Response to Review 2:

Reviewers comments are in black standard and the responses are in *blue italics.*

Anonymous Referee #2

Received and published: 9 May 2017

Overview of the paper:

In this study a series of interesting simulations of the late Permian was undertaken to ascertain the dominant forcing mechanisms on the Permian northern hemisphere 'Megamonsoon' (e.g. CO2 or paleogeography) through a series of sensitivity studies. It was found that the removal of equatorial islands which were a physical barrier to the Paleo-Tethys warm pool played a crucial role in the characteristics of the monsoon.

General comments:

I think a section right at the beginning is required to define what is meant by a monsoon in these simulations thought use of a monsoon index (e.g. Wang, et al. 2005. Global monsoon: Dominant mode of annual variation in the tropics.) as well as what is meant by a "megamonsoon". I wonder whether some of the sensitivity studies will show that the megamonsoon becomes more tropical precipitation which is suggested in figure 9 with a strong expansion of out of season precipitation. If so, this would still be a very interesting result.

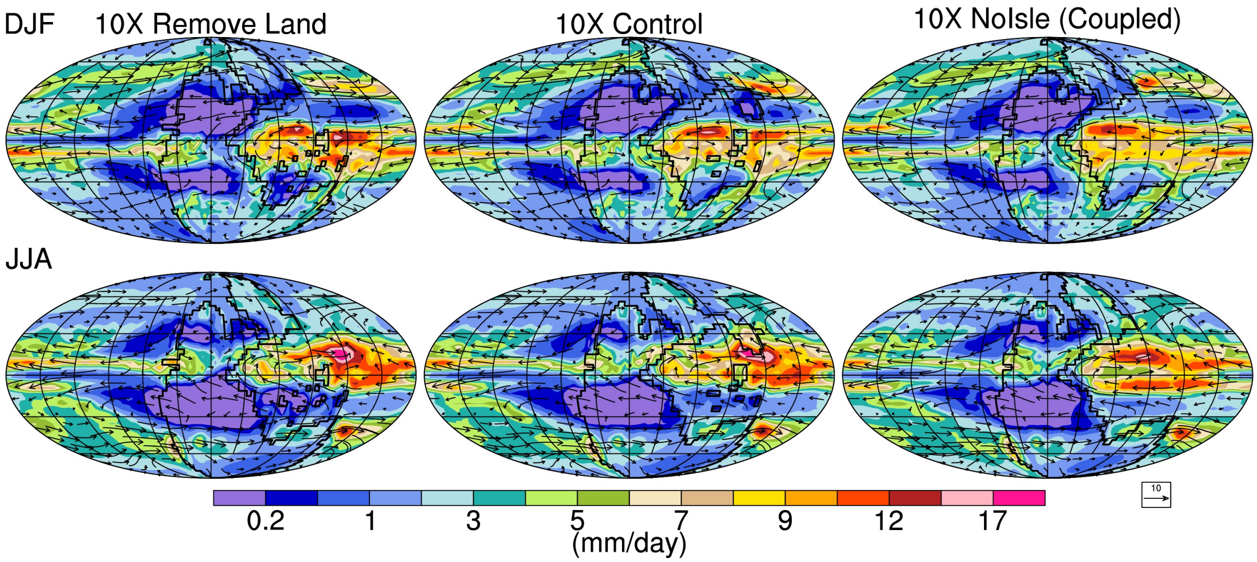
We thank Reviewer 2 for their comments.

We have expanded the introduction to include a definition of what we mean by megamonsoon. Then new text is as follows:

"The term "megamonsoon" is often referred to in the literature as the monsoonal circulation for the Pangean supercontinent and can be described as the cross-equatorial flow that brings warm, moist airflow from regions south of the equator into the Pangean supercontinent. The cross-equatorial flow provides the necessary moisture source to produce seasonal, heavy bands of precipitation to eastern Pangean. (Nordt et al 2015). To date, the surface land-sea temperature gradient has been hypothesized as the primary driver of the megamonsoon and its associated dynamical and precipitation signatures (Parrish 1993, Kutzbach and Gallimore 1989). However, in this paper, we present the idea that the Pangean megamonsoon is simply responding to the elevated sea surface temperatures in the Paleo-Tethys (i.e the warm pool), and this it is this mechanism, not a land-sea contrast, that drives the "monsoon" dynamics, cross-equatorial flow, and heavy seasonal precipitation. Traditionally, for both paleo and modern monsoonal systems, monsoon precipitation is often considered separately from tropical warm pool precipitation. Here we break again with tradition and suggest that the summertime megamonsoon precipitation, associated with the megamonsoon dynamics, is a product and response of the warm pool itself".

I do agree that the warm pool will play a significant role in the dynamics of the region, as it does today (specifically reorganising the zonal atmospheric circulation). It would be nice in the case of removing the peninsula to show the 850mb wind vectors too.

We have added the 850mb wind vectors to Figure 5 (as well as the NoIsle experiment as per Reviewer1 request). We include the figure here:



However, there does seem to be a response in precipitation with the removal of the peninsula (although not stated it is assumed the warm pool stays in the same location) precipitation does shift eastwards suggesting that the land-sea contrast may be playing a significant role.

The dynamics sections could do with some improvements. What does the Hadley and Walker circulation look like compare to the modern? How do they respond to increasedCO2 forcing? Some dynamical analysis on surface convergence and divergence aloft is undertaken, however I feel more could be done, for instance looking at the complete vertical structure of the Hadley/Walker circulation and how these change between the different experiments, maybe changes in atmospheric jets, rossby wave source from which will likely be closely linked to the migration of the warm pool and associated atmospheric heating, etc... I am not suggesting it should all be done, but it would be nice to have a bit more grounding in the dynamical response to these very interesting simulations.

Thank you for this suggestion. We agree that adding Hadley and Walker circulation cross sections improves the dynamics section of this paper and have chosen to include this in the No Island sensitivity analysis by adding a new Figure 12. We felt the NoIsle experiment cleanly highlighted the interaction of the warm pool (and thus monsoon) and these important dynamical features, particularly in a coupled air-sea context.

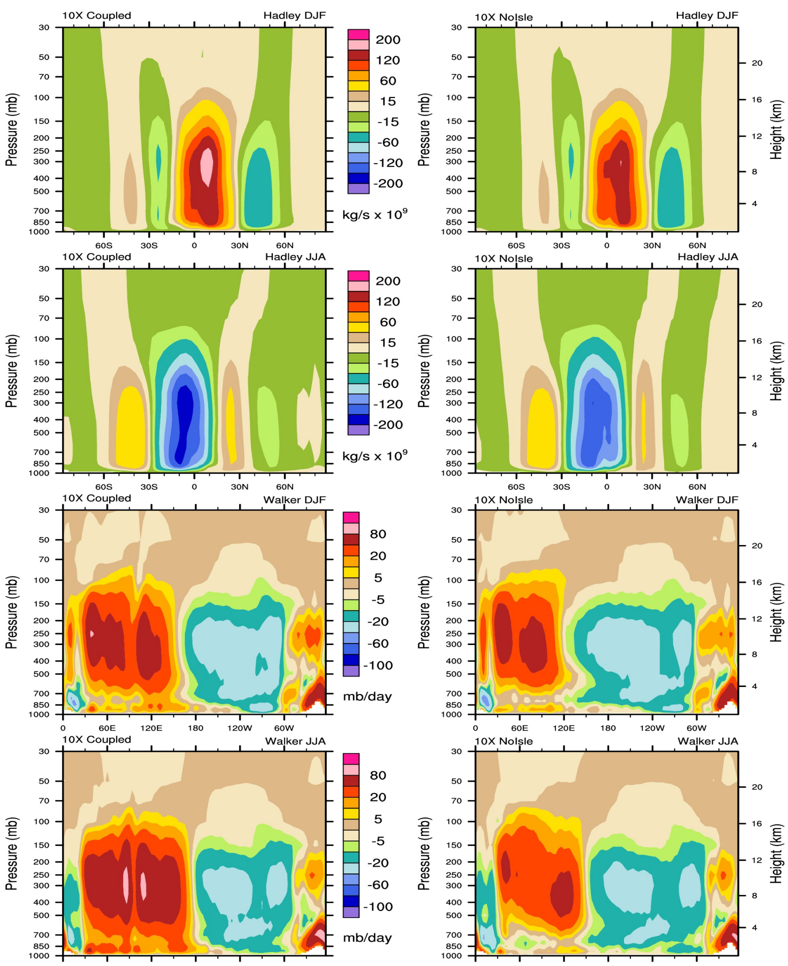
The new text is as follows:

"Coupled atmosphere-ocean dynamical responses are illustrated in Figure 12 by plotting the Hadley and Walker circulations for the original coupled case (10xPT_C) (left panels) and the no equatorial islands case (10xPT_C_NoIsle) (right panels). The Hadley circulation (upper two rows) is represented by the zonal meridonal

streamfunction (with a clockwise positive convention), and the Walker circulation (lower two rows) is represented by vertical velocity (with a positive upward motion convention). The removal of the equatorial islands does not significantly change the latitudinal span, but primarily decreases in intensity. The Walker circulation, however, shows substantial shifting eastward of the descending branch in the eastern Paleo-Tethys and a reorganization of the strongest upward branches in western Paleo-Tethys. This is consistent with the expansion and migration of the warm pool and related precipitation as seen in Figure 7".

The new figure is here:

***Figure 12**: Zonal Meridional Streamfunction and cross sections of vertical velocity representing the Hadley (top two rows, DJF and JJA, respectively) and Walker (bottom two rows, DJF and JJA, respectively) Circulations. The 10X coupled control (10xPT_C) (left columns) and 10X NoIsle (10xPT_C_NoIsle) (right columns) are shown. Meridional streamfunction is given in units of kg/s x10^9 and vertical velocity (upward positive convention, averaged from 5S to 5N) is given in mb/day.*



I do also wonder if the high topography to the North-west and west of the peninsula is playing a role and acting as an elevated heat pump, a similar role as with the Tibetan plateau. It would be nice to see the JJA/DJF 850mb wind and precipitation for the 'NoIsle' experiment to see what is happening over land for comparison. However, the regional topographic height has not been investigated.

As mentioned, we added the NoIsle to Figure 5 along with the 860mb winds. We did not do any topographical height sensitivity studies.

Specific comments:
i) The last paragraph of the introduction emphases the importance of the PT extinction event at this time, however it feels like this is shoe horned into the manuscript as it does not link to the importance or relevance of the need to better understand the monsoon system. Maybe one or two linking sentences would be appropriate here.

We have removed the final paragraph and added a discussion on the megamonsoon and linking sentences to the PT extinction and our previous work.

"Here, we expand on Kiehl and Shields 2005 (henceforce called KS2005). K2005 is a Permian modelling study that shows CCSM3 supports the current extinction hypotheses and available observational record (Black et al 2012, Kidder and Worsely 2004, Benton and Twichett 2003, Renne et al 1995, Erwin 1993) by simulating warm high latitude surface air temperature and a stagnate global ocean circulation. For the sensitivity study described in this paper, we include a series of additional CCSM3 simulations designed to highlight the importance of the Paleo-Tethys oceanic warm pool and its impact on the Permian megamonsoon.

We will organize this paper by first giving an overall description of our experimental design (full details are given in Appendix A), next we will describe the basic climate and monsoonal states, and finally we will show results from sensitivity experiments focused on the Paleo-Tethys warm pool".

ii) A proper evaluation of the model in generating the observed monsoon system is required or at least referred to from previous studies using the model (e.g. Sperber, 2012; DOI 10.1007/s00382-012-1607-6).

We have added a line to the introduction with this reference.

"Sperber et al, 2012 provides the community with an extensive analysis on the Asian monsoon comparing CMIP5 and CMIP3 (Coupled Model Intercomparison Projects) simulatons for the late 20th century".

iii) Did you have the same response with the removal of the peninsula at 1xPI-CO2 as well as in the 10xPI-CO2 or was this simulation not performed?

We did not perform a 1xCO2 with the removal of the peninsula, but expect same result given the NoIsle experiments and the work of Chao and Chen (2001) which did use modern geography in their sensitivity studies.

iv) How is a monsoon being defined (let alone a megamonsoon?) in this paper? A map with the global monsoon would also be highly beneficial to the reader.

As mentioned above, we added a paragraph in the introduction to the definition of the megamonsoon. Figure 5 shows the precipitation and wind vectors and illustrate the monsoon in geographic space.

v) Needs to be a justification as to why the Indian monsoon system is being evaluated in the model as opposed to other monsoon systems like the East Asian Monsoon.

This paper is primarily about the Permian monsoon, not modern. We show the modern control as a form of validation for the model. We chose the Indian monsoon to "compare" instead of the East Asian monsoon for a couple of reasons: 1) Geographically speaking, the Permian megamonsoon is one giant monsoonal system. The East Asian as both tropical and subtropical components and is not as clean of a comparison due to the influence of many island chains of East Asia, as well as northern Australia. 2) The Permian megamonsoon clearly occurs during Boreal summer as does the Indian monsoon. The Australia/East Asian systems include the Boreal winter influence of Australia monsoon.

We have modified the text as follows:

"For modern and observational plots, the Indian monsoon, rather than the East Asian monsoon, is used. The Indian monsoon is considered the closest comparison to the Permian megamonsoon because it is a single monsoonal system that has land in the north and ocean to the south, is uncomplicated by island chains, and occurs in Boreal summer (Wang et al 2003, Wang et al 2005)".

vi) An evaluation of the paleogeography used in the model is needed. It might be that this has already been undertaken in a previous paper, if so this should be stated.

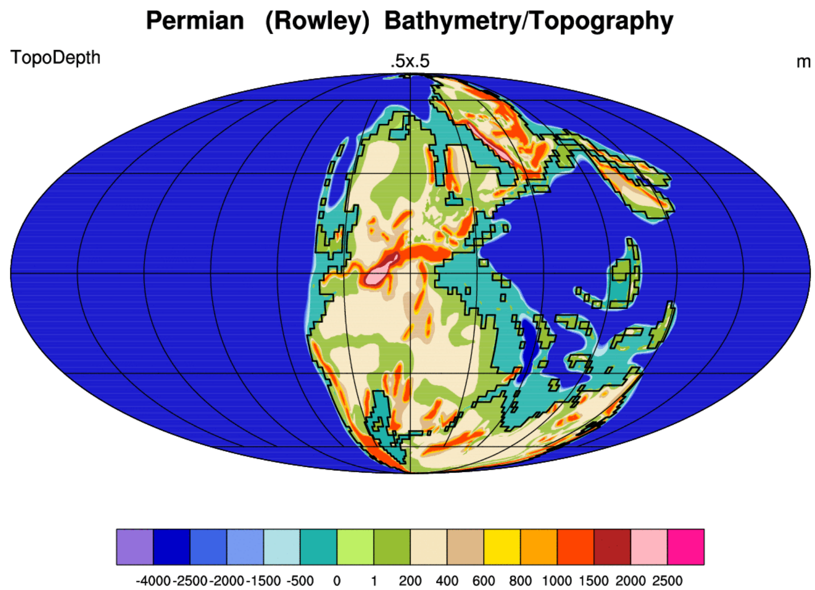
Table 2 states all forcings from KS2005. Paleogeography was obtained from D. Rowley, http://geosci.uchicago.edu/~rowley/Rowley/Paleogeographic_Atlas_Project.html.

vii) More information on the experiment design would be desirable. For instance, It would be nice to show or at least state what is meant by "equilibrated state"? Is it equilibrated in the ocean surface or at intermediate depth or ocean bottom or perhaps it is in energy balance at the surface (Gregory plot) for the KS2005 simulations. What is the topography of the paleogeography? How robust is the topographic reconstruction? (granted this far back in time there will be many uncertainties) as this can have a significant impact on the monsoon system, especially regionally.

We have added text to the Appendix with more details on the simulation and a definition of equilibrium. Full details can be found KS2005.

"*Equilibrium state is defined as the near steady state condition and is determined by considering the net flux of energy into the climate system and the trend in the deep ocean overturning circulation"*.

Topography can be found at the website specified in Table 2, but include an image here for the reviewer.



What solar constant was used, how was it derived? I suspect these are stated elsewhere (perhaps in KS2005?), but it would be nice if so, to have that stated here too and added to table 2.

S0 is stated in Table 2 as 1338 W/m2, it is also in KS2005.
We reduced the present day solar constant by 2.1% to account for the fact that solar output lower at the time of the Permian. This reduction accounts for the fact that solar luminosity increased over geologic time.

Why are 1xPI CO2 and 10xPI CO2 useful end members to investigate the monsoon in this time? A line justifying this and the concentrations would be useful.

Justification is given in Appendix A.

Was vegetation fixed or was an interactive vegetation-land surface scheme used?

We used fixed vegetation.

viii) It would be interesting to know whether there is a change in the warm pool where only the peninsula removal experiment? Further, would it not be more accurate to say that the warm pool expands westwards in the 'NoIsle' experiment rather than migrates as well, as it still covers the same region in the control.

The precipitation for the peninsula removal experiment is co-located with the warm pool. We have added this to the text. For the NoIse experiment, we do state it expands and migrates (Section 5.1).

ix) It would appear from comparison of figures 2 (top left) and Figure 9 that the monsoon has weakened, is there any potential explanation for this?

This is indeed interesting; however, we have not delved deeply into the differences in magnitude in the eastern part of the domain which may require additional sensitivity studies and is peripheral to the foci of this paper.

Technical corrections (typo's, errors, etc.: :):

P.1 (Line 21) – "The nature of monsoons has been studied extensively in the scientific community because of its significance in dominating regional weather and climate and its impact on society" A reference at the end as an example would be useful.

We have added the following reference:
Clift, P. D., & Plumb, R. A. (2008). The Asian monsoon: causes, history and effects (Vol. 270). Cambridge: Cambridge University Press.

P.1 (Line 25) – "Analyzing the underlying mechanisms behind the monsoon in past climates gives us a deeper understanding of what drives the present-day monsoon." An example reference of how some paleoclimate research has informed present-day understanding of monsoon dynamics/model evaluations would be useful.

We have added Wang 2003 and 2005.

Wang, P., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z., ... & Sarnthein, M. (2005). Evolution and variability of the Asian monsoon system: state of the art and outstanding issues. Quaternary Science Reviews, 24(5), 595-629.

Wang, B., Clemens, S. C., & Liu, P. (2003). Contrasting the Indian and East Asian monsoons: implications on geologic timescales. Marine Geology, 201(1), 5-21.

P.2 (Line 10) – The Berner reference publishing date of 2002 in the main text, however in the references, it is given as 1999. This needs to be resolved.

We have removed this reference as per Reviewer 1's comments.

P.2 (Line 21) – "provides a realistic climate solution". A reference here is required.

This is already given as Yeager et al 2006. We moved the location in the sentence to make it more obvious.

P.2 (Line 19) – The Herold, et al. 2011; 2012, Shellito, et al. 2009 and Otto-Blieser are missing in the reference list. I suspect these were accidentally removed from earlier edits of the manuscript.

This has been fixed.

P.5 (Line 17) – "To assess the atmospheric dynamics related to monsoonal circulation, the seasonal cycle of velocity potential is shown" Do you mean the seasonal difference and not cycle?

Yes, thank you.

P.6 (Line 22) – "In the original simulation" Should be changed to "In the 10x PT control simulation" to avoid any potential confusion.

Yes, this has been changed.

P.8 (Line 7) 'alters', not "alterations".

This has been fixed.

Figure colour bars could do with having the units expressed beside them.

These have been added.

Figures 3, 8, 9 – The b30.11/b30.116 simulation description could do with being changed to something more easily understandable as done in Figure 2.

This has been fixed.

Figures 3, 8 – The contour intervals are rather odd, although I assume this is done to aid interpretation of the plots to highlight the centre of the warm pool in the different CO2 states. For figure 3 It might be interesting to show the present-day simulation next to these as well to highlight the difference.

Yes, we want to highlight the warm pools differences. Although comparing to modern is interesting, we decline adding the modern warm pool to this figure because we want to highlight the warm pool for the Permian megamonsoon and only use the modern to validate the model. We prefer to keep an "apples to apples" comparison for this discussion.

Figure 6 – Please state what pressure level was used to diagnose the upper-level divergence.

This is on the figure label, it is 850mb.

Figure 10 – What is the vector length used for the divergent flow?

A reference vector has been added to the plot.