitive to the large-scale thermal forcing of TP and cannot be solely attributed to the barrier effect of TP (Wu et al., 2015, Climate Dynamics; He et al., 2015, Scientific Reports). Since these results may be model-dependent, we hope other modeling centers can also do the experiments. In addition, this experiment is listed as Tier-3 experiment (viz. low priority) and honestly we expect only a few modeling centers that have specific interest in the monsoon to do the experiment.

c. Turning off sensible heat fluxes from all Asian topography higher than 500 m in the proposed “TIP” domain amounts to imposing a huge negative heat sink over roughly half of the Asian continent. The authors propose to suppress sensible heat fluxes from most of the red and orange regions in the “Asia” box in Fig. 5, which includes parts of continental India as well as much of China and Mongolia — regions not thought to be involved in “elevated heating” when it is discussed in the monsoon literature.

In other words, it would be surprising if the monsoon did not weaken when surface sensible heat fluxes were suppressed over one-third to one-half of Asia, whether or not that terrain was elevated! These experiments thus don’t clearly test the idea that elevated heating from Tibet or from the slopes of the Himalaya are a key forcing for the South Asian monsoon (and as stated above, both Wu et al. 2012 and Boos and Kuang 2010 already agree that elevated heating from those regions forces precipitation along the Himalayas but not the interhemispheric South Asian monsoon *circulation). Finally, modern theory for tropical atmospheric dynamics places surface latent heat fluxes on the same footing as surface sensible heat fluxes in their influence on large-scale flow (e.g. see theories for convective quasi-equilbirium, reviewed by Emanuel et al. 1994 QJRMS, or theories for the energy flux equator discussed by Kang et al. 2008, J. Climate p. 3521), so it is unclear why there should be a special emphasis on surface sensible heat fluxes. I thus suggest the authors reconsider the design of the TIP-NSH experiment.*

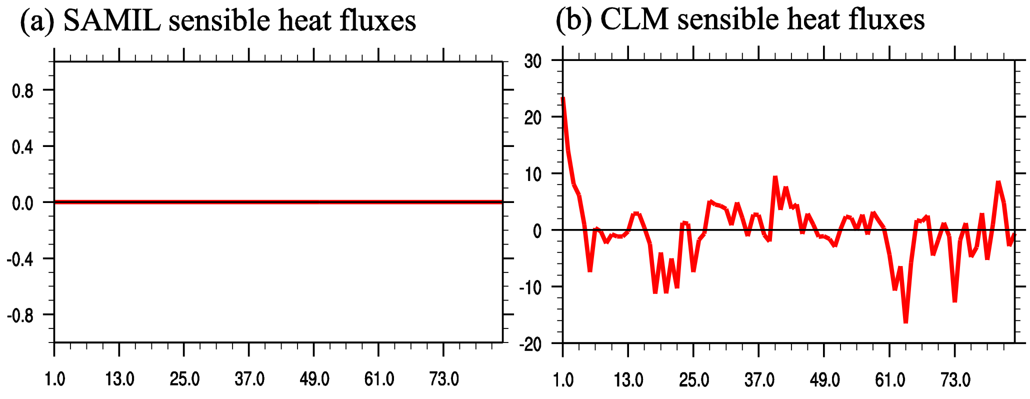
Response:

We agree that the latent heat fluxes are very important over the tropical oceans to produce low level instability for moist convection. However over the land in Asia, the link of local evaporation and precipitation is relatively weak (He et al., 2015, Scientific Reports), and the sensible heat flux is the major term which causes the PV anomaly at the surface to draw water vapor from the Indian Ocean. Meanwhile the latent heat flux (evaporation) is also affected by the SH. Therefore the SH is regarded as the main driver of the behavior of the low level atmosphere and possibly also the upper troposphere and lower stratosphere (Wu et al., 2016, *Science China Earth Sciences*). The importance of elevated heating has been emphasized by He (2016, *Theor. Appl. Climatol.*), and the responses can be obtained from the differences between AMIP-TIP-nosh and AMIP (which is the control run). Again, to examine whether the responses are model dependent, we hope other modeling centers will do the experiment. This experiment is listed as Tier-3.

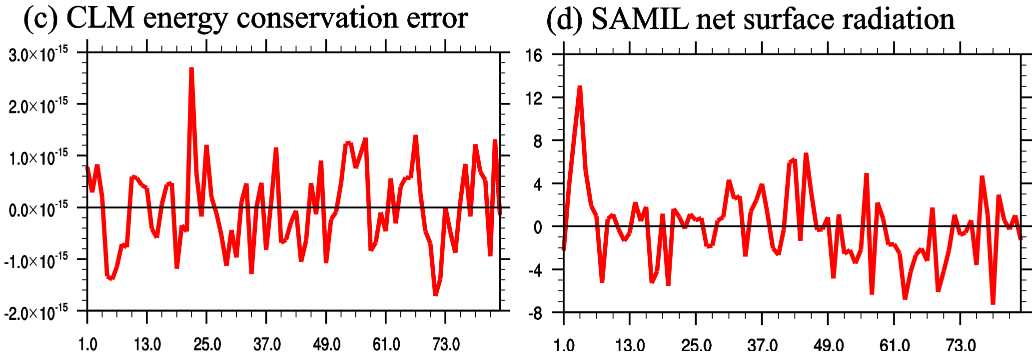
d. The methodology for eliminating the surface sensible heat flux in the orographic perturbation experiments is unclear and may lead to different approaches being taken by different modeling groups. The manuscript states that, as in Wu et al. (2012), surface sensible heating will be suppressed by setting "the vertical diffusive heating term in the atmospheric thermodynamic equation" to zero. But does this mean that heat will accumulate just above the surface and will not diffuse upward through the boundary layer, so that the column will eventually become unstable to dry convection or to grid-scale overturning? And how exactly does suppressing this *vertical diffusion alter the land surface energy budget … e.g. will land surface temperatures and longwave emission become very high because heat cannot diffuse away from the land surface? Participating models may have dramatically different methods of parameterizing the subgrid scale vertical redistribution of surface sensible heat fluxes. If one wanted to suppress surface heat fluxes (which is debatable, see previous point) it would seem better to prescribe a heat sink in the bottom layer of the atmosphere that is exactly equal to the surface sensible heat flux at that time step. Then the net land surface energy budget will not be directly altered, the surface sensible heat flux will not heat the atmosphere, and one does not need to worry about the various ways in which different models represent vertical diffusion.*

Response:

The sensible heating (vertical heat diffusion in atmosphere) is set to zero for each step in the atmospheric model, and will not be accumulated at the model surface. The sensible heat flux in the atmospheric model is zero (Fig. R1a), while the sensible heat flux in the land model continues to be updated (Fig. R1b), and the procedure will not affect the land surface energy conservation (Fig. R1c), and the net surface radiation balance on the surface of the atmosphere model is reasonable (Fig. R1d).


(a) SAMIL sensible heat fluxes

(b) CLM sensible heat fluxes


(c) CLM energy conservation error

(d) SAMIL net surface radiation

Fig. R1. The evolution (the abscissa is in units of months from the startup run of the model) of various variables anomaly in the IAP/LASG atmospheric model (SAMIL) and land model (CLM) in the amip-TIP-nosh experiment respectively: (a) Sensible heat flux in atmosphere model, (b) sensible heat flux in land model, (c), the error in energy conservation in land model, and (d) the net surface radiation in atmosphere model.

2. This manuscript seems to assume that model bias will not compromise the ability of the proposed experiments to provide insight on the cause of monsoon variability. For example, the authors state at top of p. 6 that comparing prescribed SST integrations with fully coupled integrations will allow the authors "to determine the importance of SST variability to long and short-term trends in the monsoons." But later they state that "simulations with specified SST generally have low skill in simulating the interannual variation of the summer precipitation over global monsoon domains". So it is very possible that the specified SST integrations will have such large bias that it will not be possible to use them to understand long- and short-term trends. This problem is difficult, at best, to fix, but I would have at least liked to see more acknowledgment of this problem and more attempts to gauge model skill through comparison with observations. For example, the authors state that comparison of pre-industrial control simulations with the Tier-2 experiments will "allow us to determine which parts of apparent decadal variations in the monsoons are caused by underlying SST, and which are forced solely from externally driven sources, such as volcanic emissions." But what if all of the models have a strongly biased response to volcanic emissions? Some users of the GMMIP archive might compare with observations and stratify models by their skill in simulating, e.g., the response to Pinatubo, but this cannot be assumed — there are numerous examples of model intercomparisons in which every model in an ensemble is treated equally. The bottom line is that I suggest more discussion of the possibility that model bias will make it difficult to draw conclusions about causation, and more concrete proposals *for how to deal with this bias if it is found to exist. Otherwise one runs the risk of gaining little new understanding from the proposed large amounts of simulation.*

Response:

Thanks for comments. Yes, climate models have been showing and will continue to show bias in many aspects. We have to balance the needs of scientific research and the performances of the current state of the art climate models. A multi-model intercomparison approach is a useful way to provide insights for reducing the uncertainty due to model bias. This is the reason why MIPs for CMIP6 are needed. As suggested, the impact of model bias on the conclusion should be discussed. We have added a paragraph in the revised manuscript:

> "Current state-of-the-art climate models still show bias in the simulation of monsoon (Sperber et al. 2013). We acknowledge that attention should be paid to the model bias in the analysis of model outputs, although multi-model ensemble/intercomparison approach is a useful way to better quantify the uncertainty related to model bias" **(P10, L2-4)**.

In addition, the analysis of GMMIP will focus on both monsoon circulation and monsoon precipitation. Although SST-driven AGCM simulations generally have low skill in the simulation of monsoon precipitation over the Asian-Australian monsoon domain due to the neglect of air-sea coupling and model bias, the large scale monsoon circulation changes have significant skill at both interannual and inter-decadal time scales. This has been demonstrated in many published papers. Thus at the top of p. 6 of the original manuscript, we revised the statement: "to determine the importance of SST variability to long and short-term trends in the monsoon circulations and the associated precipitation" **(P6, L4-5)**.

Minor technical issues:

3. After the introduction, the manuscript quickly becomes somewhat difficult to read for those who are not deeply familiar with the CMIP terminology. This could be easily remedied by clearly explaining the meaning of various terms when they are first introduced. E.g. what are the "DECK" experiments? What is a "pacemaker" *experiment? It is possible for the reader to figure out what is meant by a pacemaker experiment, but a clearer statement and references to literature discussing the history and caveats of pacemaker experiments would be very helpful. On p. 4, line 31 the terms "Tier-1" and "Tier-3" are used without being previously defined, and I was confused about what these terms meant until they were defined a full page later.*

Response:

Thanks. We have revised as suggested. In addition, a paper of CMIP6 design which clearly described the CMIP6 core experiments such as DECK has been cited **(P4, L29)**:

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016.

4. Unclear what is meant by "model climatology" on p. 6, line 8. Is this a cyclic seasonal cycle of daily resolution, or the full, interannually varying daily time series of SST from the coupled CMIP6 integration?

Response:

It is the former. We have clarified this in Appendix I **(P12, L12)**.

5. Equation (1) is introduced in method (b), but it also defines the "constructed SST" introduced in (a), with the linear decay of the relaxation time in the buffer zone already "built in". My point is that it would seem more clear to introduce equation (1) in method (a).

Response:

We added an equation for method (a) to make the difference between (a) and (b) clearer **(P12, L15)**.

6. Page 12, line 9: isn't 50 m a very deep mixed layer depth for the East Pacific, which is the main region of interest for the "IPO" pacemaker experiment? This could *result in a factor of 2 or more difference in the effective restoring times for SST in the IPO and AMO pacemaker experiments. Would at least be nice to see some mention of why it's acceptable to use a 50 m mixed layer depth in the East Pacific.*

Response:

The choice of 50m for hist-resIPO is based on Kosaka and Xie (2013, *Nature*). For the hist-resAMO experiment, we use a restoring time of 2 months following the DCPP Component C experiments (Boer et al., 2016). For hist-resIPO, 10m typical mixed layer and 10-day restoring time are used so the restoring intensity is comparable between hist-resIPO and hist-resAMO **(P13, L1-6)**

7. The box marked around the "Asia" domain in Fig. 5 does not agree with the coordinates given in Table 2. Should there be agreement? If not, what do the boxes in Fig. 5 represent?

Response:

The domain description has been revised. Now the text is consistent with the figure **(P25)**.

Reviewer #3: Anonymous Referee

This is an overview of one of satellite MIPs under CMIP6, which is already endorsed by the CMIP6 panel. Therefore only minor comments are given here.

Minor comments:

(1) page 2, line 7: The East Asian monsoon is controlled by zonal temperature and pressure gradient. Therefore, "meridional temperature and pressure gradients" should be replaced with "temperature and pressure gradients" without "meridional".

Response:

Done **(P2, L8)**.

(2) page 4: Four primary scientific questions are raised here, but how predictability of monsoons can be solved by GMMIP is unclear. Delete this question or include one sub-section regarding this in Section 5.

Response:

The term “predictability” is replaced with “reproducibility” in the revision **(P4, L16)**. The interannual variability of monsoons simulated by stand-alone AGCMs will be compared to the results of fully coupled models. The impact of air-sea interaction in the reproducibility of interannual monsoon variation will be addressed.

(3) page 5, line 8: regional climate information is not a part of WCRP Grand Challenges (unfortunately).

Response:

We deleted this part. In the draft version of WCRP grand challenge documentation, the regional climate information was among the list.

(4) page 8, Section (5): How is CORDEX data planned to use?

Response:

This has been clarified in the revision **(P9, L7-11)**.

“In the core framework of CORDEX phase 2 (CORDEX2 hereafter), a core set of regional climate models (RCMs) downscales a core set of GCMs over all or most

CORDEX domains at 10-20 km resolutions (Gutowski Jr., et al. 2016). The comparisons of CORDEX2 historical climate downscaling with the driving GCMs historical simulations, will give insight into the importance of model resolution and the added value of RCMs in the simulation of climatology and variability of global monsoon, especially the global land monsoon."

(5) page 9, line 29: A maximum width of the Meiyu/Baiu rain band is about 200 km in a climatological time averaging, but it consists of meso-scale cloud clusters. This is why high-resolution modeling is needed.

Response:

Thanks. We have revised the statement as suggested **(P10, L18-19)**.

(6) page 11: In the pacemaker experiments, SST is restored to daily climatological SST. On the other hand, in the AMIP experiment, the Taylor-corrected monthly mean SST is used after interpolation into daily values. Therefore temporal behavior of SST is different between the AMIP and the pacemaker experiments. Doesn't this matter?

Response:

In the pacemaker experiments, the SST is restored to a constructed SST which is climatological model SST plus observed anomalies to reduce model drift. We suggest using the same SST data as in AMIP experiments to calculate the observational anomalies. So variability at all the time scales is the same between these two types of experiments **(P12, Appendix I)**.

Reviewer #4: A. Cherchi

The manuscript deals with the description of the GMMIP experiments in the framework of the next CMIP6 effort. The Introduction is a nice overview of the main issues of monsoon variability and simulation, including still unsolved shortcoming in monsoon modelling that should benefit from the experiments and the comparison proposed. Overall the manuscript is well structured, however I have few general comments and some technical corrections as listed below.

General comments:

1 - Why the term "global monsoons" is plural? The global monsoon represents the global hydrological cycle and it is very important/interesting to have metrics to consider it as a single phenomenon. Nevertheless it is composed by the regional monsoons. I think it is important to stress on the manuscript the need to have both, as this would help merging the contribution from the different communities dedicated to the regional monsoons (actually this is done in some parts, I would check it to be consistent in the whole manuscript)

Response:

Here is a clarification for the terms “global monsoon” and “global monsoons”. . In the revised manuscript, we use “global monsoon” to highlight the consistent changes of all regional monsoons at longer time scales, and the role of the monsoon system in the global hydrological cycle; whereas we use “global monsoons” to highlight the regional features of different monsoons and the contribution of regional monsoon systems to the global hydrological cycle **(P2, L14-17)**.

2 - In the Introduction the issue of the recent observed decrease in precipitation over India and the tendency of the coupled models to have increased precipitation when the atmospheric CO2 increases should be discussed (i.e. issues of thermodynamical versus dynamical changes in precipitation as discussed in Cherchi et al., 2011 and in Endo and Kitoh, 2014 for the different monsoon regions) - see references: Cherchi et al. (2011) Clim Dyn 37 83-101 doi:10.1007/s00382-010-0801-7; Endo and Kitoh (2014) GRL 41 1704-1710 doi:10.1002/2013GL059158.

Response:

Thanks. This has been revised as suggested and the relevant papers have been cited **(P3, L14-18, L25-27)**.

3 - Table 1: a useful information that should be added in this table and that should be mentioned in paragraphs 4.2 4.3 4.4 and 4.5 is the models involved in GMMIP that will be also involved in the other respective MIPs. This would help to know how many models (i.e. how large will be the sample) could be included in the comparison

Response:

This is a good idea, but other MIPs do not provide the model information in their papers or websites, except for HighResMIP. We hope we can provide this information on the GMMIP website, pending the publication of CMIP6 documentation papers.

4 - You should specify if you have specific requirements for the variables (and respective time-frequency) that should be saved as output from the GMMIP experiments (they should be listed in the manuscript)

Response:

The variables and time frequency of model output are now listed in Appendix II **(P13-16)**.

5 - You should specify what specific criterion should be used for the TIP-NSH experiment (tier-3) to cut off the sensible heating from the selected regions

Response:

This has been clarified **(P7, L6-8; P25)**.

"…the vertical temperature diffusion term in the atmospheric thermodynamic equation at the bottom boundary layer is set to zero (Wu et al., 2012). The atmospheric component will not see the surface upward sensible heat flux (zero), whereas the land component is as usual."

Some technical corrections:

Page 1, line 20: change "during" with "in"

Response:

Corrected.

Page 1, line 23: remove the comma after the word "DECK"

Response:

In the CMIP6 framework, the “historical” simulation is not on the list of DECK experiments (see the overview paper of CMIP6, Eyring et al., 2016), so we have separated them with a comma.

Page 1, line 27: I would use "benefit monsoons prediction .." instead of "benefit monsoon prediction .."

Response:

Corrected.

Page 2, lines 15-18: I think that in the Introduction the issue of internal feedback should be separated from that of external driven processes, and discussed in more detail

Response:

We have re-organized the paragraphs **(P2-3).**

Page 6, sections 3.2 and 3.3: what are the initial conditions for these experiments? how long are these experiments? I would suggest including these information also in the text not only in the table

Response:

Added **(P6, L10-12)**.

Page 6, line 15: I would insert "coupled" between "historical" and "climate"

Response:

Corrected **(P6, L21)**.

Page 6, lines 23-24: I think it is better to consider the tier-3 as a perturbation of the Tier-1 rather to the DECK (it is the same, it is just a matter of flow of the description)

Response:

The Tier-3 experiment is to test the sensitivity of high topography and the sensible heating associated with it, mainly focusing on the effects on monsoon climatology. It is too expensive (and likely unnecessary) to run for the same period as GMMIP Tier-1 experiment.

Page 7, line 5: what do you mean by "standard CMIP6 horizontal and vertical resolutions"

Response:

This has been revised to “the same resolution as used in DECK”.

Page 7, section 4.1: the chain of comparisons between different experiments is a bit confusing. Consider rewriting the paragraph. More for the comparison of Tier-2 experiments with pre-industrial and historical simulations, please consider that in the former (tier-2 experiments) you have prescribed SST in selected regions but you have also the contribution of anthropogenic GHG and aerosols

Response:

Related parts have been rewritten. The Tier-2 experiments are assumed to have “real” forcing signal and decadal drivers in the ocean. Thus comparing it with pre-industrial simulations would allow us to check the role of external forcings, while comparing it with historical run would allow us to check the roles of internal decadal modes, e.g., IPO and AMO **(P7, L22-28)**.

Page 7, lines 28-29: not clear, please rewrite. Why high resolution in the mid-latitudes?

Response:

This has been rewritten **(P8, L12)**.

Page 7-8, section 4.3: It should be mentioned in the manuscript that in HighResMIP the SST used to build the AMIP experiments will be used as daily mean, differently from the other AMIP protocol. This should be considered also for the kind of comparison that would result. Also in HighResMIP the aerosols would be sort of prescribed (mandatory use of MPI simple plume module for anthropogenic aerosols). This should also be mentioned and discussed in terms of possible comparisons with GMMIP experiments

Response:

These points have been clarified in the revision **(L8, P13-16)**.

Page 8, lines 24-26: this could also be a hard comparison because of the specificity of the HighResMIP experiments as mentioned in the comment just above. You should mention what kind of specific metrics/analysis could be used/you have in mind for this comparison?

Response:

Yes. The statement has been revised to "A comparison of CORDEX2 evaluation framework experiments forced with daily mean SST to HighResMIP Tier 1 runs over global monsoon domains will provide information on the similarities and differences of the added values derived respectively from high resolution global models and regional climate models." **(P9, L12)**

Page 9, line 7: "ACGM" should be "AGCM"

Response:

Corrected **(P9, L23)**.

Page 9, lines 7-9: both 20CR and ERA20C are global atmospheric reanalyses that assimilate only the surface pressure (and the SST are prescribed)

Response:

This has been revised **(P9, L23-24)**.

Page 9, line 7-8: you should include references for 20CR and ERA20C

Response:

References added **(P9, L24)**.

Page 9, line 15: "global monsoon" instead of "global monsoons"

Response:

As in the response to your first comment, here we use the term “global monsoons” to emphasize different monsoon domains.

Page 11: "Data availability" should be an appendix, I guess (see also general comment above for specific requirements on variables and related time frequency)

Response:

The location of “Data availability” is suggested by the CMIP6 special issue organizer. We added a part to show data requirements in the appendix II **(P13-16)**.

Page 11, line 25: insert "coupled" between "historical" and "simulation"

Response:

Done **(P12, L13)**.

Reviewer 5: K. E. Taylor

The CMIP Panel is undertaking a review of the CMIP6 GMD special issue papers to ensure a level of consistency among the invited contributions, and to consider whether the co-chairs adequately addressed the key questions outlined in our request to submit a paper. We very much welcome the important contribution from GMMIP to the CMIP6 special issue, below are a few comments:

- *Thank you for responding to our request (through the editor) promising to revise your title consistent with others in this special issue.*
- *It would be helpful to replace "other MIPs" (and* similar constructs) *in some places with "endorsed MIPs" to make clear the cohesiveness of the CMIP6 set.*

Response:

Revised as suggested.

- *There is essentially no discussion of any special data required for your analyses.*
- *Perhaps there are no special needs, but it would be good to at least include some discussion of the priority 1 data request. In particular, if data with temporal resolution greater than a month are needed, then indicate this, especially if 3-d (spatially) fields are required. Without emphasizing this, some groups may not realize the importance of saving the needed fields.*

Response:

We now have added Appendix II to clarify what kinds of data are required **(P13-16)**.

GMMIP (v1.0) Contribution to CMIP6: Global Monsoons Model Inter-comparison Project

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Abstract. The Global Monsoons Model Inter-comparison Project (GMMIP) has been endorsed by the panel of Coupled Model Inter-comparison Project (CMIP) as one of the participating MIPs in the sixth phase of CMIP (CMIP6). The focus of GMMIP is on monsoon climatology, variability, prediction and projection, which is relevant to four of the "Grand Challenges" proposed by the World Climate Research Programme. At present, 21 international modelling groups are committed to joining GMMIP. This overview paper introduces the motivation behind GMMIP and the scientific questions it intends to answer. Three tiers of experiments, of decreasing priority, are designed to examine: (a) model skill in simulating the climatology and interannual-to-multidecadal variability of global monsoons in SST-forced experiments of the historical climate period; (b) the roles of the Interdecadal Pacific Oscillation and Atlantic Multidecadal Oscillation in driving variations of the global and regional monsoons; and (c) the effects of large orographic terrain on the establishment of the monsoons. The outputs of the CMIP6 DECK, "historical" simulation and endorsed MIPs will also be used in the diagnostic analysis of GMMIP to give a comprehensive understanding of the roles played by different external forcings, potential improvements in the simulation of monsoon rainfall at high resolution and reproducibility at decadal time scales. The implementation of GMMIP will improve our understanding of the fundamental physics of changes in the global and regional monsoons over the past 140 years and ultimately benefit monsoons prediction and projection in the current century.

Key Words Monsoon, anthropogenic forcing, internal variability, interdecadal variability, Interdecadal Pacific Oscillation, Atlantic Multidecadal Oscillation, interannual variability, elevated heating

1 Introduction

Changes in the precipitation and atmospheric circulation of the regional monsoons are of great scientific and societal importance owing to their impacts on more than two-thirds of the world's population. Prediction of changes to monsoon rainfall in the coming decades is of deep societal concern and vital for infrastructure planning, water resource management, and sustainable agricultural and economic development, often in less developed regions.

The dominant monsoon systems defined by precipitation characteristics include the Asian, Australian, Northern and Southern African, the North American, and the South American monsoons (Wang, 1994; Wang and Ding, 2008; Fig. 1). Each system generally has its own unique characteristics in terms of the evolution, variability and impacts due to its indigenous land-sea configuration and the particular atmosphere-ocean-land interaction involved. At the same time, the regional monsoons have in common the fundamental driving factors of temperature and pressure gradients, and they are bounded by the global divergent circulation necessitated by mass conservation as they evolve through the season (Trenberth et al., 2000). The global monsoon represents the dominant mode of the annual variation of precipitation and circulation in the global tropics and subtropics (Wang and Ding, 2008) and as such, the global monsoon is a defining feature of Earth's climate. On the annual time scale, the global monsoon is a planetary scale circulation system with a seasonal reversal of the three-dimensional monsoon circulation that is accompanied by the migration of the monsoon rainfall zones. However, it remains debatable to what extent and at which time scales the global monsoon – defined as the regional monsoons acting together – can be viewed as a major mode of climate variability (Wang et al., 2014). To facilitate the discussion, we use "global monsoon" to regard all the monsoon domains as a whole and a single phenomenon to highlight the integrated role of monsoons in global hydrological cycle, whereas we use "global monsoons" to highlight the regional features of different monsoon domains over the globe.

To what extent can internal feedback processes in the climate system drive the interannual variations of global monsoon precipitation? Wang et al. (2012) have shown that from one monsoon year (defined as May to the next April) to the next, most continental monsoon regions, separated by vast areas of arid trade winds and deserts, vary in a cohesive manner driven by the El Niño-Southern Oscillation (ENSO). On decadal time scales, numerous studies have investigated the linkage between regional monsoons and other major modes of climate variability. For instance, the Australian summer monsoon was linked to the Interdecadal Pacific Oscillation (IPO; Power et al., 1999a); the Indian summer monsoon precipitation has a correlation with the North Atlantic Oscillation (NAO) (Goswami et al., 2006) and the IPO (Meehl and Hu, 2006); the East Asian summer monsoon is related to the Atlantic Multidecadal Oscillation (AMO; Enfield et al., 2001; Lu et al., 2006) and the Pacific Decadal Oscillation (PDO; Mantua and Hare, 2002; Li et al., 2010; Qian and Zhou, 2014; Zhou et al., 2013); the variability of the west African and North American monsoons is related to the AMO (Sutton and Hodson, 2005; Zhang and Delworth, 2006; Gaetani and Mohino, 2013); and the African monsoon system is sensitive to inter-hemispheric SST variability in the Atlantic (Folland et al., 1986; Hoerling et al., 2006). Many decadal and interdecadal variations of regional monsoons have been identified, with differing periodicity and phase change points (Yim et al., 2014; Chen and Zhou, 2014; Lin et al. 2014). While these concepts can be collated and simplified by considering processes controlling the position of the zonal mean ITCZ (Schneider et al., 2014), a coherent global structure and the underlying causes of global monsoon interdecadal variability have yet to be widely studied.

The combination of changes in monsoon area and rainfall intensity has led to an overall weakening trend of global land monsoon rainfall since the 1950s (Wang and Ding, 2006; Zhou et al., 2008a). This decreasing tendency is dominated by the African and South Asian monsoons, as shown by the significant decreasing tendencies of both rainfall intensity and monsoon coverage area (Zhou et al., 2008b). Beginning in the 1980s, however, the Northern Hemisphere global monsoon precipitation has had an upward trend (Wang et al., 2012). These studies of the trends in relatively short precipitation records have not been able to confirm whether these trends are part of longer-period fluctuations. Recently, Wang et al. (2013) studied coherent interdecadal variations of the Northern Hemisphere summer monsoon (NHSM) by using the NHSM circulation index (defined by the vertical shear of zonal winds between 850 hPa and 200 hPa averaged in 0 °-20 °N, 120 °W-120 °E). The NHSM circulation index is highly correlated with the NHSM rainfall intensity over the modern record (r=0.85 for 1979-2011). They demonstrated that the NHSM circulation has experienced large-amplitude multidecadal fluctuations since 1871, primarily attributed to a mega-ENSO (a leading mode of interannual-to-interdecadal variation of global sea surface temperature) and the AMO. Only about one third of the recent increasing trend in the NHSM rainfall since 1979, when measured across the whole northern hemisphere, was attributed to anthropogenic warming.

How forcing agents, including both of the anthropogenic and natural, impact global monsoons changes is another important but tough question. Dynamical and thermodynamical changes of monsoon rainfall could cancel each other to some extent under greenhouse gases (GHG) forcing (Cherchi et al., 2011; Endo and Kitoh, 2014; Chen and Zhou, 2015). However, the relative contributions of these two processes to observed global monsoon rainfall changes due to anthropogenic GHG forcing are still unknown. The interaction of aerosol forcing with monsoon dynamics may alter the redistribution of energy in the atmosphere and at the Earth's surface, thereby changing the monsoon-related water cycle and climate (Lau et al., 2008). Aerosols may reduce surface solar insolation, thus weakening the land-ocean thermal contrast and modifying the formation and development of monsoons. Many mechanisms have been proposed in the past two decades regarding the impact of aerosols on monsoon circulation and precipitation. These mechanisms are complicated by the feedbacks with large-scale moist environmental dynamics, so large uncertainties still remain (Qian and Giorgi, 1999; Menon et al., 2002; Qian et al., 2002, 2009, 2011). The aerosol-monsoon interaction has attracted rapidly increasing interest in the global climate modelling community. The relative importance of aerosol forcing and global warming to observed trend of monsoon rainfall, for example the decreasing of Indian rainfall in the recent decades, also need to be clarified (Bollassina et al., 2011; Annamalai et al., 2013; He et al., 2016). Understanding the mechanisms of precipitation changes in the global monsoon system and identifying the roles of natural and anthropogenic forcing agents have been central topics of the monsoon research community (Cook et al., 2013; Liu et al., 2013; Song et al., 2014; Polson et al., 2014; Guo et al., 2015).

While all monsoons are associated with large-scale cross-equatorial overturning circulations, major differences in the characteristics of the regional monsoons arise because of the different orography and underlying surface as well as the external forcing. This is most apparent for the Asian region, due to the Tibetan – Iranian Plateau, Himalayan mountains and strong anthropogenic forcing from aerosol emissions and land-use change. The highlands may act as a physical barrier that isolates the heat and moisture south of the Himalaya and a high-level heat source (pump) that directly drives the monsoon circulation through meridional thermal contrast (Yeh, 1957; Flohn, 1957; Yeh and Wu, 1998; Yanai and Wu, 2006). However, the relative role of the two effects deserve more discussion (Boos and Kuang, 2010, 2013; Wu et al., 2012; Qiu et al., 2013).

Climate models are useful tools in climate variability and climate change studies. However, the performance of current state-of-the-art climate models is very poor and needs to be greatly improved over the monsoon domains (Cook et al., 2012; Kitoh et al., 2013; Wang et al., 2005; Zhou et al., 2009a; Sperber et al., 2013; Song and Zhou, 2014ab). As one of the endorsed MIPs in the sixth phase of the Coupled Model Inter-comparison Project (CMIP6) (Eyring et al., 2016), the Global Monsoons Model Inter-comparison Project (hereafter GMMIP) aims to improve our understanding of physical processes in global monsoon systems by performing multi-model inter-comparisons, ultimately to work towards better simulations of the mean state, interannual variability and long-term changes of the global monsoons. The contributions of internal variability (IPO and AMO) and external anthropogenic forcing to the historical evolution of global monsoons in the 20th and 21st century will also be addressed.

GMMIP aims to answer four primary scientific questions:

(1) What are the relative contributions of internal processes and external forcing that are driving the historical evolution of monsoons over the late 19th through early 21st centuries?

(2) To what extent and how does atmosphere-ocean interaction contribute to the interannual variability and reproducibility of monsoons?

(3) How can high resolution and associated improved model dynamics and physics help to reliably simulate monsoon precipitation and its variability and change?

(4) What is the effect of the orography of the Himalaya/Tibetan Plateau on the development and maintenance of the Asian monsoon? Similarly, what is the impact of orography elsewhere on other regional monsoons?

By focusing on addressing these four questions we expect to deepen our understanding of the capability of models to reproduce the monsoon mean state and its natural variability as well as the forced response to natural and anthropogenic forcing, which ultimately will help to reduce model uncertainty and improve the credibility of models in projecting future changes in the monsoon. The coordinated experiments will also help advance our physical understanding and prediction of monsoon changes.

Due to the uncertainties in physical parameterizations in current models, particularly in convection schemes (Chen et al., 2010), the best way to address the above questions is through a multi-model framework in order capture the range of possible responses to forcing. The multi-model database to be produced for CMIP6 (Eyring et al., 2016), in conjunction with the GMMIP experiments will provide an opportunity for advancement of monsoon modeling and understanding. GMMIP will also contribute to the Grand Challenges of the World Climate Research Programme (WCRP) and address them in the following way:

(1) Water Availability

The water resources in global monsoon domains are greatly affected by the anomalous activities of monsoons. The summer monsoons produce more than 80% of the annual rainfall in some areas, e.g., in India, Africa and Australia, and the percentage is more than 60% averaged across all global monsoon regions (Fig. 2). Understanding the mechanisms of monsoon variability on interannual and longer time scales as posed by GMMIP will lead to improvement of monsoon prediction and projection and provide useful information for policymakers in water availability-related decision making.

(2) Climate Extremes

Extreme events such as mega-droughts and flooding are frequent occurrences in monsoon domains. GMMIP will allow the impact of changing lower boundary forcing on the statistics of extreme events to be examined in a consistent manner.

(3) Clouds, Circulation and Climate Sensitivity

A reasonable simulation of monsoon circulation is a prerequisite for a successful simulation of monsoon precipitation (e.g., Sperber et al., 2013). At the same time, tropical precipitation is strongly dependent on convection, with monsoon precipitation biases very sensitive to convective parameterizations and therefore clouds. These parameterizations also lead to large uncertainties in climate sensitivity (e.g., Stainforth et al. 2005). By comparing the performance of climate models with relatively high and low resolutions, and model simulations with and without air-sea interaction processes, GMMIP will attempt to link monsoon precipitation simulation with the fidelity of the large-scale circulation and latest remote sensing estimates of clouds.

2 Participating models

So far 21 international modelling groups have committed to contributing to GMMIP (as shown in Table 1). The diversity of the groups from different countries and regions demonstrates that the global monsoons topic appeals to a wide range of modelling and research communities. The models with various structures, physical parameterizations, resolutions etc. will provide a large sample size to help reveal the causes of monsoon variability on interannual and longer time scales in the climate system. Based on the experimental protocol (see Section 3), both atmosphere-only and fully coupled ocean-atmosphere versions of these models will be used.

3 Experimental protocol

Based on the priority level of proposed scientific questions, the main experiments of GMMIP, which are summarized in Table 2, are divided into ***Tier-1, Tier-2, and Tier-3 of decreasing priority*** (Fig. 3). In order to diagnose internal variability, at least 3 members integrated from different initial conditions are required for Tier-1 and Tier-2 experiments. Pending the availability of computer resources at GMMIP-committed climate-modeling centers, realizations with more than 3 members are encouraged.

3.1 Tier-1: Extended AMIP experiment

The Tier-1 experiments are extended AMIP runs from 1870 to 2014. This is the entry card for GMMIP. All external forcings (solar, aerosol, GHGs, etc.) should be derived from those used in the Historical simulation of the CMIP6 fully coupled model. This will allow a direct comparison of the Historical simulation and extended AMIP run, to determine the importance of SST variability to long and short-term trends in the monsoon circulations and the associated precipitation. The boundary conditions for sea-surface temperature and sea ice are derived from a merged version of the Hadley Centre sea-Ice and SST (HadISST) and Optimum Interpolation Sea Surface Temperature (OISST) data sets (Hurrell et al., 2008), which can be downloaded from the PCMDI website[1].

3.2 Tier-2: Decadal mode relaxation experiments

The Tier-2 experiments are initialized from “historical” run year 1870 and integrated up to year 2014 with historical forcings. Additionally, the variation in the Tropical Pacific and North Atlantic SST are restored to the observation in the “hist-resIPO” and “hist-resAMO” runs, respectively. The Tier-2 “hist-resIPO” (historical anthropogenic forcing plus restoring IPO SST) run is a pacemaker historical coupled climate simulation that includes all forcings as in the CMIP6 historical experiment, but with SST restored to the model climatology plus observed historical anomaly in the tropical lobe of the Interdecadal Pacific Oscillation (IPO; Power et al., 1999; Folland et al., 2002) domain (20°S-20°N, 175°E-75°W). This relaxation is applied with weight=1 in the inner box (15°S-15°N, 180°-80°W) and linearly reduced to zero in the buffer zone (zonal and meridional ranges are both 5°) from the inner to outer box (Fig. 4a). There are several restoring methods to realize such “pacemaker” simulations (see the Appendix I). To ensure stability during integration, we recommend nudging to the specified SST described above with a 10-day time scale (see the Appendix I for technical details).

Similarly, the Tier-2 “hist-resAMO” (historical anthropogenic forcing plus restoring AMO SST) run is a pacemaker historical coupled climate simulation that includes all forcings but with the SST restored to the model climatology plus observational historical anomaly in the Atlantic Multidecadal Oscillation (AMO; Enfield et al., 2001; Trenberth and Shea, 2006) domain (0°-70°N, 70°W-0°). The restoration is fully applied in the inner box (5°N-65°N, 65°W-5°W), and linearly reduced to zero in the buffer zone (zonal and meridional ranges are both 5°) from the inner to outer box (Fig. 4b).

3.3 Tier-3: Orographic perturbation experiments

The Tier-3 experiments is generally the same as the “amip” run in the CMIP6 DECK covering 1979-2014 except that some key topographies or air-land sensible heat flux are modified. In the Tier-3 “amip-TIP” run (viz. no Tibetan - Iranian Plateau) run, following Boos and Kuang (2011, 2013) and Wu et al. (2007, 2012), the topography of the Tibetan-Iranian Plateau (hereafter TIP, see Table 2 for detailed descriptions) in the model is modified by leveling off the TIP to 500m, with other surface properties unchanged (*Asia* region in Fig. 5). Other settings of the integration are the same as the standard DECK

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[1] http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/amipbc_dwnld.php

AMIP run. This experiment represents perturbations to both thermal and mechanical forcing of the TIP with respect to the standard DECK AMIP run. In an ensemble of experiments comprising the Tier-3 “amip-hld” run (viz. no HighLanDs) group, the topography of the East African Highlands in Africa (after Slingo et al., 2005), the Sierra Madre in North America and the Andes in South America is modified by setting surface elevations to 500m in those respective regions (Fig. 5).

Finally, in the Tier-3 “amip-TIP-nosh” run (viz. Tibetan - Iranian Plateau - no sensible heating), the surface sensible heat flux at elevations above 500m over the TIP is not allowed to heat the atmosphere, i.e., the vertical temperature diffusion term in the atmospheric thermodynamic equation at the bottom boundary layer is set to zero (Wu et al., 2012). The atmospheric component will not see the surface upward sensible heat flux (zero), whereas the land component is as usual. Other settings of the integration are the same as the standard DECK AMIP run. The differences between the standard DECK AMIP run and the amip-TIP-nosh are considered to represent the removal of TIP thermal forcing only and thus the circulation pattern of amip-TIP-nosh reflects the impacts of mechanical forcing.

3.4 Experiment outputs

The recommended output variables are listed in Appendix II.

4 Connection with DECK, Historical Simulation and endorsed MIPs

The Tier-1 experiment of GMMIP, i.e. the extended AMIP, uses the same resolution as in the DECK (Eyring et al., 2016). The amip-hist specifies external forcings that are consistent with those from the same model’s CMIP6 Historical Simulation over the 1870-2014 period. To comprehensively investigate the proposed GMMIP scientific questions, such as the impact of high resolution and roles of different forcing agents, the output from other related MIPs will be used in the diagnostic analysis of GMMIP as described below.

4.1 DECK and Historical Simulation

The pre-industrial control simulations from each modelling group's DECK experiments will be used to study the relation between global monsoon and IPO/AMO at decadal time scale. Comparing the control simulation (constant forcing) with the GMMIP Tier-2 decadal mode relaxation experiments in which all historical forcings are added will then allow us to find which parts of apparent decadal variations in the monsoons are caused by underlying SST, and which are more forced by externally driven sources, such as volcanic emissions. The CMIP6 historical simulations will also be used to examine the response of the global monsoon to external forcings such as anthropogenic GHG and aerosol emissions. The results of CMIP6 historical simulation will be compared with those of hist-resIPO and hist-resAMO in Tier-2 to identify the relative contributions of external forcing and apparently internal modes of variability (IPO/AMO).

4.2 DAMIP (Detection and Attribution MIP)

Several DAMIP experiments are useful to GMMIP. The histALL (enlarged ensemble size of historical all-forcing runs in DECK), histNAT (historical natural forcings-only run), histGHG (historical well-mixed GHG-only run), and histAER experiments (historical anthropogenic-Aerosols-only run) of DAMIP will be used in the analysis of changes in global monsoons dating back to 1870.

Analyzing combinations of the histALL, histNAT and histGHG ensembles will allow us to understand the observed evolution of global monsoon precipitation and circulation changes since 1870 in the context of contributions from GHG, the other anthropogenic factors and natural forcing. The contributions of these external forcings to global monsoon changes will be compared to those from modes of internal variability such as the IPO and AMO.

4.3 HighResMIP (High Resolution MIP)

The Tier-1 experiments of HighResMIP, which consist of AMIP runs with a minimum horizontal resolution of 25-50 km, will be used to compare with standard resolution control configurations and examine the added benefit, if any, of high-resolution models in reproducing both the mean state and year-to-year variability of global monsoons. It should be noted that the boundary conditions (both of SST and sea ice) used to build the AMIP experiments of HighResMIP is a new dataset with daily time frequency (Haarsma et al., 2016), which may make differences when comparing with standard AMIP forced by monthly datasets.

The Tier-2 experiments of HighResMIP, which are coupled runs consisting of pairs of both historic runs and control runs using fixed 1950s forcing including anthropogenic GHG concentrations and aerosol forcing, will be used in the analysis of climatology and variability of global monsoons, which aims to understand the role of air-sea interaction in modulating the simulation skill of the monsoon mean state and year-to-year variability. The anthropogenic aerosols are required to be prescribed in HighResMIP experiments following a standard method in CMIP6 DECK (Haarsma et al., 2016), rather than interactive aerosol processes embedded in atmosphere general circulation models (AGCMs). Different ways to deal with aerosols could lead to different aerosol distributions as well as aerosol forcings, which should be taken in consideration when comparing with GMMIP experiments.

4.4 VolMIP (Volcanic forcing MIP)

The Tier-1 experiment of the short set of VolMIP simulations is designed to create a large ensemble of short-term simulations of the 1991 Pinatubo eruption, using the same volcanic forcing recommended for the CMIP6 Historical simulation. It will be used in comparison with observations to understand the global monsoon response to injection of stratospheric aerosols over the tropics and to study impact mechanisms on global monsoon precipitation and circulation changes. Via its ensemble design, VolMIP can address the substantial uncertainty associated with the effects of volcanism during the historical period.

4.5 DCPP (Decadal Climate Prediction Project)

The outputs of DCPP near-term climate prediction experiments will be used to assess the skill of global monsoons in initialized decadal climate prediction. The C-component of DCPP is similar to the Tier-2 experiment of GMMIP but focuses on a shorter time period starting from 1950 (Boer et al. 2016). The outputs will be used to add to the ensemble size of pacemaker experiments from GMMIP Tier-2 during the 1950-2014 period.

4.6 CORDEX (international Coordinated Regional Downscaling Experiment)

In the core framework of CORDEX phase 2 (CORDEX2 hereafter), a core set of regional climate models (RCMs) downscales a core set of GCMs over all or most CORDEX domains at 10-20 km resolutions (Gutowski Jr., et al. 2016). The comparisons of CORDEX2 historical climate downscaling with the driving GCMs historical simulations, will give insight into the importance of model resolution and the added value of RCMs in the simulation of climatology and variability of global monsoon, especially the global land monsoon. A comparison of CORDEX2 evaluation framework experiments forced with daily mean SST to HighResMIP Tier 1 runs over global monsoon domains will provide information on the similarities and differences of the added values derived respectively from high resolution global models and regional climate models.

5 Analysis plan

The analysis plan will focus on the scientific objectives of GMMIP. We list the key scientific questions that we hope that the community will be able to answer following the implementation of GMMIP below.

5.1 Understanding the changes of global monsoons since the 1870s

We will examine whether decadal and multi-decadal variability of local monsoon systems and coherent changes of the global monsoon can be reproduced in the amip-hist experiment. Firstly, the skill of reproducing interannual and interdecadal changes in the regional monsoons will be compared with long-term observed records in local monsoon regions, such as using the All-India Rainfall index from 1870 (Parthasarathy et al., 1994) and the CRU global land precipitation from 1901 (Harris et al., 2014; Zhang and Zhou, 2011). The simulated monsoon circulation can be compared with 20CR and ERA20C reanalysis, which are also derived from AGCM simulations driven by observational SST, with surface pressure (marine wind additionally used in ERA20C) records are assimilated (Compo et al., 2011; Poli et al., 2016).

Secondly, the interannual variability of the monsoon systems has experienced dramatic interdecadal variations during past 60 years (e.g., since the 1950s to present, Wang and Ding 2006). The amip-hist results will be used to explore whether similar modulations occurred during the past 150 years, and what mechanisms are responsible for them.

Thirdly, the contributions of apparently internal variability modes (IPO and AMO) to global monsoon variability and the role of air-sea interaction will be evaluated based on the hist-resIPO and hist-resAMO experiments of Tier-2. Combined with CMIP6 DECK and DAMIP experiments, the roles of external forcing (GHG, aerosol, solar, etc.) and internal variability can be quantified. The impact of tropical volcanic eruption on the global monsoons can be explored specifically by analyzing VolMIP. Current state-of-the-art climate models still show bias in the simulation of monsoon (Sperber et al., 2013). We acknowledge that attention should be paid to the model bias in the analysis of model outputs, although multi-model ensemble/intercomparison approach is a useful way to reduce the uncertainty related to model bias.

5.2 Effect of air-sea interaction on interannual variability of precipitation in the global monsoons

Previous studies have noted that AGCM simulations with specified SST generally have low skill in simulating the interannual variation of the summer precipitation over global monsoon domains, especially the East Asian-western North Pacific summer monsoon domain (Wang et al., 2005). It is noted that in the real world the precipitation is negatively correlated with underlying SST in the western North Pacific monsoon domain, which is not reproduced by the AMIP runs (Wang et al., 2005). The deficiency of the AMIP simulations can be partially attributed to the exclusion of air-sea interactions (Song and Zhou, 2014b). Comparison between the Tier-1 and Tier-2 experiments of GMMIP can provide information about how the air-sea interactions influence the monsoon simulations on the interannual and interdecadal time scales in different monsoon domains. However, mean state tropical SST biases prevalent in coupled models are also known to affect the accurate connection of monsoon interannual variability with teleconnected drivers such as ENSO (Turner et al., 2005).

5.3 Measuring improvement in the global monsoons with high resolution modeling

Monsoon rainbands such as the Mei-yu/Baiu/Changma front usually have a maximum width of about 200 km (Zhou et al., 2009b). Climate models with low or moderate resolution are generally unable to realistically reproduce meso-scale cloud clusters embedded in the rainbands, thus partly leading to biases in the mean state, variability of monsoon precipitation and the northward propagation of these rainbands. We will examine the performance of high-resolution models in reproducing both the mean state and year-to-year variability of global monsoons. High-resolution rain-gauge observations and satellite precipitation products will be used to evaluate model performance.

5.4 Effects of large orographic terrain on the regional/global monsoons

The influence of the large-scale orography on the Asian summer monsoon includes both mechanical and thermal forcing. Various mechanisms have been suggested concerning the topographic effects; however, an overarching paradigm delineating the dominant factors determining these effects and the strength of impacts needs further study. We will analyze the Tier-3 experiments to provide a benchmark of current model behavior in simulating the impact on the monsoon of the Tibetan-Iranian Plateau (TIP, as well as surrounding regions of significant orography, see Table 2 for detailed descriptions) so as to stimulate further research on the thermodynamic and dynamic influence of the TIP on the monsoon. In particular the relative contributions of thermal and orographic mechanical forcing by the TIP on the Asian monsoon will be addressed. We will extend the studies from the TIP to other highlands including highlands in Africa, North America and South America.

5.5 Aerosol-monsoon interaction

While aerosol-cloud interaction (ACI) effects are partially incorporated in GCMs with various levels of complexity, the aerosol-radiation interaction (ARI) effect, which is believed to have more explicit impact on land-sea thermal contrast by reducing the surface solar insolation, is fully incorporated in most of CMIP6 models. To investigate the aerosol impacts on monsoon climate including both local forcing and remote forcing effects, we will examine the responses of climate models to natural (solar variability and volcanic aerosols) and anthropogenic (GHGs and aerosols) forcings based on DECK and DAMIP experiments. In particular, we will quantify and compare the separate climatic response of natural vs. anthropogenic forcing, and aerosol vs. GHG forcing, over the global monsoon area (e.g., Song et al., 2014). We will analyze how different forcings influence the general circulation and precipitation characteristics, such as extreme events, shift of precipitation spectrum, and diurnal cycle etc.

6 Concluding remarks

Several regions of the world are dominated by a monsoon-like cycle of rainy and dry seasons, which have a profound influence on ecosystems and human agriculture, economy and culture. Diabatic heating released during monsoon rainfall and its effect on the tropical and global atmospheric circulation extend the influence of monsoons globally. It is critical, then, to improve our understanding of the global monsoon, both in terms of better predicting the monsoon on short time scales and developing better projections of how the monsoon is likely to change in the future. The set of numerical experiments proposed for the GMMIP project, in conjunction with the experiments of partner MIPs such as DAMIP, HighResMIP, VolMIP, DCPP, and CORDEX, will help answer some fundamental scientific questions about the global monsoon and will help provide guidance about the future of monsoons as the planet’s climate changes. It is also hoped that the GMMIP will provide a good platform for the international climate modeling community in the collaboration of monsoon studies.

Data Availability

The model output from the GMMIP simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. As in CMIP5, the model output will be freely accessible through data portals after registration. In order to document CMIP6’s scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centres (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). Further information about the infrastructure supporting CMIP6, the metadata describing the model output, and the terms governing its use are provided by the WGCM Infrastructure Panel (WIP) in their invited contribution to this Special Issue. Along with the data itself, the provenance of the data will be recorded, and DOI’s will be assigned to collections of output so that they can be appropriately cited. This information will be made readily available so that published research results can be verified and credit can be given to the modelling groups providing the data. The WIP is coordinating and encouraging the development of the infrastructure needed to archive and deliver this information. In order to run the experiments, datasets for natural and anthropogenic forcings are required. These forcing datasets are described in separate invited contributions to this Special Issue. The forcing datasets will be made available through the ESGF with version control and DOIs assigned. In addition, observational SST and sea ice data are also required. These data are derived from a merged version of the HadISST and OISST datasets, which can be downloaded from the PCMDI website.

Appendix I: Restoring methods used in the "pacemaker" experiment

Owing to the difference in model formulation and the difficulty that some users may face in operating pacemaker experiments in coupled models, we offer a choice of three recommended methods for restoring the SST in the hist-resIPO experiments. The first method is recommended for hist-resAMO experiments.

(a) Restoring model SST in every model time step to the corresponding constructed daily SST with a time scale τ. To reduce model drift, the constructed SST is the sum of the model daily climatological SST with seasonal cycle for the period of 1950-2014 from the corresponding historical coupled simulation and the daily SST anomalies in the observation, which are interpolated from the raw observed monthly SST anomalies with the seasonal cycle for the same period removed. We suggest to use the AMIP SST to calculate the observational anomalies, consistent with Tier-1 experiment.

$$\frac{dT}{dt} = \text{Original trend terms} + \frac{(\overline{T_*}+T')-T}{\tau}. \tag{1}$$

Here T denotes the SST and the asterisks represent model-diagnosed values. The prime (bar) refers to the anomaly (climatology). Here the anomaly is based on AMIP SST, while the model's climatology refers to the seasonally evolved daily mean during 1950-2014 based on historical simulations. For the hist-resIPO (hist-resAMO) experiments, the restoring timescale is $\tau = 10$ days ($\tau = 60$ days). The reason for a short timescale (10 days) used in hist-resIPO is that we also aim to study the decadal difference of interannal variability. Too weak restoring may reduce the observed interannual signal.

(b) Prescribing the SST directly in the first layer of ocean component. In the restoring regions, the SST is equal to the model climatology plus the observational anomaly using formula (2).

$$T = (1-\alpha)T_* + \alpha\left(\overline{T_*} + T'\right). \tag{2}$$

In the inner box (Figure 4), the weighting term $\alpha = 1$, then α is linearly reduced to zero in the buffer zone between inner and outer boxes.

(c) Prescribing the surface net heat flux to restore the SST indirectly. This method has been used in Kosaka and Xie (2013) for hist-resIPO like experiment. In the restoring regions, the heat flux is restored using formula (3). Here α has the same meaning as that described in (2).

$$F = F_* + \alpha\left(\frac{c_p\rho D}{\tau}\right)(T' - T'_*). \tag{3}$$

Here F denotes the heat flux; c_p denotes constant-pressure specific heat of sea water; ρ is the density of the sea water. For the hist-resIPO (hist-resAMO) experiments, the typical depth of the ocean mixed layer is $D = 10$ m ($D = 50$ m) and the restoring timescale is $\tau = 10$ days ($\tau = 60$ days). T' and T'_* are the SST anomalies of AMIP and model SST, respectively, relative to the climatology during 1950–2014. The model's climatology is calculated from the historical simulation. The anomalies instead of full SST used here is to reduce possible drift. A similar restoring method is recommended in DCPP Component C experiments (C1.9 and C1.10) except that full SST is used (Boer et al., 2016).

Appendix II: Description of the recommended output

The following tables list the recommended variables at three time frequencies. There are three priority levels. Smaller number means higher level. Variable names refer to those in the CMIP5. The monthly data is used to analyze the long-term trend and variability from interannual to multi-decadal time scales. The daily and 6-hourly data is used to study intraseasonal phenomenon and extreme climate.

Table A1 Recommended GMMIP output. The variables in ocean and sea ice realms are only for Tier-2 experiments.

Output name	Description	Priority		
		Monthly	Daily	6-hourly
TOA fluxes				
rlut	TOA outgoing longwave radiation	1	2	3
rsdt	TOA incident shortwave radiation	1	3	
rsut	TOA outgoing shortwave radiation	1	3	
rlutcs	TOA outgoing clear-sky longwave radiation	1		
rsutcs	TOA outgoing clear-sky shortwave radiation	1		
2D atmosphere and surface variables				
ts	surface “skin” temperature (i.e., SST for open ocean)	1	1	
tas	near-surface air temperature	1	1	3
tasmax	daily maximum near-surface air temperature	1	1	
tasmin	daily minimum near-surface air temperature	1	1	
uas	eastward near-surface wind	1	2	
vas	northward near-surface wind	1	2	
sfcWind	near-surface wind speed	1		
huss	near-surface specific humidity	1		
hurs	near-surface relative humidity	1		

clt	total cloud fraction	1	2	
ps	surface air pressure	1	2	
psl	sea level pressure	1	2	
BOA fluxes				
rlds	surface downwelling longwave radiation	1	1	
rlus	surface upwelling longwave radiation	1	1	
rsds	surface downwelling shortwave radiation	1	1	
rsus	surface upwelling shortwave radiation	1	1	
rldscs	surface downwelling clear-sky longwave radiation	1	2	
rsdscs	surface downwelling clear-sky shortwave radiation	1	2	
rsuscs	surface upwelling clear-sky shortwave radiation	1	2	
tauu	surface downward eastward wind stress	2		
tauv	surface downward northward wind stress	2		
hfss	surface upward sensible heat flux	1		
hfls	surface upward latent heat flux	1		
pr	precipitation	1	1	3
prc	convective precipitation	1	2	
prsn	snowfall flux	3	3	
evspsbl	evaporation	1		
Land				
ts	skin temperature	1		
alb	surface albedo	1		
mrso	total soil moisture content	1	3	
mrfso	soil frozen water content	1		
snd	snow depth	1	3	
snc	snow area fraction	1		
snw	surface snow amount	1		
mrro	total runoff	1		
Sea Ice (Only for Tier-2)				
tsice	surface temperature of sea ice	3		
sic	sea ice area fraction	1		
sit	sea ice thickness	1		

snd	snow depth	2		
hflssi	surface upward latent heat flux over sea ice	3		
strairx	x-component of atmospheric stress on sea ice	3		
strairy	y-component of atmospheric stress on sea ice	3		
transix	x-component of sea ice mass transport	3		
transiy	y-component of sea ice mass transport	3		
2D Ocean (Only for Tier-2; preferably on regular grid)				
Physical variables				
tos	sea surface temperature	1		
hfnorth	northward ocean heat transport	2		
sltnorth	northward ocean salt transport	2		
zos	sea surface height	1		
zossq	square of sea surface height above geoid	2		
zosga	global average sea level change	2		
zossga	global average steric sea level change	2		
zostoga	global average thermosteric sea level change	2		
volo	sea water volume	2		
hfds	downward heat flux at sea water surface	1		
vsf	virtual salt flux into sea water (or equivalent fresh water flux)	1		
Biophysical variables (Only for Tier-2; for ESMs)				
intpp	primary organic carbon production	2		
epc100	downward flux of particle organic carbon	2		
epcalc100	downward flux of calcite	2		
epsi100	downward flux of particulate silica	2		
phyc	phytoplankton carbon concentration at surface	2		
chl	total chlorophyll mass concentration at surface	2		
spco2	surface aqueous partial pressure of co2	2		
fgco2	gas exchange flux of co2 (positive into ocean)	2		
3D Atmosphere (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa)				
ta	air temperature	1		
ta850	air temperature at 850 hPa		1	

ua	eastward wind	1	2	
va	northward wind	1	2	
wap	lagrangian tendency of air pressure	1	2	
zg	geopotential height	1		
zg500	geopotential height at 500 hPa		1	
hus	specific humidity	1	2	
hur	relative humidity	1		
co2 (For ESMs)	mole fraction of CO2	2		
3D Ocean (Only for Tier-2; preferably on a regular grid at standard levels)				
Physical variables				
thetao	sea water potential temperature	1		
so	sea water salinity	1		
uo	sea water x velocity	1		
vo	sea water y velocity	1		
wo	sea water z velocity	1		
Biophysical variables (Only for Tier-2; for ESMs)				
dissic	Dissolved Inorganic Carbon Concentration	2		
talk	Total Alkalinity	2		
no3	Dissolved Nitrate Concentration	2		
o2	Dissolved Oxygen Concentration	2		

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Table 1. Description of models participating GMMIP

Model	Institute/Country
ACCESS	CSIRO-BOM/Australia
BCC-CSM2-MR	BCC/China
BNU-ESM	BNU/China
CAMS-CSM	CAMS/China
CanESM	CCCma/Canada
CAS-ESM	CAS-IAP/China
CESM	NCAR-COLA/USA
CESS-THU	THU/China
CMCC	CMCC/Italy
CNRM-CM	CNRM-CERFACS/France
FGOALS	IAP-LASG/China
FIO	FIO/China
GFDL	NOAA-GFDL/USA
GISS	NASA-GISS/USA
HadGEM3	MOHC-NCAS/UK
IITM	IITM/India
IPSL-CM6	IPSL/France
MIROC6-CGCM	AORI-UT-JAMSTEC-NIES/Japan
MPI-ESM	MPI-M/Germany
MRI-ESM1.x	MRI/Japan
NUIST-CSM	NUIST/China

Table 2. Experiment list of GMMIP

	EXP name	Integration time	Short description and purpose of the EXP design	Model type
Tier-1	amip-hist	1870-2014	Extended AMIP run that covers 1870-2014. All natural and anthropogenic historical forcings as used in *CMIP6 Historical Simulation* will be included. AGCM resolution as *CMIP6 Historical Simulation*. The HadISST data will be used. Minimum number of integrations is 3, more realizations are encouraged.	AGCM
Tier-2	hist-resIPO	1870-2014	Pacemaker historical run that includes all forcing as used in *CMIP6 Historical Simulation*, and the observational historical SST is restored in the tropical lobe of the IPO domain (20 °S-20 °N, 175 °E-75 °W); to understand the forcing of IPO-related tropical SST to global monsoon changes. How to restore the SST refers to the appendix. Models resolutions as *CMIP6 Historical Simulation*. The HadISST data will be used. Minimum number of integrations is 3, more realizations are encouraged.	CGCM with SST restored to the model climatology plus observational historical anomaly in the tropical lobe of IPO domain
	hist-resAMO	1870-2014	Pacemaker historical run that includes all forcing as used in *CMIP6 Historical Simulation*, and the observational historical SST is restored in the AMO domain (0 °-70 °N, 70 °W-0 °); to understand the forcing of AMO-related SST to global monsoon changes. How to restore the SST refers to the appendix. Models resolutions as *CMIP6 Historical Simulation*. The HadISST data will be used. Minimum number of integrations is 3, more realizations are encouraged.	CGCM with SST restored to the model climatology plus observational historical anomaly in the AMO domain

Table 2. Continued

	EXP name	Integration time	Short description and purpose of the EXP design	Model type
Tier-3	amip-TIP	1979-2014	The topography of the TIP is modified by setting surface elevations to 500m; to understand the combined thermal and mechanical forcing of the TIP. Same model as DECK. Minimum number of integrations is 1. The topography above 500m is set to 500m in a polygon region. Coordinates of the polygon corners are as follows: longitude (from west to east), 25 °E, 40 °E, 50 °E, 70 °E, 90 °E and 180 °E; latitude (from south to north), 5 °N, 15 °N, 20 °N, 25 °N, 35 °N, 45 °N and 75 °N. The reason to remove all the topography above 500m over the Asian continent is to avoid any artificial forcings from the topography gradient when suddenly cut off at a certain height, and we also suppose the circulation response to the difference of topography between 0 to 500m can be neglected in climate models with resolutions from 100-200km. This experiment is also close to the no topography settings such as setting the topography to zero over whole Asian continent as far as possible.	AGCM
	amip-TIP-nosh	1979-2014	Surface sensible heat released at the elevation above 500m over the TIP is not allowed to heat the atmosphere; to compare of impact of removing thermal effects. Same model as DECK. Minimum number of integrations is 1. The sensible heating is removed on the topography where is above 500m as in the same polygon region in amip-TIP; in these experiment, we have to artificially cut off the sensible heating region with a specific criterion. One practical method is set vertical temperature diffusion term to zero in the atmospheric thermodynamic equation at the bottom boundary layer. There are obvious concerns over the energy conservation here, but because the suppression of heating is only in a fairly small limited area, one expects the energy balance to be compensated elsewhere.	AGCM
	amip-hld	1979-2014	The topography of the East African Highlands in Africa and Arabian Peninsula, Sierra Madre in N. America and Andes in S.	AGCM

	America is modified by setting surface elevations to a certain height (500m) in separate experiments. Same model as DECK. Minimum number of integrations is 1. See descriptions of amip-TIP for technical details and regions as outlined in Fig. 5. The East African Highlands is in a polygon region. Coordinates of the polygon is as follows: longitude (from west to east), 27°E and 52°E; latitude (from south to north), 17°S, 20°N and 25°N, 35°N. Sierra Madre domain is 120°-90°W, 15°-30°N. Andes domain is 90°-60°W, 40°S-10°N.

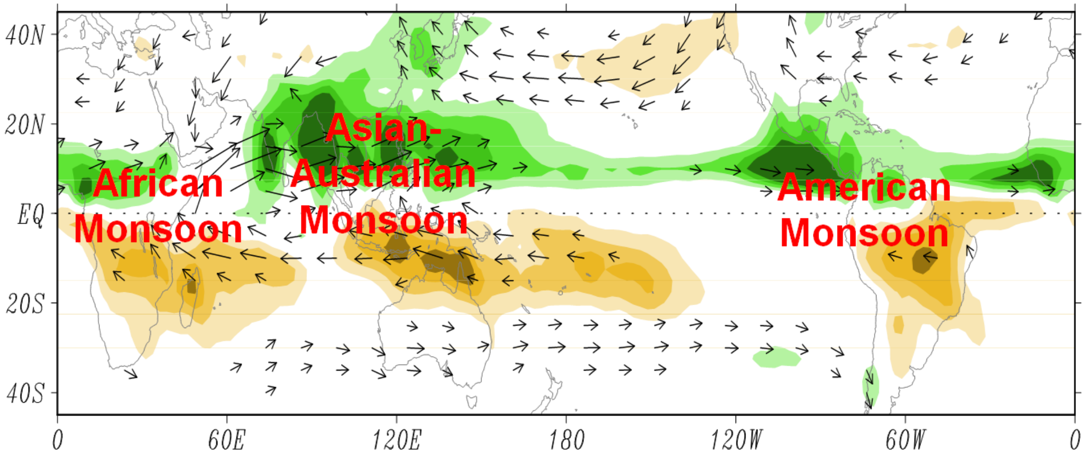

Figure 1. Global monsoon domain and its local component, indicating by the differences of 850 hPa wind and precipitation between the June-July-August and December-January-February mean, modified from Wang and Ding (2008).

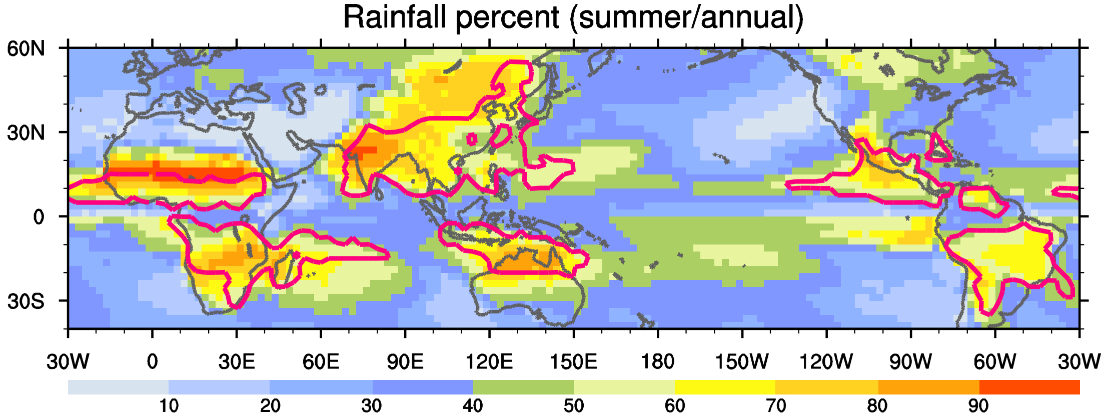

Figure 2. Climatological percentage of summertime rainfall amount (JJAS in the Northern Hemisphere and DJFM in the Southern Hemisphere) in annual accumulation. Monsoon region is circled by red curves. GPCP data is used and the time covers 1979-2014.

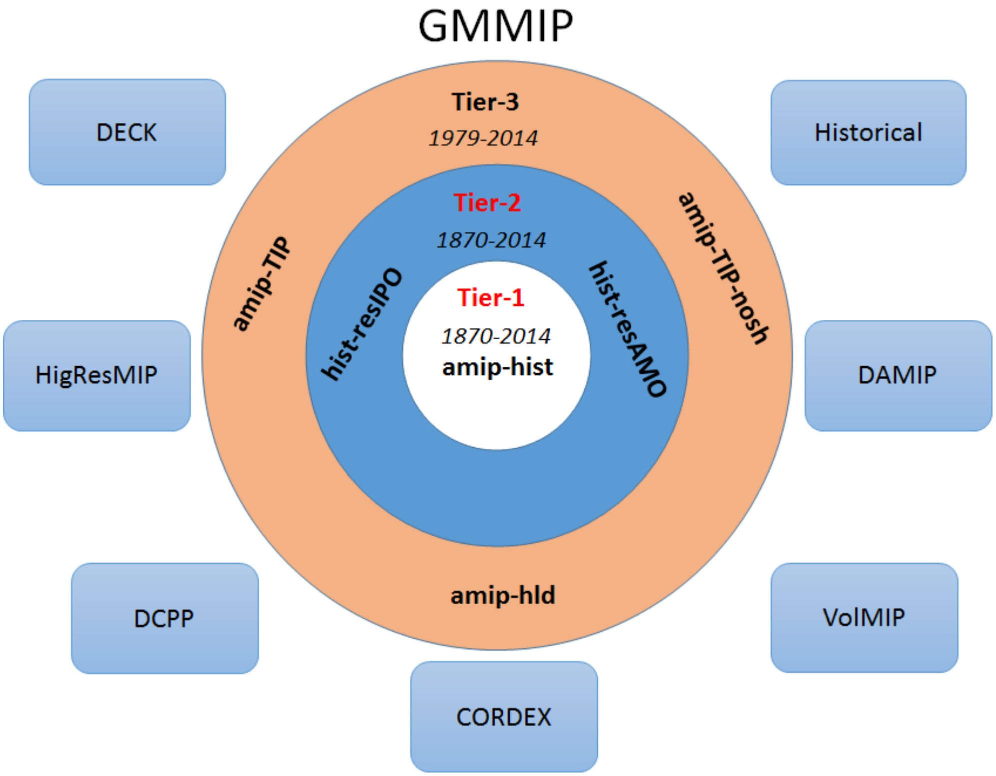

Figure 3. Three-Tier experiments of GMMIP and its connections with DECK, Historical Simulation and endorsed MIPs.

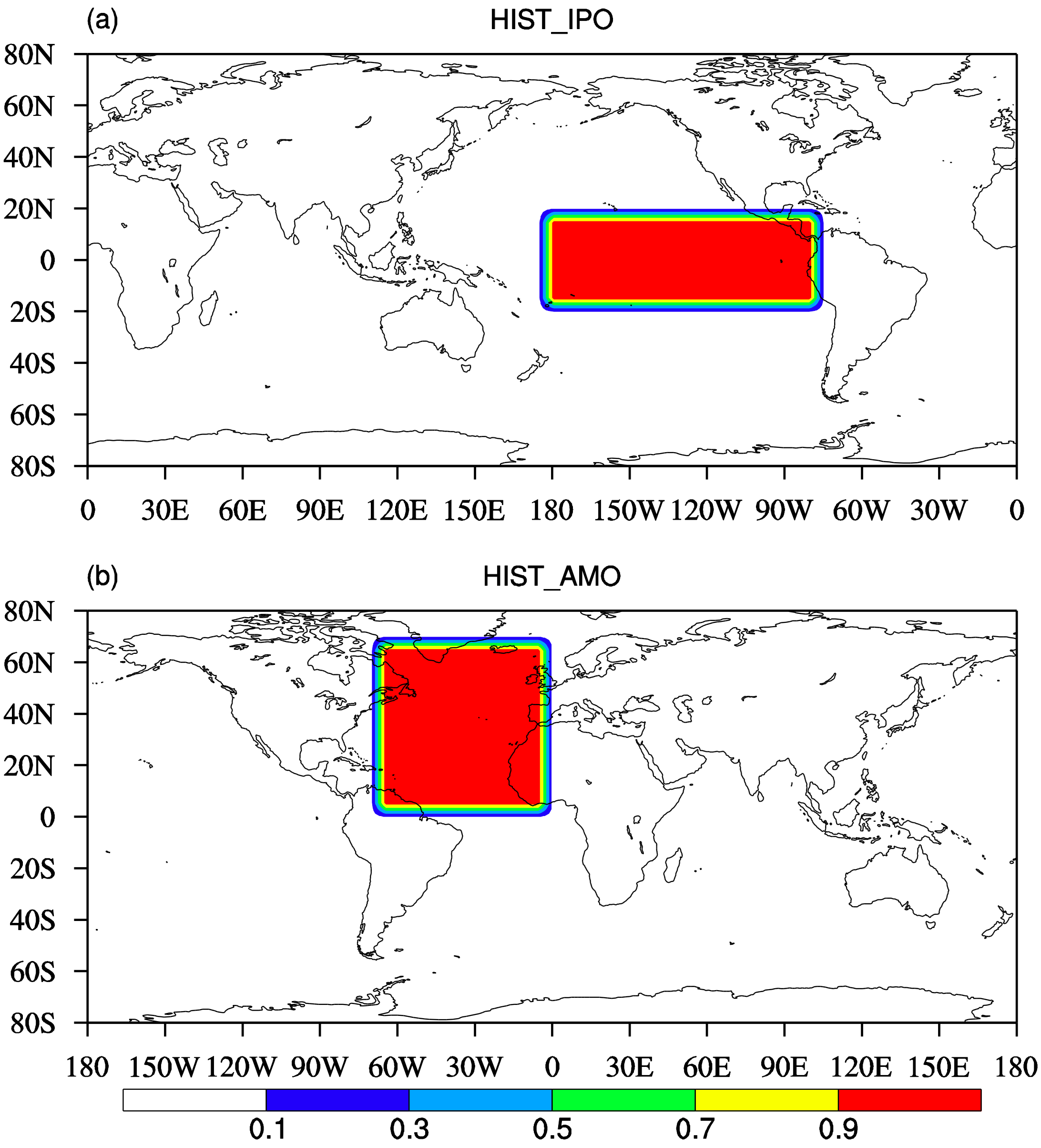

Figure 4. The restoring regions for Tier-2 experiments HIST-IPO (a) and HIST-AMO (b).

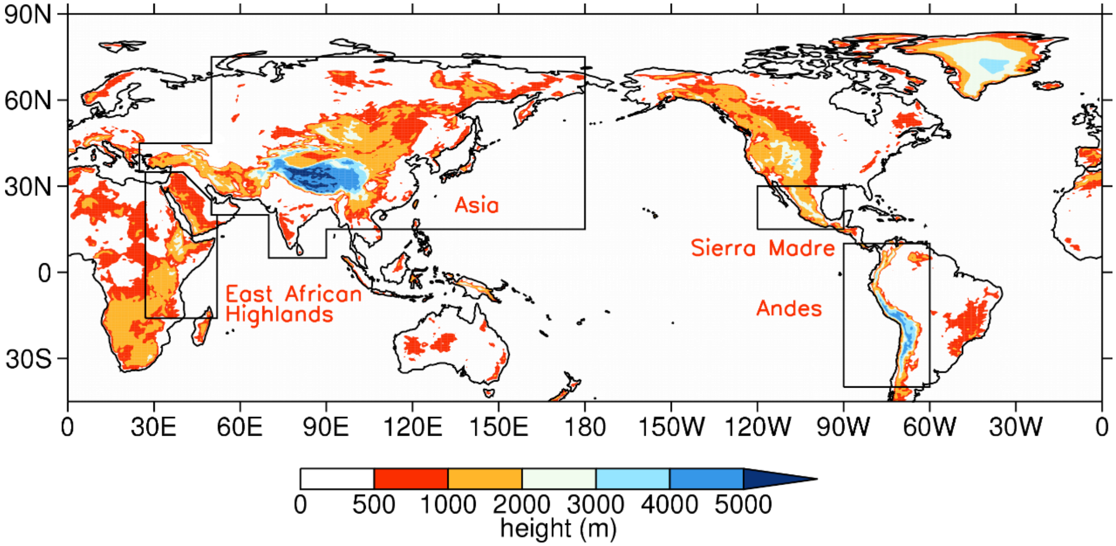

Figure 5. The orography regions specified for the Tier-3 experiments for the Asia region (comprising the Tibetan-Iranian Plateau and Himalayas), the East African Highlands (adapted from Slingo et al., 2005), the Andes and the Sierra Madre. Within each marked region, orography would be capped at 500m height. Orographic data derived from a ~30km resolution (N512) boundary field of the Met Office HadGEM3 model.