1) Comments from referees/public:

Anonymous Referee #1

Received and published: 3 October 2017

GENERAL REMARKS:

The manuscript "Assessing the impact of large volcanic eruptions of the Last Millennium on Australian rainfall regimes" in consideration for publication in Climate of the Past investigates the impacts of tropical explosive volcanic eruptions on Australian rainfall regimes, ENSO, and the Indian Ocean Dipole. The authors use a set of specific global climate model realisations to address questions about the importance of volcanic forcing power and timing of the above mentioned impacts.

Generally, the topic of the manuscript fits Climate of the Past and is a valuable contribution to the community. The study sheds light on volcanic climate impacts in the Southern Hemisphere, for which only few studies exist so far.

However, I feel like the manuscript lacks content in some important parts. In my opinion, the three main weaknesses are:

1) Experimental design: Since the study largely focuses on the IOD and ENSO, the authors should describe in detail how SSTs and evaporation over oceans is handled in the model. Is it AMIP run? Is it coupled? Slab ocean? And if the SSTs are prescribed, can it be used at all? These things are completely disregarded in the manuscript at hand.
2) Model evaluation: There is NO effort made to convince me that this model is doing a good job in terms of precipitation. I would like to see a comparison between model and proxy data, or model and (PDSI) reconstructions.
3) Physical mechanisms behind the shown effect on ENSO and IOD: Although a lot of studies are cited as to show that there is agreement with previous work, I didn't find a proper physical explanation for the effects we see in the plots besides the paragraph in the introduction. I would like to see a discussion about the mechanisms in this specific model.

See below for specific remarks.

SPECIFIC REMARKS:

Line 34: I would add here newer studies about precipitation like Iles et al 2013 or Wegmann et al 2014

Line 93: Not sure what exactly is unclear? Do you mean dynamic vs radiative changes? Please explain further what gap your study is filling.

Line 103: Here I really would like to see a thorough description of the ocean setting for this model (see above). What kind of SSTs are used? Is there a dynamic ocean? How is the volcanic signal supposed to show in the SSTs? Is it valid to use the model to investigate ocean surface changes? CMIP5 also had AMIP run included, so I can't really infer if your model was coupled or not.

Line 103: I assume CO_2 forcing is done in CMIP5 fashion?

Line 148: As I said before, I would like to see an evaluation for starters. How good is the model in terms of precipitation? The comparison doesn't have to be for Australia, but I want to be convinced that the model gets the broader precipitation response. Otherwise, the rest of the results is less meaningful.

Figure 2: Is this the annual mean? If so please indicate the fact. Maybe it would be nice to see DJF and JJA anomalies? Is the model able to do the NH winter warming? And if not, is there an argument to make that the model doesn't get the dynamics right (as is the case with many CMIP5 models)?

Line 176: Again, I wonder about NH winter warming. Should counteract the summer cooling over the NH.

Line 194: Indeed it suggests that. But how does it work? Where is the discussion of the physical mechanisms? How is the signal transported in the model? Maybe show evaporation, heat content and other metrics to show the mechanisms in the model.

Line 241: Okay, but how does this effect override the impact of IOD?

Table 1: It says strongest eruptions in the last millennium but I am pretty sure that Tambora was stronger than Huaynaptina as Figure 1 shows. In fact even the unknown 1809 eruption is bigger. Please adjust your table description.

Figure 3: In fact 2xCG is not an ensemble and should not be marked as such.

Figure 4: The 90th percentile of what? The ensemble members? If so, please adjust. (also for the rest of the Samalas & Huaynaputina plots.

Figure 10: Here it says Australian precipitation whereas Figure 9 says NW Australian precipitation and Figure 11 says SE Australian precipitation. I assume Figure 10 also is SE precipitation?

Anonymous Referee #2

Received and published: 12 October 2017

This work analysed the precipitation response to large volcanic perturbation in Australian, using GISS Model E millennium simulations. The topic is an important contribution to the systematic assessment of global hydroclimate response to the volcanic radiative influence. The paper is well written; the results are clearly presented and discussed. I would recommend a major revision of the paper by addressing the following issues, before it could be accepted for publication:

1. In the "Introduction" section 1.1 It is not clear from the description which relationships between volcanic eruptions and Australian rainfall are unclear and are explored in this paper. Please be more specific. A significant part of the introduction is devoted to the literature review of the volcanism and ENSO relationship, while the focus of this study is on volcanic eruptions and Australian rainfall. Please modify either the title, or the structure of introduction. For example, the authors may consider introduce the role of ENSO in changing Australian rainfall before discuss the volcanism and ENSO. Relationship

2. In the "Data and Methods" section 2.1. Line 99, please explain briefly why the last millennium period is especially chosen. 2.2 Please provide a short description of model performance, especially those closely related to the ENSO, IOD and volcanic climate responses. Please also provide a short explanation of why the five volcanically forced scenarios were chosen. 2.3 Line 134, please also discuss the ENSO impact in the chosen north-west and south-east regions.

3. In the "Results" section 3.1 Please explain the advantages of comparing the response between the largest 1257 Samalas and the smallest 1600 Huaynaptina eruption, rather than a series comparison among the 6 eruptions of various size. 3.2 Line 164, there is no ensemble runs for the 2xGC case, please make the distinction. 3.3 One of Figure 8 or Figure 9 should be "SE (instead of NW) Australia" response. Please also correct the reference to the Figure 10 in Line 179. The use of "multi-model mean" in several figures is misleading, please consider

change to model ensemble. 3.4 The focus of this work is Australia, however, there is no spatial figures dedicated to the particular area of study. 3.5 Please verify the use of 0.6 standard deviation as the significant level.

4. In the "Discussion and Conclusions" section 4.1 line 218-221, the difference between Samalas and Huaynaptina response does not seem significant and the use of it as support for the persistence of a high pIOD sounds weak to me. Please consider the use of all six (or even more eruptions) of different sizes to analyse the role of eruption magnitude. 4.2 Line 228-235, I do not see the El Nino response persist from year 0 to year 6 in both Fig. 5 and Fig. 2. Please explain why the El Nino-like pattern in the eastern Pacific is most visible in year 4, but not earlier. 4.3 Line 241-243, please demonstrate in more detail how did the direct precipitation effect of volcanic aerosols override the impact of the IOD on Australian precipitation. Which parameter represents the direct precipitation effect of volcanic aerosols? How was the override effect appear in the results? By the time difference? 4.4 The most important advantage of using modelling results is the capacity of exam the physical mechanisms behind the shown effects (such as the impact on ENSO and IOD, and their influence on Australian rainfall). Please provide some discussion of mechanism using the original results from this paper, rather than referring to previous studies.

Public Review #1:

This paper is about the responses of the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and Australian precipitation to tropical volcanic eruptions. 9 ensembles from the NASA GISS ModelE2-R were analysed and run for the six largest tropical volcanic eruptions between 850 and 1850 CE. Anomalous conditions in ENSO, the IOD and Australian rainfall as a result of these volcanic eruptions were explored. Results show that large tropical eruptions during the last millennium indeed impact the large-scale IOD and ENSO systems and the Australian rainfall regimes. Larger mean atmospheric sulfate loading results in more persistent and more extreme positive IOD conditions and a stronger ENSO response. A positive response of Australian precipitation to volcanic forcing was found, although this response is stronger in NW Australia than in SE Australia.

The still relatively unclear relationships between tropical volcanic eruptions and the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and Australian precipitation were thus successfully explored with your research. Since you give a clear overview of these relationships and your approach can also be applied for exploring the impact of time-evolving forcings, such as volcanism, in other regions, this research strongly contributes to this field of research. Moreover, the paper fits the scope of the journal 'Climate of the Past', since the impact of historic volcanic eruptions on climatic variables is evaluated.

You start the paper with an elaborate introduction where a lot of references to previously published literature on this topic are made. You compare the results of several papers, which provides the reader already with some idea of the relationships that can be expected to be found in this paper and an overview of the state of the art of this field of research. A clear objective of the study is stated at the end of the introduction, which provides a concrete overview of the content of the paper. The results of the research are well-structured and have a logical order, since the results of all relationships between the variables are discussed one by one. Moreover, the figures of the results are clear and provide a good overview of all final results. The text in the results section and the result figures match and complement each other. The statements that are made in the discussion are well- funded on the results or on information from previous papers. I like the fact that differences between the results of this paper and of previous research are compared and possible explanations are given. Besides, the discussion and conclusion fit well to the relationships that were going to be explored as stated in the introduction, so the circle of the paper is closed. The paper contains a nice discussion on the limitations of the approach. Based on other literature some improvements are stated that should be made in future modelling in order to improve the accuracy of volcanic eruption model simulations. The improvements stated here form actually a small summary of previously published literature that can be consulted in order to figure out the exact adaptations that will improve the modelling of volcanic eruptions and corresponding processes.

In conclusion, I think your paper is well-written and a valuable contribution to this field of research. However, there are three major weaknesses that I think need to be solved before your paper can be published. These are explained below in this review and I also included some minor points that need to be improved in order to clarify some points in your paper.

MAJOR ARGUEMENTS

1. Your methodology contains in line 102 the statement that the Coupled Model Intercomparison Project Phase (CMIP5) is used in the NASA GISS ModelE2-R. However, Taylor et al. (2012) explain that the CMIP5 strategy can be used for long-term (century time scale) and near-term integrations (10-30 year). You explored anomalous conditions in the ENSO, the IOD and Australian rainfall for 7 years in total and only five years after a volcanic eruption, since this minimizes the effect of trends or low-frequency climate variability, which is a good argumentation. However, I wonder if the use of the CMIP5 gives reliable short-term model results for this short time period. Since you make you use of the NASA GISS ModelE2-R General Circulation Model and you refer to Schmidt et al. (2014) in line 100, I assume that your model contains all components that are taken into account by Schmidt et al. (2014) and that it includes an interactive representation of the atmosphere, ocean, land and sea ice. I expect that for most atmospheric processes the shorter timescale of your research will not be a problem, since most of these atmospheric processes are fast. The influence of aerosol injection into the atmosphere after a volcanic eruption will quickly have a noticeable influence in the model on for example atmospheric temperature, incoming shortwave solar radiation and cloud formation. However, ocean and land, domains that are also taken into account in the model, will have slower responses to volcanic eruptions. For example sea surface temperature, ocean currents and permafrost presence will take longer to adapt to the aerosol injection and corresponding atmospheric changes. For these variables the five year time scale that is investigated in your research might possibly be too short in order to explore the trend that occurs after a volcanic eruption. My recommendation is to validate the model results of these 7 year runs with available data and add these results to your paper. Is it a possibility to gather data of the ENSO, IOD and Australian rainfall anomalies for the times following the six eruptions used in you research and compare these with your model results? If this data is not available, because your eruptions occurred a long time ago, it might also be possible to use more recent data of the ENSO, IOD and Australian rainfall anomalies in years with more recent volcanic eruptions and compare these with new model results of these more recent volcanic eruptions. These volcanic eruptions are maybe smaller in size and have a smaller sulfate aerosol injection, but at least a validation of the model can be made in this way in order to check the use of CMIP5 for the relative short time period.

2. I do not think that the methodology, mainly section 2.1 Simulations, contains enough information to understand your exact process in order to set up and make use of the model. Information that is missing is which data you used and what its source is, why you chose to make use of the specific NASA GISS ModelE2-R and the CMIP5, which variation of this model and which configuration were used and which values were for example used for

the effective radius of the sulfate droplets. Schmidt et al. (2014) discuss different model configurations of the NASA GISS ModelE2-R, different ocean models and global annual mean features over the period 1980-2004 for the different models, which gives me the idea that you also made these kind of choices before you started modelling. Miller et al. (2014) show that there are three versions of the atmospheric model (NINT, TCADI and TCAD) which treat the atmospheric constituents and the aerosol indirect effect differently. I assume that you also used one of these models, but it is not described which one you chose and why. Moreover, you do not explain why you chose to analyse nine ensembles from the NASA GISS ModelE2-R, as stated in line 100, and not more or less. It is also not explained why five ensembles were forced with volcanic forcing, while four were not. Of the five run with volcanic forcing, four were forced with Crowley and Unterman (2013)'s aerosol optical depth data and one with double the Ice-core Volcanic Index 2 by Gao et al. (2008), but why are these not equally divided? Is it not more logical to force for example three ensembles with Crowley and Unterman (2013) and three with Gao et al. (2008)? I would recommend to expand the methodology section of your paper with a more elaborate description of the exact methods. It will improve the paper if an overview of the steps that were taken is added, including the data that is used, model configurations and parameter values. Also an argumentation for the choices that were made will result in a more complete understanding of the methodology. A more extended discussion can also be added to the paragraph starting at line 264 then, discussing whether the chosen methodology turned out to be appropriate or if other choices should have been made.

3. A lot of relationships are stated in the introduction between tropical eruptions and the ENSO, IOD and Australian rainfall. For example, volcanism leads to negative global precipitation anomalies, large tropical eruptions can increase the likelihood and amplitude of an El Niño event in following years and a negative IOD occurs immediately after an eruption and a positive IOD one year later. For the relationship between volcanic eruptions and the ENSO, two possible mechanisms are mentioned in lines 49-53, although not in much detail, and the other relationships are not explained at all. However, you already refer to quite some papers that contain a more elaborate description behind the relationships.

   If the mechanisms behind the processes would have been incorporated in the introduction, these mechanisms could also have been used in the discussion and conclusions section to explain the results that were found in your study. It could be checked whether the results correspond to these processes or if other processes are needed to explain the results. An example is that it would be useful if the processes that are taking place can be used to explain the difference between the timing of the peaks in figure 3 and 5, since this is currently not discussed in the paper.

   There are two specific results mentioned that I think will definitely become more understandable if a discussion in which the processes are taken into account is added. Line 239 in the discussion and conclusions section tells us that tropical volcanism leads to positive precipitation anomalies over SE and NW Australia. In line 34 in the introduction it was stated, however, that sulfate aerosols result in negative global precipitation anomalies. I am puzzled by this contradiction, could it be caused by different processes that are occurring at different scales? Moreover, in line 232-233 of the discussion it is stated that an El Niño-like pattern in the eastern Pacific is most visible in year 4, but also in year 0, 1 and 3. However, an explanation for this occurrence is not given, while I am wondering what occurred during year 2 that no El Niño was observed. I would recommend to include a broader overview of all mechanisms behind the relationships in the introduction and take these mechanisms into account in the discussion of your results. The references in your paper about the mechanisms can be used for this adaptation, for example Clement et al. (1996), Mann et al. (2005), Pausata et al. (2015), Cheung & Abram (2016) and Meyers et al. (2007). Adding these explanations to your paper would really help the reader with understanding the physical processes and consequently the relationships that are discussed. Besides, if these physical processes are more discussed in the introduction, they can also be used to explain the results of your research, for example the two specific results whose causes were unclear to me, as I mentioned above.

MINOR ARGUEMENTS

1. A result of your research that is not mentioned in the abstract is that volcanic aerosol cooling dominates the precipitation response, while this is, in my opinion, an important result that should also be stated in the abstract. I would recommend to add this result to your abstract after the other results that are mentioned.

2. In the introduction the research question(s) is/are not clearly stated, although this would help with providing the reader with a better overview of the contents of the paper. I am also missing a broader aim of the paper and societal relevance, since it does not become completely clear what you actually want to achieve with your research and how you think your research will contribute to society. I would recommend to add the research question(s) and societal relevance to the introduction of the paper and the societal relevance might also be mentioned in the conclusion, stating what the results and conclusions can be used for.

3. In line 127-128 you explain why you chose to examine the IOD over the July-November period and you refer to Weller et al. (2014). However, their paper and also their results are only about positive IOD's. Negative IOD's are mentioned only twice in the whole paper, so I am not sure you can refer to this paper when your research examines both positive and negative IOD's. If you think you were right to still use the statement of Weller et al. (2014), I would like to see your explanation about this and otherwise you might consider taking into account a different period.

4. You state in line 134-136 the reason why you chose to analyse precipitation anomalies in southeast and northwest Australia and you refer to Ashok et al. (2004). However, most results of Ashok et al. (2004) are only about India, Pakistan and the monsoon trough and I do not find any mentioning of Australia. It would be good to check this reference and, if it turns out to be still the right one, to mention which results of their research you used. If the reference is not correct, please change the reference into the one that you based your statement on.

5. In line 133 in the methodology it is stated that the rainfall anomalies were examined over the July-November period, but it is not explained why you chose this period. It could be that the precipitation results are completely different during the other part of the year, for example that precipitation anomalies are negative instead of positive. I think it would be interesting to also take this into account in your research in order to have a more complete yearly overview, so maybe you could also perform these model simulations. Otherwise you could explain in your methodology why this was not necessary or possible.

6. You chose to do your research for the six largest tropical eruptions between 850-1850 CE as stated in line 114 in the methodology, while previous research, for example Cheung & Abram (2015) and Maher et al. (2015), took also smaller eruptions into account. Would it not be useful to also include these smaller eruptions in your

research, since a better comparison between your study and these other studies can be made then? If you have a specific reason why you only chose the six largest eruptions, I would recommend to explain this reason in the methodology section after you mention which eruptions you analysed.

MINOR ISSUES

Page 3, line 126: Please add a reference for the use of the NINO3.4 index and its calculation.

Page 6, line 236: ‘Increases’ should be ‘increase’.

Page 15, caption figure 10: ‘Mean SE’ is missing in the caption of this figure if I compare it with the caption of figure 8, so please add this. The rest of the paper is very well-structured and does not contain any mistakes.

2) Author's Response:

Dear Reviewers,

Thank you for taking the time to read and comment on our paper. Your reviews were very helpful and we have now made several important revisions in light of these recommendations.

Anonymous Referee #1

1) Experimental design: Since the study largely focuses on the IOD and ENSO, the authors should describe in detail how SSTs and evaporation over oceans is handled in the model. Is it AMIP run? Is it coupled? Slab ocean? And if the SSTs are prescribed, can it be used at all? These things are completely disregarded in the manuscript at hand.

We have addressed this concern at line 634-635. The atmospheric model is coupled with the dynamical Russel Ocean Model, and a reference (Schmidt et al., 2014) provided for further detail on the Russel Ocean Model configuration.

2) Model evaluation: There is NO effort made to convince me that this model is doing a good job in terms of precipitation. I would like to see a comparison between model and proxy data, or model and (PDSI) reconstructions.

The GISS E2-R model has previously undergone comprehensive evaluation for rainfall metrics and drivers in previous studies (Flato et al., 2013; Schmidt et al., 2014; Moise et al., 2015; and Miller et al., 2015). We have now included a literature review of these studies covering surface temperature, precipitation, volcanic aerosols, the ENSO and the IOD (line 637-651) and conducted additional comparisons of modelled and observed NINO3 index intensity, seasonality and regression against SST and precipitation (Line 652-682 and Figure 1). We have not included a comparison of the model output with the PDSI as we do not believe that this provides greater insight into the model skills than investigating precipitation metrics directly.

3) Physical mechanisms behind the shown effect on ENSO and IOD: Although a lot of studies are cited as to show that there is agreement with previous work, I didn't find a proper physical explanation for the effects we see in the plots besides the paragraph in the introduction. I would like to see a discussion about the mechanisms in this specific model.

We have conducted further examination of the physical mechanisms driving the response of the IOD (line 863-870) and ENSO (line 876-881) in GISS to contribute to our studies agreement with previous work in the results and discussion, and included a description of the anomalous wind direction (Fig. 13) and speed (Fig. 14) following eruptions to contribute to the IOD and ENSO response (line 807-812).

Line 34: I would add here newer studies about precipitation like Iles et al 2013 or Wegmann et al 2014

The Illes et al. (2013) reference was reviewed and added here (line 554).

Line 93: Not sure what exactly is unclear? Do you mean dynamic vs radiative changes? Please explain further what gap your study is filling.

We have modified the structure of the introduction to further outline the premise of this study: to analyse the impact of volcanic forcing on Australian rainfall due to its direct effect and the feedback effects of ENSO and the IOD. The lack of clarity on this subject is present due to lack of literature focused specifically on it (line 556-557 and line 623-624).

Figure 2: Is this the annual mean? If so please indicate the fact. Maybe it would be nice to see DJF and JJA anomalies?

This is the July-September mean (JASON). Clarification has been provided in figure titles (line 1156, 1191, 1229, 1231)

Table 1: It says strongest eruptions in the last millennium but I am pretty sure that Tambora was stronger than Huaynaptina as Figure 1 shows. In fact even the unknown 1809 eruption is bigger. Please adjust your table description.

We plan to keep our table description as it is. Tambora is included in the table, and listed as the 3rd largest eruption, while Huaynaputina is listed as the 6th. The 1809 eruption was not larger than Huaynaputina, with a total global stratospheric sulfate loading (Tg) of 53.74, compared to Huaynaputina's 56.59. We presume that instead referee #1 was referring to the 1783 eruption, with a Tg of 92.96. We specify in the table title that we are looking at the largest 'tropical' eruptions, which are defined in the paper as eruptions that significantly impacted both hemispheres, as recorded by Gao et al., (2012), of which the 1783 eruption was not, with the entire 92.96 Tg limited to the northern hemisphere.

Figure 3: In fact 2xCG is not an ensemble and should not be marked as such.

We agree, and this clarification has been added to all figures.

Figure 4: The 90th percentile of what? The ensemble members? If so, please adjust. (also for the rest of the Samalas and Huaynaputina plots.

It is the 90th and 10th percentile of the ensemble members. Clarification has been provided in figure titles (line 1173, 1188, 1206, 1220)

Figure 10: Here it says Australian precipitation whereas Figure 9 says NW Australian precipitation and Figure 11 says SE Australian precipitation. I assume Figure 10 also is SE precipitation?

This figure was meant to say SE, this alteration has been made (line 1212).

Anonymous Referee #2

In the "Introduction" section 1.1 It is not clear from the description which relationships between volcanic eruptions and Australian rainfall are unclear and are explored in this paper. Please be more specific. A significant part of the *introduction is devoted to the literature review of the volcanism and ENSO relationship, while the focus of this study is on volcanic eruptions and Australian rainfall. Please modify either the title, or the structure of introduction. For example, the authors may consider introduce the role of ENSO in changing Australian rainfall before discuss the volcanism and ENSO. Relationship*

We have improved the structure of the introduction, now beginning with a description of Australian rainfall characteristics, before introducing the relationship between volcanic aerosols and ENSO and IOD systems. We have also clarified that the uncertainties in the relationship between volcanic aerosols and Australian rainfall lie in the lack of research devoted solely to the subject and due to the contrasting precipitation surplus impact of the direct radiative effect of aerosols, with the precipitation supressing impact of generated El Nino and positive IOD phases (line 554-558).

In the "Data and Methods" section 2.1. Line 99, please explain briefly why the last millennium period is especially chosen. 2.2 Please provide a short description of model performance, especially those closely related to the ENSO, IOD and volcanic climate responses. Please also provide a short explanation of why the five volcanically forced scenarios were chosen. 2.3 Line 134, please also discuss the ENSO impact in the chosen north-west and south-east regions.

Clarifications have been included to the data and methods section in light of these comments. A short literature review of previous model evaluation of GISS E2-R and further evaluations conducted on ENSO have been included (line 637-682 and Figure 1), and the reason for choosing the Last Millennium as a target period (due to a large number of recorded volcanic eruptions) has been outlined (line 688-689).

In the "Results" section 3.1 Please explain the advantages of comparing the response between the largest 1257 Samalas and the smallest 1600 Huaynaptina eruption, rather than a series comparison among the 6 eruptions of various size.

While a comparison of all 6 eruptions individually to the IOD, ENSO and Australia rainfall is possible, we believe that providing the overall multi-ensemble multi-volcanic mean as well as the multi-ensemble mean for the largest and smallest eruptions individually was sufficient to support the arguments made in this paper. We are not arguing that larger eruptions will exponentially cause stronger responses in the IOD and ENSO, however we do argue that significantly larger eruptions e.g. Samalas (257.91 Tg) when compared to Huaynaptina (56.59 Tg), are more likely to cause a stronger and more persistent response, which the graphs provided, do show.

3.4 The focus of this work is Australia, however, there is no spatial figures dedicated to the particular area of study. 3.5 Please verify the use of 0.6 standard deviation as the significant level.

While we understand this concern, we believe the results from our paper will be of broader interest, so we have chosen to show global maps. These maps are sufficiently detailed to show the Australian response, as well as the broader one, and thus, chose not to include maps dedicated solely to Australia.

4.2 Line 228-235, I do not see the El Nino response persist from year 0 to year 6 in both Fig. 5 and Fig. 2. Please *explain why the El Nino-like pattern in the eastern Pacific is most visible in year 4, but not earlier.*

Evaluation of the physical mechanisms driving the more visible El Nino-like anomaly seem in Fig 3 in year 4 have been included in the discussion (line 876).

4.4 The most important advantage of using modelling results is the capacity of exam the physical mechanisms behind the shown effects (such as the impact on ENSO and IOD, and their influence on Australian rainfall). Please provide some discussion of mechanism using the original results from this paper, rather than referring to previous studies.

We have conducted further examination of the physical mechanisms driving the response of the IOD (line 863-870) and ENSO (line 876-881) in GISS to contribute to our studies agreement with previous work in the results and discussion, and included a description of the anomalous wind direction (Fig. 13) and speed (Fig. 14) following eruptions to contribute to the IOD and ENSO response (line 808-812).

Public Reviewer #1:

Your methodology contains in line 102 the statement that the Coupled Model Intercomparison Project Phase (CMIP5) is used in the NASA GISS ModelE2-R. However, Taylor et al. (2012) explain that the CMIP5 strategy can be used for long-term (century time scale) and near-term integrations (10-30 year). You explored anomalous conditions in the ENSO, the IOD and Australian rainfall for 7 years in total and only five years after a volcanic eruption, since this minimizes the effect of trends or low-frequency climate variability, which is a good argumentation. However, I wonder if the use of the CMIP5 gives reliable short-term model results for this short time period. Since you make you use of the NASA GISS ModelE2-R General Circulation Model and you refer to Schmidt et al. (2014) in line 100, I assume that your model contains all components that are taken into account by Schmidt et al. (2014) and that it includes an interactive representation of the atmosphere, ocean, land and sea ice. I expect that for most atmospheric processes the shorter timescale of your research will not be a problem, since most of these atmospheric processes are fast. The influence of aerosol injection into the atmosphere after a volcanic eruption will quickly have a noticeable influence in the model on for example atmospheric temperature, incoming shortwave solar radiation and cloud formation. However, ocean and land, domains that are also taken into account in the model, will have slower responses to volcanic eruptions. For example sea surface temperature, ocean currents and permafrost presence will take longer to adapt to the aerosol injection and corresponding atmospheric changes. For these variables the five year time scale that is investigated in your research might possibly be too short in order to explore the trend that occurs after a volcanic eruption.

While we understand these concerns that the effect of volcanic aerosols have a delayed response in the ocean and land domains when compared to the atmosphere, we believe these concerns are outside the scope of this paper. There is extensive literature that supports the view that precipitation, surface temperature, the ENSO and the IOD all only show a statistically significant response to volcanic aerosols within the first five years post eruption (Adams et al., 2003; Cheung & Abram., 2016; Emile-Geay et al., 2008; Gillett et al., 2004; Illes et al., 2013; Joseph and Zeng et al., 2011; Maher et al., 2015; Mann et al., 2005; McGregor et al., 2010; Pausata et al., 2014; Predybaylo et al., 2017; Schneider et al., 2009; Soden et al., 2002; Wahl et al., 2014) . While ocean currents and the deep ocean do take longer to respond, these processes are not examined in this paper. We therefore consider it unnecessary to alter the timescales used in our analysis, though would consider this comment for future research.

I do not think that the methodology, mainly section 2.1 Simulations, contains enough information to understand your exact process in order to set up and make use of the model. Information that is missing is which data you used and what its source is, why you chose to make use of the specific NASA GISS ModelE2-R and the CMIP5, which variation of this model and which configuration were used and which values were for example used for the effective radius of the sulfate droplets.

We have addressed this concern at line 634-635. The atmospheric model was run with the Non-Interactive (NINT) atmospheric composition and is coupled with the dynamical Russel Ocean Model, and a reference (Schmidt et al., 2014) provided for further detail on both model configurations. A small literature review of previous evaluation of GISS E2-R and a personally conducted evaluation of ENSO is also provided to justify the use of the model in these studies (line 637-682) and the configuration of volcanic aerosols in the model described (line 689-691).

It is also not explained why five ensembles were forced with volcanic forcing, while four were not. Of the five run with volcanic forcing, four were forced with Crowley and Unterman (2013)'s aerosol optical depth data and one with double the Ice-core Volcanic Index 2 by Gao et al. (2008), but why are these not equally divided? Is it not more logical to force for example three ensembles with Crowley and Unterman (2013) and three with Gao et al. (2008)? I would recommend to expand the methodology section of your paper with a more elaborate description of the exact methods.

Our choice of the combination of 5 volcanically forced ensembles, and 4 non-volcanically forced ensembles was driven by a desire to see a comparison of the effect of volcanic aerosols with non-volcanically influenced scenarios to strengthen any arguments for the effect of aerosols (line 685). The use of more Crowley and Unterman AOD is due to the fact that Gao et al. (2008)'s data was multiplied by 2 (line 687).

I would recommend to include a broader overview of all mechanisms behind the relationships in the introduction and take these mechanisms into account in the discussion of your results. The references in your paper about the mechanisms can be used for this adaptation, for example Clement et al. (1996), Mann et al. (2005), Pausata et al. (2015), Cheung & Abram (2016) and Meyers et al. (2007). Adding these explanations to your paper would really help the reader with understanding the physical processes and consequently the relationships that are discussed. Besides, if these physical processes are more discussed in the introduction, they can also be used to explain the results of your research.

Examination of the mechanisms driving the response in GISS was undertaken, and provided explanation for responses seen in the model results to compliment the mechanisms described by the referenced paper (line 863-870, 876-881, 807-812).

3) Changes to manuscript

Assessing the impact of large volcanic eruptions of the Last Millennium on Australian rainfall regimes

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Abstract. Explosive volcanism is an important natural climate forcing, impacting global surface temperatures and regional precipitation. Although previous studies have investigated aspects of the impact of tropical volcanism on various ocean-atmosphere systems and regional climate regimes, volcanic eruptions remain a poorly understood climate forcing and climatic responses are not well constrained. In this study, volcanic eruptions are explored in particular reference to Australian precipitation, and both the Indian Ocean Dipole (IOD) and El Nino-Southern Oscillation (ENSO). Using nine realisations of the Last Millennium (LM) with different time-evolving forcing combinations, from the NASA GISS ModelE2-R, the impact of the 6 largest tropical volcanic eruptions of this period are investigated. Overall, we find that volcanic aerosol forcing increased the likelihood of El Nino and positive IOD conditions for up to four years following an eruption, and resulted in positive precipitation anomalies over northwest (NW) and southeast (SE) Australia. Larger atmospheric sulfate loading during larger volcanic eruptions coincided with more persistent positive IOD and El Nino conditions, enhanced positive precipitation anomalies over NW Australia, and dampened precipitation anomalies over SE Australia.

1. Introduction

Volcanic eruptions have significant impacts on weather and climate variability through the injection of volcanogenic material into the atmosphere. Sulfate aerosols, formed through the reaction of SO_2 and OH^- in the volcanic cloud, decrease incoming shortwave radiation, and if injected into the stratosphere, can generate a global response (Driscoll et al., 2012; LeGrande et al., 2016). Previous studies have identified relationships between volcanism and surface and tropospheric cooling (Driscoll et al., 2012), local stratospheric warming (Wielicki et al., 2002), strengthening of the Arctic Oscillation and Atlantic meridional overturning circulation (Oman et al., 2005; Stenchikov et al., 2006, 2009 & Shindell et al., 2004), and negative global precipitation anomalies (Gillet et al., 2004, Iles et al., 2013). The present study focuses on the under-studied relationship between large, globally significant tropical eruptions in the Last Millennium (850-1850CE) and Australian precipitation through examination of the direct radiative aerosol effect and the feedbacks of two tropical modes that strongly influence Australian rainfall: the El-Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD).

ENSO's effect on Australian precipitation has long been recognized. El Nino events typically cause averaged precipitation deficits, while La Nina cause positive precipitation anomalies (Meyers et al., 2007; Pepler et al., 2014). In addition, a statistical relationship has been demonstrated between explosive tropical volcanism and ENSO where large

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tropical eruptions can increase the likelihood and amplitude of an El Nino event in following years, followed by a weaker La Nina state (Adams et al., 2003). Further work by Mann et al. (2005), Emile-Geay et al. (2008), McGregor et al. (2010), Wahl et al. (2014) and Predybaylo et al. (2017) supported this result. Pausata et al. (2015) identified that a radiative forcing threshold value of more than 15 W m^{-2} is required to affect the ENSO, and that high latitude Northern Hemisphere eruptions, in addition to tropical eruptions, are capable of doing so, as long as the forcing is asymmetric with regards to the equator.

The relationship between volcanic forcing and ENSO has been attributed to two contrasting, though not unrelated, mechanisms. The dynamical thermostat mechanism (Clement et al., 1996), whereby a uniform reduction of the surface heat flux due to volcanism causes warming of the eastern equatorial Pacific, was identified as the driver of ENSO's response to volcanism by Mann et al. (2005) and Emile-Geay et al. (2008). Conversely, a shift in the Intertropical Convergence Zone (ITCZ) induced by strong radiative forcing, was accredited in more recent studies (Pausata et al., 2015; Stevenson et al., 2016). Preconditioning does impact the severity of the ENSO response. Predybaylo et al. (2017) found that years with an initial central Pacific El Nino ENSO phase show the largest statistical impact from Pinatubo-sized eruptions and that summer eruptions coincided with a more pronounced El Nino response.

Despite the understanding that volcanism can trigger or amplify El Nino events in the following years, the exact relationship between ENSO and volcanic forcing is still debated. McGregor and Timmermann (2011) and Zanchettin et al. (2012) reported an enhanced probability of La Nina events occurring in the immediate years after a volcanic eruption, rather than El Nino, while several other studies (Self et al., 1997; Robock, 2000; Ding et al., 2014) found no relationship between ENSO and volcanic forcing. Robock (2000) argued that both El Chichon and Pinatubo reached their peak forcing after the initiation of El Nino events, indicating a coincidental relationship, while other studies (Driscoll et al., 2012; Lewis & Karoly, 2014; Lewis & LeGrande, 2015; Predybaylo et al., 2017) have pointed out challenges in determining long-term characteristics of ENSO due to short instrumental records, and its relationship to volcanic forcing due to variable representations of both ENSO and volcanic aerosols in GCMs (Global Climate Models).

Comparatively little research has gone into the effects of volcanic forcing on the Indian Ocean Dipole (IOD), despite its known climatic impacts on Indian Ocean basin countries, such as Australia, South Africa, India and Indonesia (Cheung & Abram, 2016). The IOD is the zonal sea surface temperature (SST) gradient between the tropical western Indian Ocean (WIO) and the tropical south eastern Indian Ocean (EIO) (Roxy et al., 2011), defined by the Dipole Mode Index (DMI). Positive IOD (pIOD) states typically cause averaged precipitation deficits over Australia, and negative IOD (nIOD) cause a surplus (Meyers et al., 2007; Pepler et al., 2014). While ENSO is often considered primarily responsible for triggering Australian droughts, the IOD has been shown to have an equal, if not larger, impact on heavily populated areas of Australia, with all significant southeastern Australian droughts in the 20th C showing a larger response to pIOD events than El Ninos (Ummenhofer et al., 2009).

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Cheung & Abram (2016) found that the DMI shows a statistically significant correlation to volcanic forcing, with a negative IOD (nIOD) occurring immediately after an eruption and a positive IOD (pIOD) one year later. Maher et al. (2015) found a similar relationship, with coinciding El Nino and pIOD events occurring 6-12 months after the peak of volcanic forcing. The response of the IOD to volcanic forcing has been hypothesised to result from either the IOD's relationship with ENSO (Cheung & Abram, 2016), or the volcanically-induced reduction of the Asian Monsoon (Anchukaitis et al., 2010; Zambri et al., 2017).

The direct radiative effect of volcanic aerosols have been found to cause global precipitation deficits for up to 5 years post-eruption (Robock & Lui, 1994; Iles et al., 2013; Gillett et al., 2004; Gu & Adler, 2011; Soden et al., 2002; Joseph & Zeng, 2011; Schneider et al., 2009; Timmreck et al., 2012; Iles et al., 2015). However, these deficits have been shown to vary seasonally (Joseph & Zeng, 2011), and cause positive precipitation anomalies over the NW and SE of Australia in the Southern Hemisphere (SH) winter and early spring (July-September - JASON), despite significant precipitation deficits in the summer (Joseph & Zeng, 2011; Schneider et al., 2009). This current study explores these relationships between volcanic eruptions and Australian rainfall during JASON, with reference to the direct radiative effect and the feedback effects of the ENSO and IOD.

2. Data and methods

2.1 Simulations

To understand the response of the IOD, ENSO and Australian precipitation to volcanic forcing in the Last Millennium, we analysed 9 ensembles from the NASA GISS ModelE2-R (hereafter simply GISS) (Schmidt et al., 2014). The GISS ensemble was run for the pre-industrial part of the Last Millennium (LM), from 850-1850 CE, which is defined by the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). GISS is run at 2 degrees x 2.5 degrees horizontal resolution, with 40 vertical levels up to 0.1 hPa. The "non-interactive" atmospheric composition model, or NINT, is coupled with the dynamic Russell ocean model (Schmidt et al., 2014).

Evaluations of the accuracy of ENSO, IOD, surface temperature, precipitation and volcanic aerosols modelled in GISS have been conducted by Flato et al. (2013), Schmidt et al. (2014), Moise et al. (2015) and Miller et al. (2015). Global temperature observed at surface, middle troposphere and lower stratosphere are all accurate to within 2 standard deviations in the Historical ensemble (Miller et al., 2015), with GISS surface temperatures agreeing with observations in all areas of interest to this study to within 2°C and correctly simulating surface cooling following volcanic eruptions (Flato et al., 2013; Miller et al., 2015). In the Southern Ocean some systematic deficiencies cause large SST biases, however overall biases remain below 0.7-0.8°C (Schmidt et al., 2014).

Mean global precipitation is too high during the historical period, particularly around the tropics, when compared to observations (Schmidt et al., 2014), however the spatial pattern of precipitation agreed with trends calculated from Global Precipitation Climatology Project retrievals (Miller et al., 2015). Australian precipitation had a spatial-temporal root square mean error (RSME) of ~1mm/day and the model was deemed to provide good representations of surface temperature and precipitation over the entirety of Australia (Moise et al., 2015).

GISS captures the basic east-west structure of the tropical Pacific well, and follows the trend of the NINO3.4 index with the greatest accuracy between 2-3 years of an ENSO event (Flato et al., 2013; Schmidt et al., 2014). Calculation of the NINO3 index (150-90W and 6N-6S) for GISS and the Reynolds OI SST (https://www.ncdc.noaa.gov/oisst) observations for the first 50 years of the GISS piControl displayed an underestimation of ENSO intensity in GISS (Fig 1 (a,b)), meaning the modelled SST anomalies were weaker than observations. However, variability throughout the year

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is consistent with observations (Fig 1 (c,d)), and regression of the index onto SST, scaled by the standard deviation of the NINO3 index, shows the global spatial pattern is also in good agreement for ENSO and the IOD (Fig 1 (e, f)). Similar regression of the NINO3 index against precipitation (Fig 1 (g, h)) also showed spatial concurrence between GISS and GPCP (https://precip.gsfc.nasa.gov/) observations, displaying the precipitation dipole over the Indian Ocean associated with the IOD.

Five ensembles were forced with volcanic forcing, while four were not to compare the effect of volcanic aerosols with non-volcanically influenced scenarios. Of the five run with volcanic forcing, four were forced with Crowley and Unterman (2013)'s aerosol optical depth data (CR), and one with double the Ice-core Volcanic Index 2 by Gao et al. (2008) (2xG) (see Table 1 for experiment summary). The LM was chosen for analysis as the period contains the majority of large tropical volcanic eruptions recorded in these datasets. The GISS model is forced with prescribed Aerosol Optical Depth (AOD) from 15-35 km, with a 4-layer vertical (15-20km, 20-25km, 25-30km and 30-35km and 24 layer (8°) longitudinally independent latitude, with Reff specified as per Sato et al. (1993). The LM simulations also include transient solar and land use histories that differ between ensembles. However, as this analysis focuses primarily on the immediate post-volcanic response, the impact of these smaller amplitude and slow-varying forcings is likely to be insignificant (Colose et al., 2016).

2.2 Methods

First, the six largest tropical eruptions between 850-1850CE were identified by the magnitude of their total global stratospheric sulfate aerosol injection (Tg) from the IVI2 Version 2 dataset, revised in 2012 (Gao et al., 2008), and the years surrounding eruption extracted for analysis (see Table 2 and Figure 2). Eruptions were deemed as tropical if volcanic aerosols were present in significant amounts in both hemispheres. The Kuwae eruption is included within the analysed eruptions, and is dated to 1452CE. While this year contains the bi-hemispheric deposition from the Kuwae eruption in both volcanic datasets used in this study, it is important to note that Sigl et al. (2013) recently constructed an ice-core record of volcanism that dates the Kuwae eruption to 1459/1459CE, with another, smaller eruption occurring at 1452. For the purposes of this paper, however, Kuwae will be considered as the 1452 deposition event.

We explored anomalous conditions in ENSO, the IOD and Australian rainfall. For ENSO, the period December-February (DJF) was examined using the NINO3.4 index, defined by the averaged sea surface temperature (SST) anomalies between 5N-5S and 170-120W. When analysing the IOD, the July-November (JASON) period was examined due to the tendency for pIODs to develop and mature over these months (Weller et al., 2014). The IOD was measured using the Dipole Mode Index (DMI), which subtracts the averaged SST in the EIO (90-110E; 10S-0) from the averaged SST in the WIO (50-70E; 10S-10N).

Australian precipitation was processed to find the anomalies of each season and year relative to the long-term mean over the JASON period. Analyses were conducted on area-averaged rainfall for the south-eastern Australian (132.5-155E; 27.5-45S) and north-western Australian (110-132.5E; 10-27.5S) regions. The south-east and north-west were chosen for analysis as the effect of the IOD on Australian precipitation is largest in, and potentially limited to, these general areas (Ashok et al., 2003).

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The response of these large-scale modes of variability and rainfall are investigated using an epoch approach. For each major identified eruption, a response was defined by subtracting a reference period (the mean of 5 years pre-eruption) from the eruption year and the six years following eruption individually. A reference period of five years was chosen as it minimised the effect of trends or low-frequency climate variability (Iles et al., 2013). Mode specific graphs (IOD, ENSO, Australian Precipitation) focused on the nine years surrounding eruption (years -2 to 6, with year 0 being the year of eruption). The mean of all six eruptions in each ensemble were calculated for individual years, and then the mean of all ensembles included in each forcing category were compared (CR, 2xG or None).

3. Results

The global SST response for the CR forcing group shows predominantly surface cooling anomalies (Fig. 3). More specifically, cooling occurs in the Northern Hemisphere from years 0-3, while the south Atlantic, Indian and Pacific oceans show mostly minor warming. The uniform reduction and re-distribution of surface temperature causes an El Nino-like warming temperature gradient in years 0, 1 and 4 post eruption. In the Southern Hemisphere, cooling is most pronounced over land masses, particularly Australia and the southern tip of Africa.

The DMI response showed a significant pIOD condition one year after major eruptions in all volcanically forced ensembles that persists until year 5, where an abrupt negative IOD phase occurs (Fig. 4). This response can also be seen in Fig. 2, where the EIO region shows larger and more widespread cooling anomalies than the WIO region in years 1, 2 and 4. This response contrasts to the non-volcanically forced ensembles, which show neither a prolonged pIOD nor nIOD condition.

The response of the DMI to the largest and smallest eruptions were also extracted. Fig. 5 show the mean DMI response to the 1258 Samalas eruption (257.91 Tg) and the 1600 Huaynaptina eruption (56.59 Tg). Our results show that while both eruptions caused a significant simulated pIOD at year 1, the larger 1258 Samalas eruption persisted with a significant pIOD condition in years 2 and 4, while the 1600 Huaynaptina eruption did not.

The mean NINO3.4 multi-volcano response to ensemble forcing showed a statistically significant El-Nino like response for all 6 years following eruption, with a peak at year 3 in both the CR and 2xG ensembles (Fig. 6). The non-volcanically forced ensemble group showed neither a significant El Nino nor La Nina tendency, with the NINO3.4 index remaining within 0.4/-0.4. The index also showed an increase in the intensity and endurance, of post-volcanic El Ninos between the Samalas and Huaynaptina eruptions (Fig. 7). The Samalas eruption was followed by an El Nino that endured for 3 years, from years 1-3, peaking at a NINO3.4 anomaly of 0.68 in year 3, while Huaynaptina peaked at 0.53 in year 2 from an El Nino that endured for 2 years.

Fig. 8 shows the mean precipitation response of all volcanically forced ensembles. Precipitation deficits can be seen in the tropics in years 0-2, the most substantial and widespread of which occur in the Asian monsoonal area and the western Pacific basin. Bands of decreased precipitation also occur at approximately 40°S, between 0-40°N in the North Atlantic Ocean and between 40-80°N over Northern America and Europe. The Southern Hemisphere subtropics appear to have a slight increase in precipitation in years 0-2, most prominently over Australia and southernmost Africa, while the southern polar region (60-90°S) shows only variable minor precipitation anomalies occurring in all 6 years post eruption.

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Ensembles with volcanic forcing showed an increase in precipitation over southeast (SE) (Fig. 11) and northwestern (NW) (Fig. 9) Australia between July to November (JASON). Both areas showed predominantly positive anomalies in years 0-5 post-eruption, with the largest response seen between years 0-2. NW Australia (Fig. 9) showed larger positive precipitation anomalies between years 0-2 than SE Australia (Fig. 11) in the CR ensemble mean, and in years 0 and 2 in the 2xG ensemble mean.

Comparison of the precipitation anomalies following the Samalas and Huaynaptina eruptions in NW Australia (Fig. 10) showed that the smaller eruption had a delayed and smaller positive precipitation peak, with Samalas peaking in year 0 with an anomaly of 0.23 and Huaynaptina in year 2 at 0.14. While the Huaynaptina eruption also showed a delayed peak in precipitation in SE Australia (Fig 12), the persistence of positive precipitation anomalies exceeded those of the Samalas eruption. Huaynaptina recorded values > 0.17 in years 1-2 and a value of 0.12 in year 4, all of which were larger anomalies than the peak of the Samalas eruption at 0.11 in year 1 (Fig. 12).

Figures 13 and 14 show multi-volcano mean anomalous changes to the surface wind direction (Fig. 13) and speed (Fig. 14) over the 5 years following eruptions in the CR forcing group. The most notable changes occur in years 0 and +1 where anomalously strong Southern Hemisphere westerlies and anomalously weak south easterly trade winds occurred, accompanied by strong north-easterlies off the south-east coast of China and an intensification of North Atlantic circulation. In year +3 anomalous south easterly winds off the south-western coast, and anomalous westerlies off the central western coast, of South America are seen.

4. Discussion and conclusions

Our results suggest that the large-scale IOD and ENSO systems, and Australian rainfall regimes, were all impacted by large tropical eruptions of the Last Millennium.

The DMI response simulated in the GISS ensemble following large eruptions is complimentary to previous research conducted by Cheung & Abram (2015) and Maher et al. (2015). The pIOD peak in year 1 (Fig. 4) is consistent with both studies, in which statistically significant pIOD conditions occurred between 6 months to 2 years after an eruption. Cheung & Abram (2015) also found a statistically significant negative condition immediately after eruption at year 0, however this was absent from both Maher et al.'s (2015) results and the CR forcing category in this study. The 2xG category does show a nIOD condition at year 0, but is not believed to be a response to volcanic forcing as a similar nIOD condition can be seen at year -1. The abrupt shift to a negative condition at year 5 was not found in either Cheung & Abram (2015) or Maher et al. (2015)'s results. Both studies found a gradual decrease in DMI from year 1 to years 3-4.

The smooth transition to a lower DMI following eruptions found by Cheung & Abram (2015) and Maher et al. (2015) contrasts with the abrupt change from a pIOD of approximately 0.13 at year 4, to an nIOD of -0.069 in the CR ensembles and -0.083 in the 2xG ensemble at year 5 (Fig. 4). This inconsistency between studies could be due to the selection of eruptions analysed by each paper. Cheung & Abram (2015) included all eruptions from 850-2005CE recorded on the IVI2 in their analysis. While this encompasses all eruptions analysed here, it also included many smaller eruptions that would likely have dampened the climatic response, a response that has been analysed in previous

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papers (Zambri & Robock, 2016). Maher et al. (2015) looked at the five largest eruptions from 1880 to present, of which the largest was Pinatubo (1991), measured at 30.10 Tg globally on the IVI2 (Gao et al., 2008). In comparison, our research deals with eruptions of much larger atmospheric loading, ranging from 56.59 to 257.91 Tg.

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Therefore, the persistence of a high pIOD through to year 5 seen here may result from the larger mean atmospheric sulfate loading imposed. This theory is supported by the comparison between the Samalas and Huaynaptina (Fig. 5) eruptions. Our results showed that while both eruptions caused a significant pIOD at year 1, the larger 1258 Samalas eruption alone persisted with a significant pIOD condition in following years. Further support can be gathered from the comparison between the 2xG and CR ensemble means in fig. 4. Years 0-3 show more extreme values in the 2xG ensemble mean, while years 4-6 show similar values for both forcing categories. Maher et al. (2015) found a similar response, with the two largest eruptions analysed in the paper showing the largest and longest enduring pIOD anomalies. This suggests that larger mean atmospheric sulfate loading can cause not only more persistent, but also more extreme pIOD conditions.

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The phase and intensity of the IOD is known to be influenced by the Asian monsoon (Brown et al., 2009; Xiang et al., 2011), and the physical mechanisms driving the pIOD response to volcanic forcing in GISS likely stems from this relationship. In GISS, the Asian monsoon was suppressed by the anomalous north easterly flow off the south-east coast of China in years 0 and +1 (Fig. 13; Fig. 14) generated by volcanic aerosols, and a decrease of convection over the warm pool, cause by El Nino-like anomalies in those same years (Fig 3). These feedbacks caused a comparatively warmer WIO, generating a pIOD. The Asian monsoon suppression following volcanic eruptions was also noted by Stevenson et al. (2016).

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The NINO3.4 response found in this research supports previous studies by Adams et al. (2003), Mann et al. (2005), Emile-Geay et al. (2008), McGregor et al. (2010) and Maher et al. (2015), despite GISS modelling weaker SST anomalies than observations (Fig. 1 (a,b)). Fig. 6 shows a very prominent and persistent El-Nino response in all 6 years following eruption, however it lacks the weaker La Nina-like state that was observed 3-6 years after eruption in these previous papers. Spatial maps of SST (Fig. 3), while dominated by the overall volcanic cooling, show an El Nino-like pattern in the eastern Pacific that is most visible in year 4, possibly driven by the anomalous winds off the western coast of South America in year +3 (Fig. 13). but is also distinctive in years 0, 1 and 3. We can therefore conclude that an El Nino-like anomaly was generated in the multimodel mean response in years 0-6 following eruption by a uniform reduction in surface temperature, driven by a decrease in the surface heat flux, a response also observed by Mann et al. (2005) and Emile-Geay et al. (2008). Comparison of the Samalas and Huaynaptina (Fig. 7) eruptions also suggest that, similar to the DMI, the intensity and endurance of the ENSO response to volcanic forcing increases with increasing mean atmospheric sulfate loading. This once again supports the findings of Maher et al. (2015) that identified a similar pattern.

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The positive response of Australian precipitation to volcanic forcing as seen here (Fig. 8, 9 &11) is in agreement with several papers that identified positive precipitation responses over Australia to large volcanic eruptions (Schneider et al., 2009; Joseph & Zeng, 2011). Our results suggest that the direct precipitation effect of volcanic aerosols override the impact of the IOD on Australian precipitation in the years following large tropical volcanic eruptions. NW Australia (Fig. 9) showed larger positive precipitation anomalies between years 0-2 than SE Australia (Fig. 11) in the CR ensemble mean, and in years 0 and 2 in the 2xG ensemble mean. This could be due to the positive precipitation

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anomalies that can be generated by combined El Nino and pIOD events in the NW Australian region (Meyers et al., 2007 & Pepler et al., 2014), enhancing the precipitation surplus caused by volcanic aerosols.

The varying response of NW Australia to the Samalas and Huaynaptina eruptions (Fig. 10) also supports the enhancement of the volcanically induced precipitation surplus by combined El Nino and pIOD events. The Samalas eruption was followed by strong and enduring El Nino and pIOD conditions for up to 4 years post volcanism, and showed larger positive precipitation anomalies from years 0-3 than the Huaynaptina eruption, that was accompanied by smaller, shorter-lived El Nino and pIOD conditions. The precipitation surplus to the Samalas eruption in NW and SE Australia also peaked earlier than Huaynaptina, which could be a response to the larger atmospheric sulfate loading. Interestingly, previous papers have not reported a relationship between atmospheric sulfate loading and the peak in precipitation response (Robock & Lui, 1994; Iles et al., 2013; Iles et al., 2015).

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The precipitation anomalies of SE Australia (Fig. 12) further supports this theory. The response to the Huaynaptina eruption, while peaking later than Samalas, endured longer, and with larger positive anomalies. The effect of strong, combined El Nino and pIOD conditions on SE Australia is significant precipitation deficits (Meyers et al., 2007 & Pepler et al., 2014), and could explain the negative precipitation anomalies that occur in the Samalas response from year 2 onwards, where the combined influence of a strong El Nino and pIOD dampened the positive precipitation response generated by the atmospheric sulfate loading.

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We note that our study has provided an analysis of climatic response to a set of forcings in a single climate model, which may limit the precise interpretation of responses to eruptions. Overall, volcanic aerosols remain an understudied climatic forcing such that the timing, magnitude and spatial footprint of past eruptions remains uncertain (Colose et al., 2016). In addition to uncertainties around the fundamental physical forcings, limitations still exist in the implementation of volcanic eruptions in climate models (Colose et al., 2016; Zambri et al., 2017). For example, Colose et al. (2016) suggest that improvements in model representations of volcanic particle size may improve the accuracy of model simulations. Furthermore, LeGrande et al. (2016) note that the chemistry and composition of a volcanic plume affects its climatic impact, which requires realistic representation in climatic models. Overall, these limitations in modeling eruptions and the idealised approach adopted here may mean that impacts simulated do not precisely match those of the proxy record.

In summary, this paper aimed to identify the impact of large, tropical volcanism on the ENSO, IOD and Australian rainfall. Results showed an El Nino and pIOD response in the immediate years following eruption, accompanied by positive precipitation anomalies over SE and NW Australia. The positive precipitation anomalies suggest that volcanic aerosol cooling dominates the precipitation response, rather than the effect of ENSO or IOD, despite aerosols also proving to be an important influence on these large-scale modes. Although this study focused on Australian rainfall regimes and its main climatic drivers, this approach can be applied for exploring the impact of time-evolving forcings, such as volcanism, in other regions.

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Acknowledgements

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Volcanic forcing	Ensembles
None	E4rhLMgTs, E4rhLMgTnck, E4rhLMgTKk, E4rhLMgTk
Crowley & Unterman (2012)	E4rhLMgTncck, E4rhLMgTKck, E4rhLMgTcs, E4rhLMgTck
2 x Gao et al. (2008)	E4rhLMgTKgk

Table 1: Volcanic forcing used for ensembles.

Eruption Name	Year	Tg

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Samalas	1258	257.91
Kuwae	1452	137.50
Tambora	1815	109.72
Unknown 1	1227	67.52
Unknown 2	1275	63.72
Huaynaputina	1600	56.59

Table 2: The six largest tropical eruptions of the Last Millennium and their total global stratospheric sulfate injection (Tg) as recorded by Gao et al. (2008), revised in 2012.

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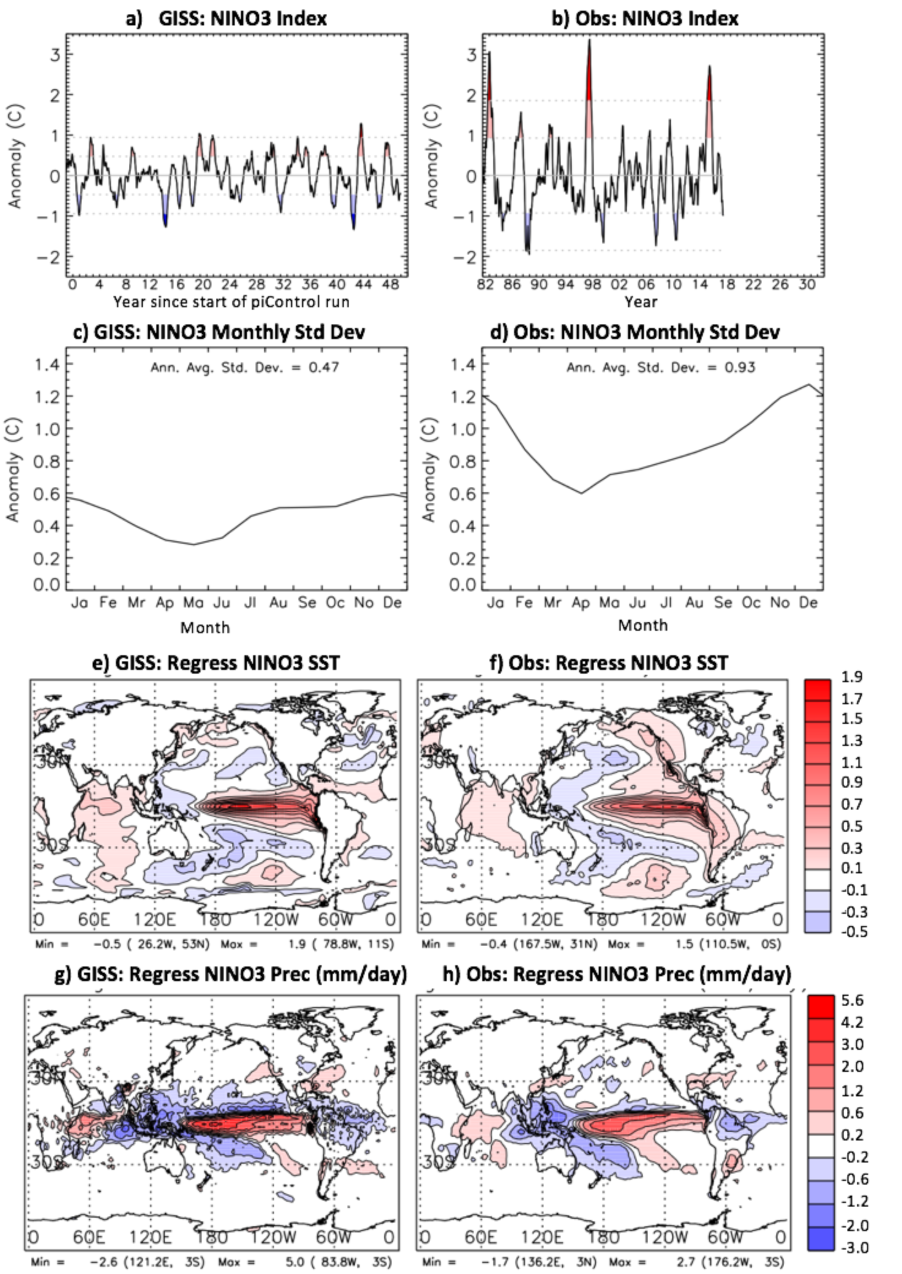

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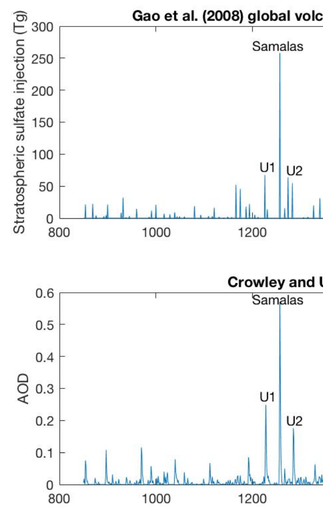

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Fig 1: Evaluation of GISS model against Reynold's OISST observations and GPCP calculated for first 50 years of the E2-R piControl.

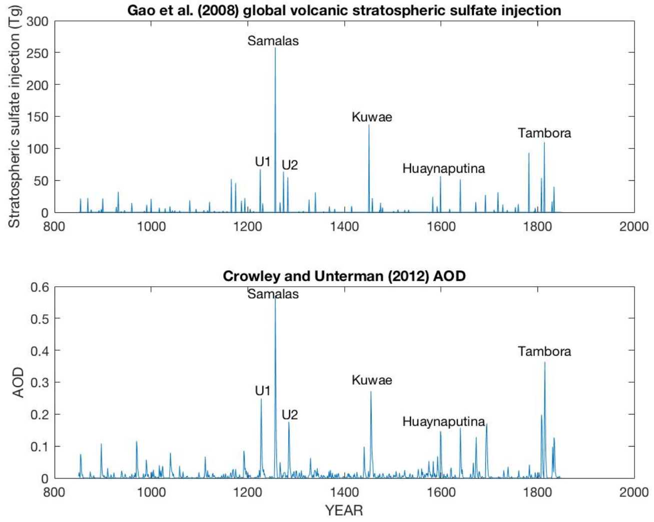

Fig 2: Timeseries of volcanic forcing from Gao et al. (2008) (upper) and Crowley and Unterman (2012) (lower). The specific subset of volcanic eruptions investigated is labelled.

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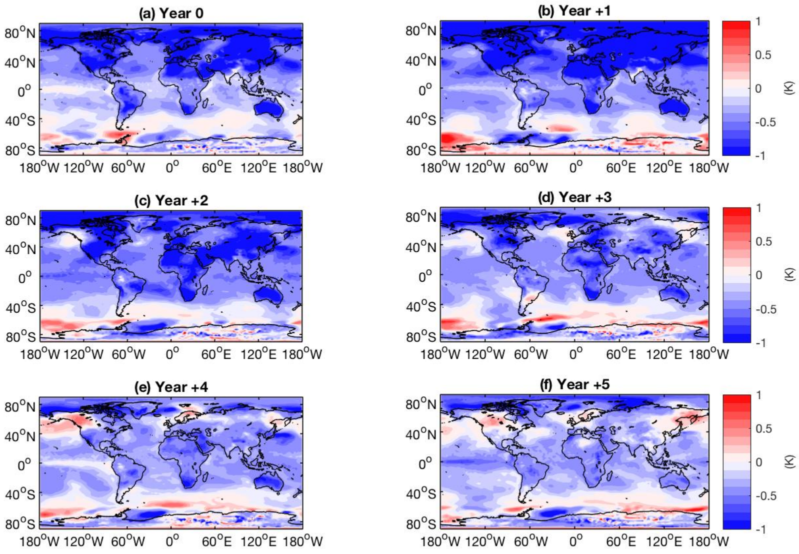

Fig 3: Global SST anomalies (K) in response to the Crowley (CR) forcings, showing multi-model mean response over JASON averaged across all analysed eruptions for years 0 to +5 after eruption

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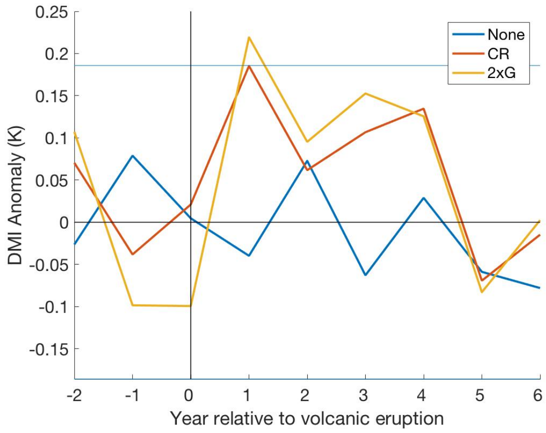

Fig 4: Multi-model and multi-volcano mean DMI (Dipole Mode Index) response to CR and None forcing groups and multi-volcano mean DMI response to the 2xG forcing group over July-November (JASON). Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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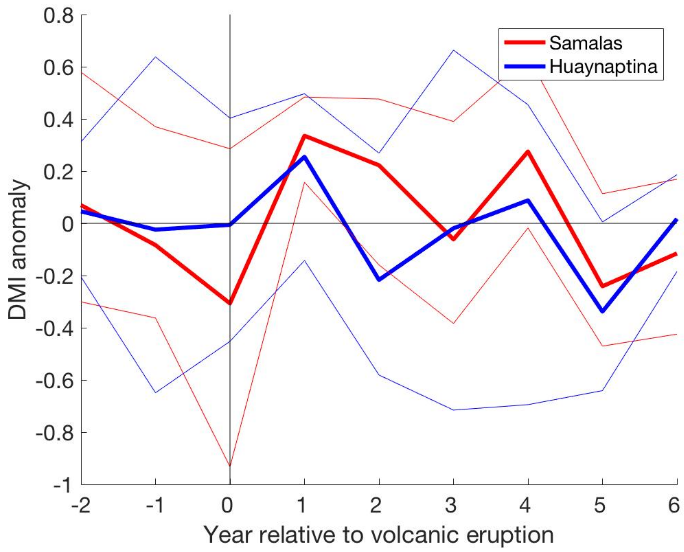

Fig 5: Mean DMI response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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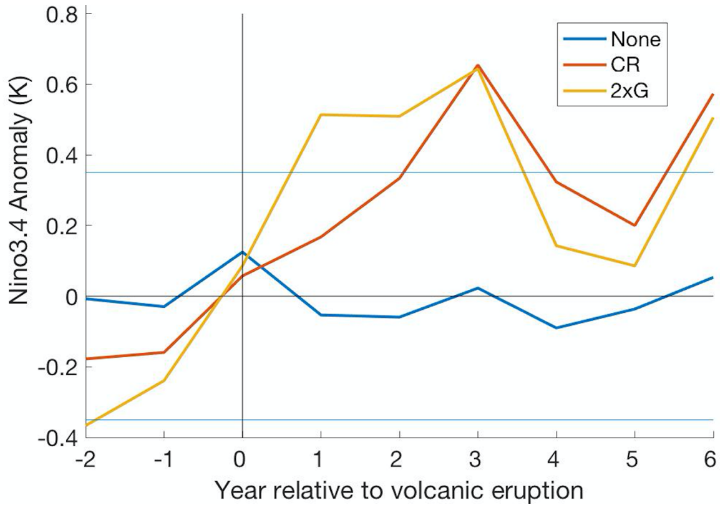

Fig 6: Multi-model and multi-volcano mean NINO3.4 response to CR and None ensemble forcing groups and multi-volcano mean DMI response to the 2xG forcing group over DJF. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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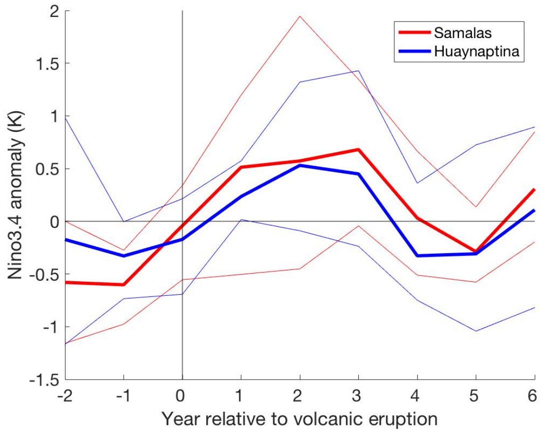

Fig 7: Mean NINO3.4 response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analyzed over DJF. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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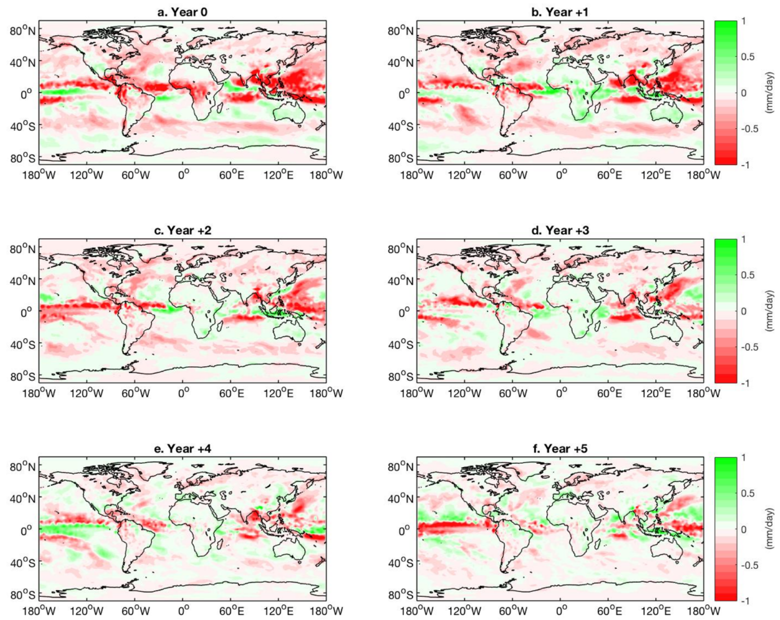

Fig 8: Global precipitation anomalies (mm/day) in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

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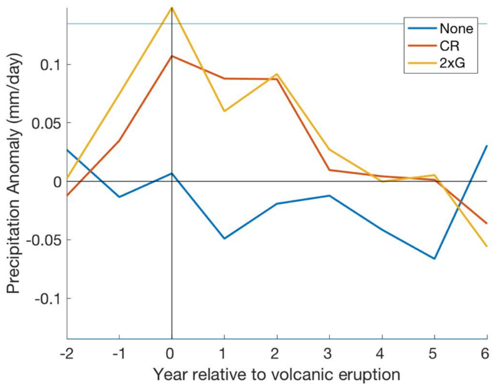

Fig 9: Mean NW Australian precipitation (mm/day) response to CR, 2xG and None forcing groups in the eight years surrounding eruption over JASON. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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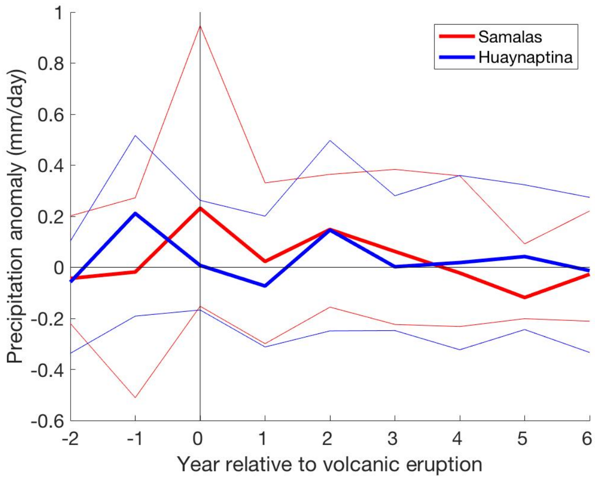

Fig 10: Mean NW Australian precipitation (mm/day) response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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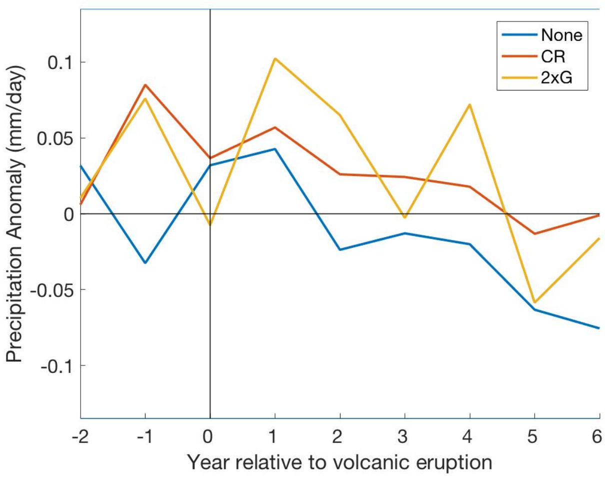

Fig 11: Mean SE Australian precipitation (mm/day) response to CR, 2xG and None forcing groups in the eight years surrounding eruption over JASON. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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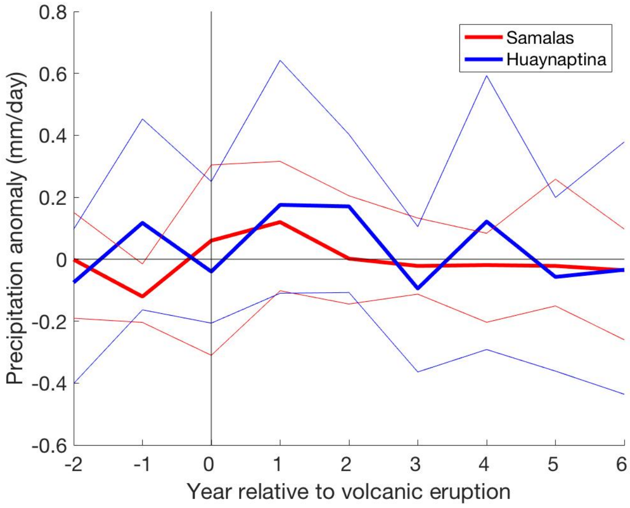

Fig 12: Mean SE Australian precipitation (mm/day) response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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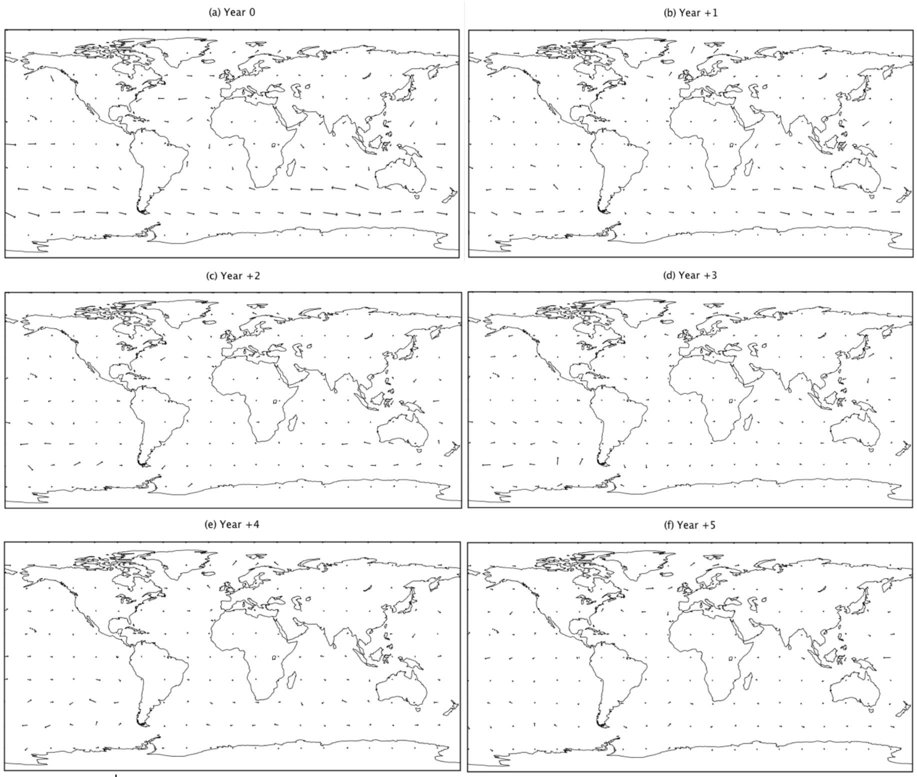

Fig 13: Global surface wind direction anomalies in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

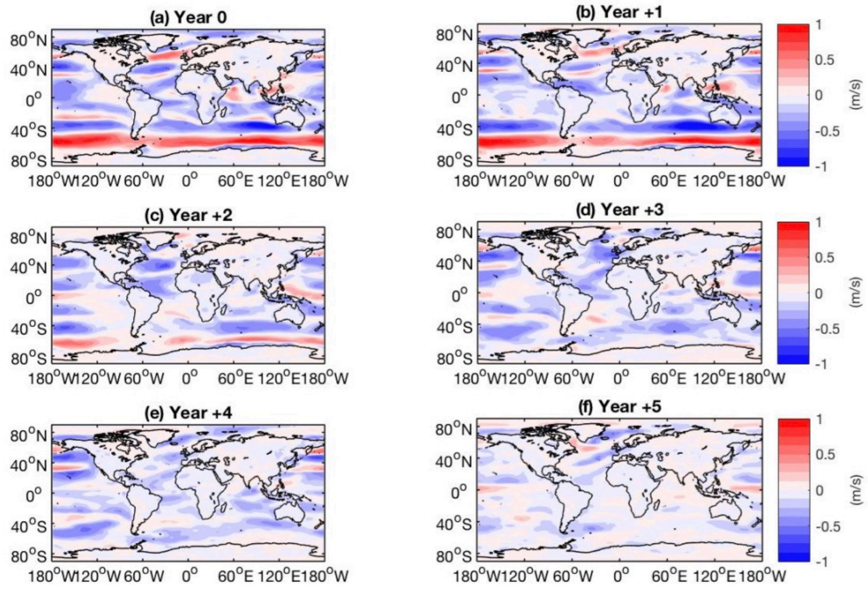

Fig 14: Global surface wind speed (m/s) anomalies in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

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Australian precipitation is affected by both the IOD and ENSO. Positive IOD (pIOD) and El Nino events typically cause averaged precipitation deficits, while negative IOD (nIOD) events and La Nina cause positive precipitation anomalies (Meyers et al., 2007; Pepler et al., 2014). While ENSO is often held responsible for triggering Australian droughts, the IOD has been shown to have an equal, if not larger, impact on heavily populated areas of Australia, with all significant southeastern Australia droughts in the 20th C showing a larger response to pIOD events than El Ninos (Ummenhofer et al., 2009).

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Assessing the impact of large volcanic eruptions of the Last Millennium on Australian rainfall regimes

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Abstract. Explosive volcanism is an important natural climate forcing, impacting global surface temperatures and regional precipitation. Although previous studies have investigated aspects of the impact of tropical volcanism on various ocean-atmosphere systems and regional climate regimes, volcanic eruptions remain a poorly understood climate forcing and climatic responses are not well constrained. In this study, volcanic eruptions are explored in particular reference to Australian precipitation, and both the Indian Ocean Dipole (IOD) and El Nino-Southern Oscillation (ENSO). Using nine realisations of the Last Millennium (LM) with different time-evolving forcing combinations, from the NASA GISS ModelE2-R, the impact of the 6 largest tropical volcanic eruptions of this period are investigated. Overall, we find that volcanic aerosol forcing increased the likelihood of El Nino and positive IOD conditions for up to four years following an eruption, and resulted in positive precipitation anomalies over northwest (NW) and southeast (SE) Australia. Larger atmospheric sulfate loading during larger volcanic eruptions coincided with more persistent positive IOD and El Nino conditions, enhanced positive precipitation anomalies over NW Australia, and dampened precipitation anomalies over SE Australia.

1. Introduction

Volcanic eruptions have significant impacts on weather and climate variability through the injection of volcanogenic material into the atmosphere. Sulfate aerosols, formed through the reaction of SO_2 and OH^- in the volcanic cloud, decrease incoming shortwave radiation, and if injected into the stratosphere, can generate a global response (Driscoll et al., 2012; LeGrande et al., 2016). Previous studies have identified relationships between volcanism and surface and tropospheric cooling (Driscoll et al., 2012), local stratospheric warming (Wielicki et al., 2002), strengthening of the Arctic Oscillation and Atlantic meridional overturning circulation (Oman et al., 2005; Stenchikov et al., 2006, 2009 & Shindell et al., 2004), and negative global precipitation anomalies (Gillet et al., 2004, Iles et al., 2013). The present study focuses on the under-studied relationship between large, globally significant tropical eruptions in the Last Millennium (850-1850CE) and Australian precipitation through examination of the direct radiative aerosol effect and the feedbacks of two tropical modes that strongly influence Australian rainfall: the El-Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD).

ENSO's effect on Australian precipitation has long been recognized. El Nino events typically cause averaged precipitation deficits, while La Nina cause positive precipitation anomalies (Meyers et al., 2007; Pepler et al., 2014). In addition, a statistical relationship has been demonstrated between explosive tropical volcanism and ENSO where large tropical eruptions can increase the likelihood and amplitude of an El Nino event in following years, followed by a weaker La Nina state (Adams et al., 2003). Further work by Mann et al. (2005), Emile-Geay et al. (2008), McGregor et

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al. (2010), Wahl et al. (2014) and Predybaylo et al. (2017) supported this result. Pausata et al. (2015) identified that a radiative forcing threshold value of more than 15 W m^{-2} is required to affect the ENSO, and that high latitude Northern Hemisphere eruptions, in addition to tropical eruptions, are capable of doing so, as long as the forcing is asymmetric with regards to the equator.

The relationship between volcanic forcing and ENSO has been attributed to two contrasting, though not unrelated, mechanisms. The dynamical thermostat mechanism (Clement et al., 1996), whereby a uniform reduction of the surface heat flux due to volcanism causes warming of the eastern equatorial Pacific, was identified as the driver of ENSO's response to volcanism by Mann et al. (2005) and Emile-Geay et al. (2008). Conversely, a shift in the Intertropical Convergence Zone (ITCZ) induced by strong radiative forcing, was accredited in more recent studies (Pausata et al., 2015; Stevenson et al., 2016). Preconditioning does impact the severity of the ENSO response. Predybaylo et al. (2017) found that years with an initial central Pacific El Nino ENSO phase show the largest statistical impact from Pinatubo-sized eruptions and that summer eruptions coincided with a more pronounced El Nino response.

Despite the understanding that volcanism can trigger or amplify El Nino events in the following years, the exact relationship between ENSO and volcanic forcing is still debated. McGregor and Timmermann (2011) and Zanchettin et al. (2012) reported an enhanced probability of La Nina events occurring in the immediate years after a volcanic eruption, rather than El Nino, while several other studies (Self et al., 1997; Robock, 2000; Ding et al., 2014) found no relationship between ENSO and volcanic forcing. Robock (2000) argued that both El Chichon and Pinatubo reached their peak forcing after the initiation of El Nino events, indicating a coincidental relationship, while other studies (Driscoll et al., 2012; Lewis & Karoly, 2014; Lewis & LeGrande, 2015; Predybaylo et al., 2017) have pointed out challenges in determining long-term characteristics of ENSO due to short instrumental records, and its relationship to volcanic forcing due to variable representations of both ENSO and volcanic aerosols in GCMs (Global Climate Models).

Comparatively little research has gone into the effects of volcanic forcing on the Indian Ocean Dipole (IOD), despite its known climatic impacts on Indian Ocean basin countries, such as Australia, South Africa, India and Indonesia (Cheung & Abram, 2016). The IOD is the zonal sea surface temperature (SST) gradient between the tropical western Indian Ocean (WIO) and the tropical south eastern Indian Ocean (EIO) (Roxy et al., 2011), defined by the Dipole Mode Index (DMI). Positive IOD (pIOD) states typically cause averaged precipitation deficits over Australia, and negative IOD (nIOD) cause a surplus (Meyers et al., 2007; Pepler et al., 2014). While ENSO is often considered primarily responsible for triggering Australian droughts, the IOD has been shown to have an equal, if not larger, impact on heavily populated areas of Australia, with all significant southeastern Australian droughts in the 20^{th} C showing a larger response to pIOD events than El Ninos (Ummenhofer et al., 2009).

Cheung & Abram (2016) found that the DMI shows a statistically significant correlation to volcanic forcing, with a negative IOD (nIOD) occurring immediately after an eruption and a positive IOD (pIOD) one year later. Maher et al. (2015) found a similar relationship, with coinciding El Nino and pIOD events occurring 6-12 months after the peak of volcanic forcing. The response of the IOD to volcanic forcing has been hypothesised to result from either the IOD's relationship with ENSO (Cheung & Abram, 2016), or the volcanically-induced reduction of the Asian Monsoon (Anchukaitis et al., 2010; Zambri et al., 2017).

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The direct radiative effect of volcanic aerosols have been found to cause global precipitation deficits for up to 5 years post-eruption (Robock & Lui, 1994; Iles et al., 2013; Gillett et al., 2004; Gu & Adler, 2011; Soden et al., 2002; Joseph & Zeng, 2011; Schneider et al., 2009; Timmreck et al., 2012; Iles et al., 2015). However, these deficits have been shown to vary seasonally (Joseph & Zeng, 2011), and cause positive precipitation anomalies over the NW and SE of Australia in the Southern Hemisphere (SH) winter and early spring (July-September - JASON), despite significant precipitation deficits in the summer (Joseph & Zeng, 2011; Schneider et al., 2009). This current study explores these relationships between volcanic eruptions and Australian rainfall during JASON, with reference to the direct radiative effect and the feedback effects of the ENSO and IOD.

2. Data and methods

2.1 Simulations

To understand the response of the IOD, ENSO and Australian precipitation to volcanic forcing in the Last Millennium, we analysed 9 ensembles from the NASA GISS ModelE2-R (hereafter simply GISS) (Schmidt et al., 2014). The GISS ensemble was run for the pre-industrial part of the Last Millennium (LM), from 850-1850 CE, which is defined by the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). GISS is run at 2 degrees x 2.5 degrees horizontal resolution, with 40 vertical levels up to 0.1 hPa. The “non-interactive” atmospheric composition model, or NINT, is coupled with the dynamic Russell ocean model (Schmidt et al., 2014).

Evaluations of the accuracy of ENSO, IOD, surface temperature, precipitation and volcanic aerosols modelled in GISS have been conducted by Flato et al. (2013), Schmidt et al. (2014), Moise et al. (2015) and Miller et al. (2015). Global temperature observed at surface, middle troposphere and lower stratosphere are all accurate to within 2 standard deviations in the Historical ensemble (Miller et al., 2015), with GISS surface temperatures agreeing with observations in all areas of interest to this study to within 2°C and correctly simulating surface cooling following volcanic eruptions (Flato et al., 2013; Miller et al., 2015). In the Southern Ocean some systematic deficiencies cause large SST biases, however overall biases remain below 0.7-0.8°C (Schmidt et al., 2014).

Mean global precipitation is too high during the historical period, particularly around the tropics, when compared to observations (Schmidt et al., 2014), however the spatial pattern of precipitation agreed with trends calculated from Global Precipitation Climatology Project retrievals (Miller et al., 2015). Australian precipitation had a spatial-temporal root square mean error (RSME) of ~1mm/day and the model was deemed to provide good representations of surface temperature and precipitation over the entirety of Australia (Moise et al., 2015).

GISS captures the basic east-west structure of the tropical Pacific well, and follows the trend of the NINO3.4 index with the greatest accuracy between 2-3 years of an ENSO event (Flato et al., 2013; Schmidt et al., 2014). Calculation of the NINO3 index (150-90W and 6N-6S) for GISS and the Reynolds OI SST (https://www.ncdc.noaa.gov/oisst) observations for the first 50 years of the GISS piControl displayed an underestimation of ENSO intensity in GISS (Fig 1 (a,b)), meaning the modelled SST anomalies were weaker than observations. However, variability throughout the year is consistent with observations (Fig 1 (c,d)), and regression of the index onto SST, scaled by the standard deviation of the NINO3 index, shows the global spatial pattern is also in good agreement for ENSO and the IOD (Fig 1 (e, f)). Similar regression of the NINO3 index against precipitation (Fig 1 (g, h)) also showed spatial concurrence between

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GISS and GPCP (https://precip.gsfc.nasa.gov/) observations, displaying the precipitation dipole over the Indian Ocean associated with the IOD.

Five ensembles were forced with volcanic forcing, while four were not to compare the effect of volcanic aerosols with non-volcanically influenced scenarios. Of the five run with volcanic forcing, four were forced with Crowley and Unterman (2013)'s aerosol optical depth data (CR), and one with double the Ice-core Volcanic Index 2 by Gao et al. (2008) (2xG) (see Table 1 for experiment summary). The LM was chosen for analysis as the period contains the majority of large tropical volcanic eruptions recorded in these datasets. The GISS model is forced with prescribed Aerosol Optical Depth (AOD) from 15-35 km, with a 4-layer vertical (15-20km, 20-25km, 25-30km and 30-35km and 24 layer (8°) longitudinally independent latitude, with Reff specified as per Sato et al. (1993). The LM simulations also include transient solar and land use histories that differ between ensembles. However, as this analysis focuses primarily on the immediate post-volcanic response, the impact of these smaller amplitude and slow-varying forcings is likely to be insignificant (Colose et al., 2016).

2.2 Methods

First, the six largest tropical eruptions between 850-1850CE were identified by the magnitude of their total global stratospheric sulfate aerosol injection (Tg) from the IVI2 Version 2 dataset, revised in 2012 (Gao et al., 2008), and the years surrounding eruption extracted for analysis (see Table 2 and Figure 2). Eruptions were deemed as tropical if volcanic aerosols were present in significant amounts in both hemispheres. The Kuwae eruption is included within the analysed eruptions, and is dated to 1452CE. While this year contains the bi-hemispheric deposition from the Kuwae eruption in both volcanic datasets used in this study, it is important to note that Sigl et al. (2013) recently constructed an ice-core record of volcanism that dates the Kuwae eruption to 1459/1459CE, with another, smaller eruption occurring at 1452. For the purposes of this paper, however, Kuwae will be considered as the 1452 deposition event.

We explored anomalous conditions in ENSO, the IOD and Australian rainfall. For ENSO, the period December-February (DJF) was examined using the NINO3.4 index, defined by the averaged sea surface temperature (SST) anomalies between 5N-5S and 170-120W. When analysing the IOD, the July-November (JASON) period was examined due to the tendency for pIODs to develop and mature over these months (Weller et al., 2014). The IOD was measured using the Dipole Mode Index (DMI), which subtracts the averaged SST in the EIO (90-110E; 10S-0) from the averaged SST in the WIO (50-70E; 10S-10N).

Australian precipitation was processed to find the anomalies of each season and year relative to the long-term mean over the JASON period. Analyses were conducted on area-averaged rainfall for the south-eastern Australian (132.5-155E; 27.5-45S) and north-western Australian (110-132.5E; 10-27.5S) regions. The south-east and north-west were chosen for analysis as the effect of the IOD on Australian precipitation is largest in, and potentially limited to, these general areas (Ashok et al., 2003).

The response of these large-scale modes of variability and rainfall are investigated using an epoch approach. For each major identified eruption, a response was defined by subtracting a reference period (the mean of 5 years pre-eruption) from the eruption year and the six years following eruption individually. A reference period of five years was chosen as

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it minimised the effect of trends or low-frequency climate variability (Iles et al., 2013). Mode specific graphs (IOD, ENSO, Australian Precipitation) focused on the nine years surrounding eruption (years -2 to 6, with year 0 being the year of eruption). The mean of all six eruptions in each ensemble were calculated for individual years, and then the mean of all ensembles included in each forcing category were compared (CR, 2xG or None).

3. Results

The global SST response for the CR forcing group shows predominantly surface cooling anomalies (Fig. 3). More specifically, cooling occurs in the Northern Hemisphere from years 0-3, while the south Atlantic, Indian and Pacific oceans show mostly minor warming. The uniform reduction and re-distribution of surface temperature causes an El Nino-like warming temperature gradient in years 0, 1 and 4 post eruption. In the Southern Hemisphere, cooling is most pronounced over land masses, particularly Australia and the southern tip of Africa.

The DMI response showed a significant pIOD condition one year after major eruptions in all volcanically forced ensembles that persists until year 5, where an abrupt negative IOD phase occurs (Fig. 4). This response can also be seen in Fig. 2, where the EIO region shows larger and more widespread cooling anomalies than the WIO region in years 1, 2 and 4. This response contrasts to the non-volcanically forced ensembles, which show neither a prolonged pIOD nor nIOD condition.

The response of the DMI to the largest and smallest eruptions were also extracted. Fig. 5 show the mean DMI response to the 1258 Samalas eruption (257.91 Tg) and the 1600 Huaynaptina eruption (56.59 Tg). Our results show that while both eruptions caused a significant simulated pIOD at year 1, the larger 1258 Samalas eruption persisted with a significant pIOD condition in years 2 and 4, while the 1600 Huaynaptina eruption did not.

The mean NINO3.4 multi-volcano response to ensemble forcing showed a statistically significant El-Nino like response for all 6 years following eruption, with a peak at year 3 in both the CR and 2xG ensembles (Fig. 6). The non-volcanically forced ensemble group showed neither a significant El Nino nor La Nina tendency, with the NINO3.4 index remaining within 0.4/-0.4. The index also showed an increase in the intensity and endurance, of post-volcanic El Ninos between the Samalas and Huaynaptina eruptions (Fig. 7). The Samalas eruption was followed by an El Nino that endured for 3 years, from years 1-3, peaking at a NINO3.4 anomaly of 0.68 in year 3, while Huaynaptina peaked at 0.53 in year 2 from an El Nino that endured for 2 years.

Fig. 8 shows the mean precipitation response of all volcanically forced ensembles. Precipitation deficits can be seen in the tropics in years 0-2, the most substantial and widespread of which occur in the Asian monsoonal area and the western Pacific basin. Bands of decreased precipitation also occur at approximately 40°S, between 0-40°N in the North Atlantic Ocean and between 40-80°N over Northern America and Europe. The Southern Hemisphere subtropics appear to have a slight increase in precipitation in years 0-2, most prominently over Australia and southernmost Africa, while the southern polar region (60-90°S) shows only variable minor precipitation anomalies occurring in all 6 years post eruption.

Ensembles with volcanic forcing showed an increase in precipitation over southeast (SE) (Fig. 11) and northwestern (NW) (Fig. 9) Australia between July to November (JASON). Both areas showed predominantly positive anomalies in

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years 0-5 post-eruption, with the largest response seen between years 0-2. NW Australia (Fig. 9) showed larger positive precipitation anomalies between years 0-2 than SE Australia (Fig. 11) in the CR ensemble mean, and in years 0 and 2 in the 2xG ensemble mean.

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Comparison of the precipitation anomalies following the Samalas and Huaynaptina eruptions in NW Australia (Fig. 10) showed that the smaller eruption had a delayed and smaller positive precipitation peak, with Samalas peaking in year 0 with an anomaly of 0.23 and Huaynaptina in year 2 at 0.14. While the Huaynaptina eruption also showed a delayed peak in precipitation in SE Australia (Fig 12), the persistence of positive precipitation anomalies exceeded those of the Samalas eruption. Huaynaptina recorded values > 0.17 in years 1-2 and a value of 0.12 in year 4, all of which were larger anomalies than the peak of the Samalas eruption at 0.11 in year 1 (Fig. 12).

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Figures 13 and 14 show multi-volcano mean anomalous changes to the surface wind direction (Fig. 13) and speed (Fig. 14) over the 5 years following eruptions in the CR forcing group. The most notable changes occur in years 0 and +1 where anomalously strong Southern Hemisphere westerlies and anomalously weak south easterly trade winds occurred, accompanied by strong north-easterlies off the south-east coast of China and an intensification of North Atlantic circulation. In year +3 anomalous south easterly winds off the south-western coast, and anomalous westerlies off the central western coast, of South America are seen.

4. Discussion and conclusions

Our results suggest that the large-scale IOD and ENSO systems, and Australian rainfall regimes, were all impacted by large tropical eruptions of the Last Millennium.

The DMI response simulated in the GISS ensemble following large eruptions is complimentary to previous research conducted by Cheung & Abram (2015) and Maher et al. (2015). The pIOD peak in year 1 (Fig. 4) is consistent with both studies, in which statistically significant pIOD conditions occurred between 6 months to 2 years after an eruption. Cheung & Abram (2015) also found a statistically significant negative condition immediately after eruption at year 0, however this was absent from both Maher et al.'s (2015) results and the CR forcing category in this study. The 2xG category does show a nIOD condition at year 0, but is not believed to be a response to volcanic forcing as a similar nIOD condition can be seen at year -1. The abrupt shift to a negative condition at year 5 was not found in either Cheung & Abram (2015) or Maher et al. (2015)'s results. Both studies found a gradual decrease in DMI from year 1 to years 3-4.

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The smooth transition to a lower DMI following eruptions found by Cheung & Abram (2015) and Maher et al. (2015) contrasts with the abrupt change from a pIOD of approximately 0.13 at year 4, to an nIOD of -0.069 in the CR ensembles and -0.083 in the 2xG ensemble at year 5 (Fig. 4). This inconsistency between studies could be due to the selection of eruptions analysed by each paper. Cheung & Abram (2015) included all eruptions from 850-2005CE recorded on the IVI2 in their analysis. While this encompasses all eruptions analysed here, it also included many smaller eruptions that would likely have dampened the climatic response, a response that has been analysed in previous papers (Zambri & Robock, 2016). Maher et al. (2015) looked at the five largest eruptions from 1880 to present, of which the largest was Pinatubo (1991), measured at 30.10 Tg globally on the IVI2 (Gao et al., 2008). In comparison, our research deals with eruptions of much larger atmospheric loading, ranging from 56.59 to 257.91 Tg.

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Therefore, the persistence of a high pIOD through to year 5 seen here may result from the larger mean atmospheric sulfate loading imposed. This theory is supported by the comparison between the Samalas and Huaynaptina (Fig. 5) eruptions. Our results showed that while both eruptions caused a significant pIOD at year 1, the larger 1258 Samalas eruption alone persisted with a significant pIOD condition in following years. Further support can be gathered from the comparison between the 2xG and CR ensemble means in fig. 4. Years 0-3 show more extreme values in the 2xG ensemble mean, while years 4-6 show similar values for both forcing categories. Maher et al. (2015) found a similar response, with the two largest eruptions analysed in the paper showing the largest and longest enduring pIOD anomalies. This suggests that larger mean atmospheric sulfate loading can cause not only more persistent, but also more extreme pIOD conditions.

The phase and intensity of the IOD is known to be influenced by the Asian monsoon (Brown et al., 2009; Xiang et al., 2011), and the physical mechanisms driving the pIOD response to volcanic forcing in GISS likely stems from this relationship. In GISS, the Asian monsoon was suppressed by the anomalous north easterly flow off the south-east coast of China in years 0 and +1 (Fig. 13; Fig. 14) generated by volcanic aerosols, and a decrease of convection over the warm pool, cause by El Nino-like anomalies in those same years (Fig 3). These feedbacks caused a comparatively warmer WIO, generating a pIOD. The Asian monsoon suppression following volcanic eruptions was also noted by Stevenson et al. (2016).

The NINO3.4 response found in this research supports previous studies by Adams et al. (2003), Mann et al. (2005), Emile-Geay et al. (2008), McGregor et al. (2010) and Maher et al. (2015), despite GISS modelling weaker SST anomalies than observations (Fig. 1 (a,b)). Fig. 6 shows a very prominent and persistent El-Nino response in all 6 years following eruption, however it lacks the weaker La Nina-like state that was observed 3-6 years after eruption in these previous papers. Spatial maps of SST (Fig. 3), while dominated by the overall volcanic cooling, show an El Nino-like pattern in the eastern Pacific that is most visible in year 4, possibly driven by the anomalous winds off the western coast of South America in year +3 (Fig. 13). but is also distinctive in years 0, 1 and 3. We can therefore conclude that an El Nino-like anomaly was generated in the multimodel mean response in years 0-6 following eruption by a uniform reduction in surface temperature, driven by a decrease in the surface heat flux, a response also observed by Mann et al. (2005) and Emile-Geay et al. (2008). Comparison of the Samalas and Huaynaptina (Fig. 7) eruptions also suggest that, similar to the DMI, the intensity and endurance of the ENSO response to volcanic forcing increases with increasing mean atmospheric sulfate loading. This once again supports the findings of Maher et al. (2015) that identified a similar pattern.

The positive response of Australian precipitation to volcanic forcing as seen here (Fig. 8, 9 & 11) is in agreement with several papers that identified positive precipitation responses over Australia to large volcanic eruptions (Schneider et al., 2009; Joseph & Zeng, 2011). Our results suggest that the direct precipitation effect of volcanic aerosols override the impact of the IOD on Australian precipitation in the years following large tropical volcanic eruptions. NW Australia (Fig. 9) showed larger positive precipitation anomalies between years 0-2 than SE Australia (Fig. 11) in the CR ensemble mean, and in years 0 and 2 in the 2xG ensemble mean. This could be due to the positive precipitation anomalies that can be generated by combined El Nino and pIOD events in the NW Australian region (Meyers et al., 2007 & Pepler et al., 2014), enhancing the precipitation surplus caused by volcanic aerosols.

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The varying response of NW Australia to the Samalas and Huaynaptina eruptions (Fig. 10) also supports the enhancement of the volcanically induced precipitation surplus by combined El Nino and pIOD events. The Samalas eruption was followed by strong and enduring El Nino and pIOD conditions for up to 4 years post volcanism, and showed larger positive precipitation anomalies from years 0-3 than the Huaynaptina eruption, that was accompanied by smaller, shorter-lived El Nino and pIOD conditions. The precipitation surplus to the Samalas eruption in NW and SE Australia also peaked earlier than Huaynaptina, which could be a response to the larger atmospheric sulfate loading. Interestingly, previous papers have not reported a relationship between atmospheric sulfate loading and the peak in precipitation response (Robock & Lui, 1994; Iles et al., 2013; Iles et al., 2015).

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The precipitation anomalies of SE Australia (Fig. 12) further supports this theory. The response to the Huaynaptina eruption, while peaking later than Samalas, endured longer, and with larger positive anomalies. The effect of strong, combined El Nino and pIOD conditions on SE Australia is significant precipitation deficits (Meyers et al., 2007 & Pepler et al., 2014), and could explain the negative precipitation anomalies that occur in the Samalas response from year 2 onwards, where the combined influence of a strong El Nino and pIOD dampened the positive precipitation response generated by the atmospheric sulfate loading.

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We note that our study has provided an analysis of climatic response to a set of forcings in a single climate model, which may limit the precise interpretation of responses to eruptions. Overall, volcanic aerosols remain an understudied climatic forcing such that the timing, magnitude and spatial footprint of past eruptions remains uncertain (Colose et al., 2016). In addition to uncertainties around the fundamental physical forcings, limitations still exist in the implementation of volcanic eruptions in climate models (Colose et al., 2016; Zambri et al., 2017). For example, Colose et al. (2016) suggest that improvements in model representations of volcanic particle size may improve the accuracy of model simulations. Furthermore, LeGrande et al. (2016) note that the chemistry and composition of a volcanic plume affects its climatic impact, which requires realistic representation in climatic models. Overall, these limitations in modeling eruptions and the idealised approach adopted here may mean that impacts simulated do not precisely match those of the proxy record.

In summary, this paper aimed to identify the impact of large, tropical volcanism on the ENSO, IOD and Australian rainfall. Results showed an El Nino and pIOD response in the immediate years following eruption, accompanied by positive precipitation anomalies over SE and NW Australia. The positive precipitation anomalies suggest that volcanic aerosol cooling dominates the precipitation response, rather than the effect of ENSO or IOD, despite aerosols also proving to be an important influence on these large-scale modes. Although this study focused on Australian rainfall regimes and its main climatic drivers, this approach can be applied for exploring the impact of time-evolving forcings, such as volcanism, in other regions.

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Acknowledgements

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Volcanic forcing	Ensembles
None	E4rhLMgTs, E4rhLMgTnck, E4rhLMgTKk, E4rhLMgTk
Crowley & Unterman (2012)	E4rhLMgTncck, E4rhLMgTKck, E4rhLMgTcs, E4rhLMgTck
2 x Gao et al. (2008)	E4rhLMgTKgk

Table 1: Volcanic forcing used for ensembles.

Eruption Name	Year	Tg
Samalas	1258	257.91

Kuwae	1452	137.50
Tambora	1815	109.72
Unknown 1	1227	67.52
Unknown 2	1275	63.72
Huaynaputina	1600	56.59

Table 2: The six largest tropical eruptions of the Last Millennium and their total global stratospheric sulfate injection (Tg) as recorded by Gao et al. (2008), revised in 2012.

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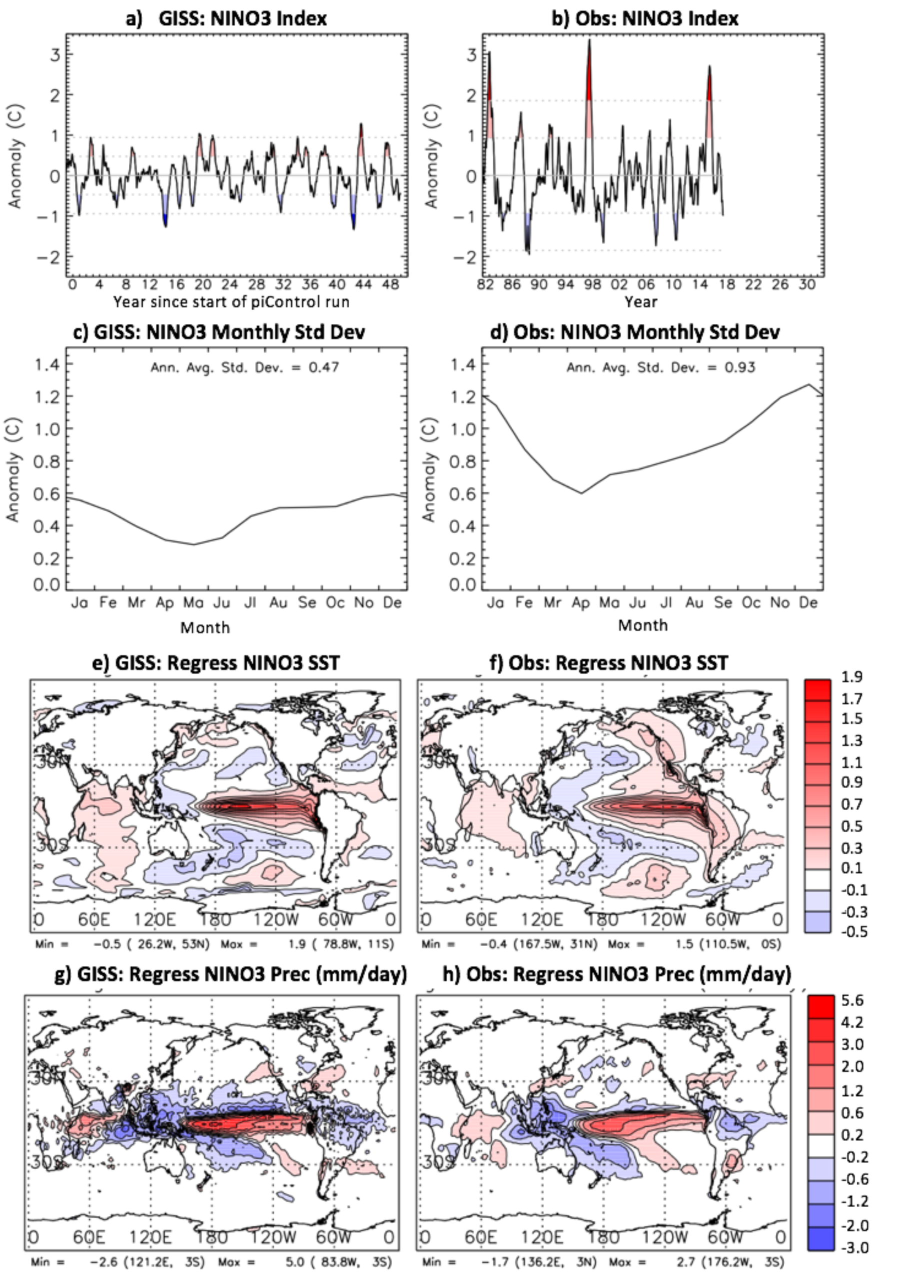

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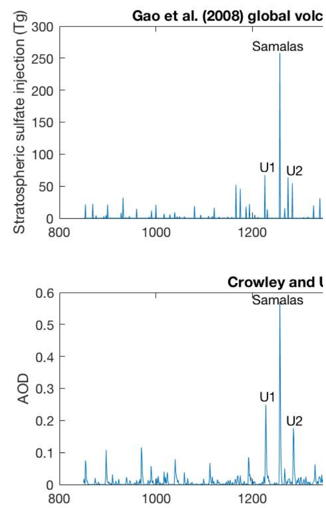

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Fig 1: Evaluation of GISS model against Reynold's OISST observations and GPCP calculated for first 50 years of the E2-R piControl.

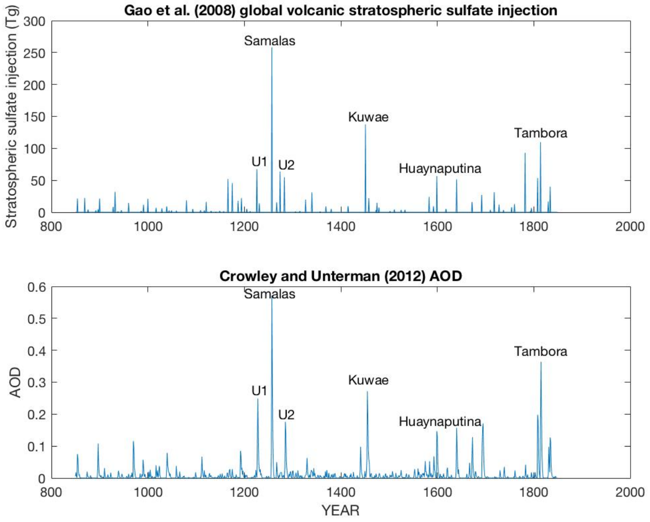

Fig 2: Timeseries of volcanic forcing from Gao et al. (2008) (upper) and Crowley and Unterman (2012) (lower). The specific subset of volcanic eruptions investigated is labelled.

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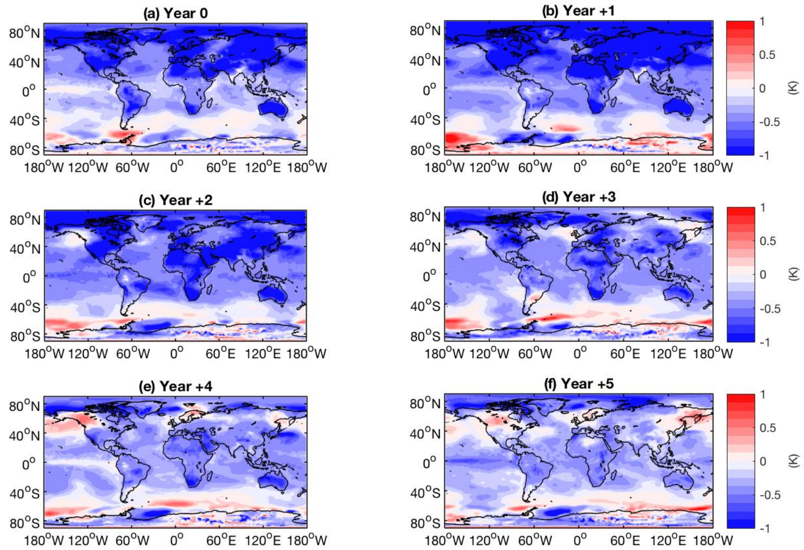

Fig 3: Global SST anomalies (K) in response to the Crowley (CR) forcings, showing multi-model mean response over JASON averaged across all analysed eruptions for years 0 to +5 after eruption

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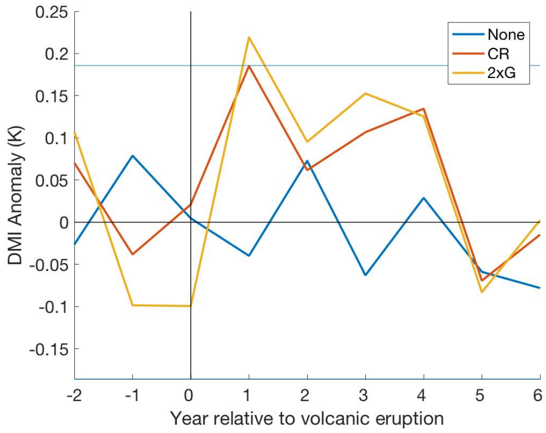

Fig 4: Multi-model and multi-volcano mean DMI (Dipole Mode Index) response to CR and None forcing groups and multi-volcano mean DMI response to the 2xG forcing group over July-November (JASON). Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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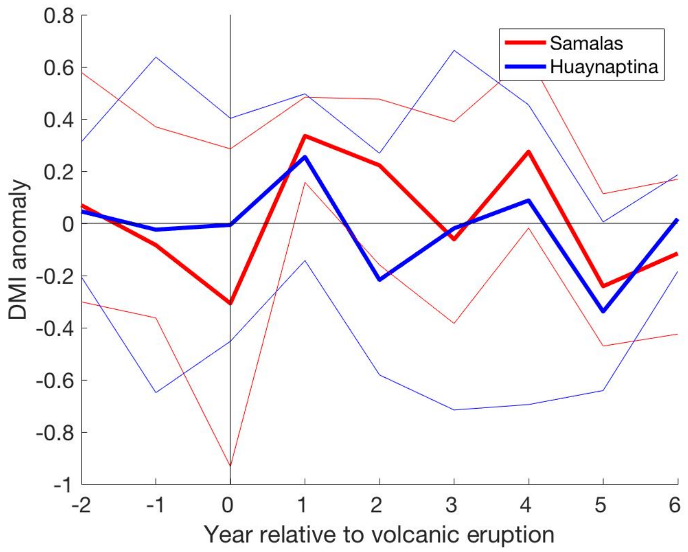

Fig 5: Mean DMI response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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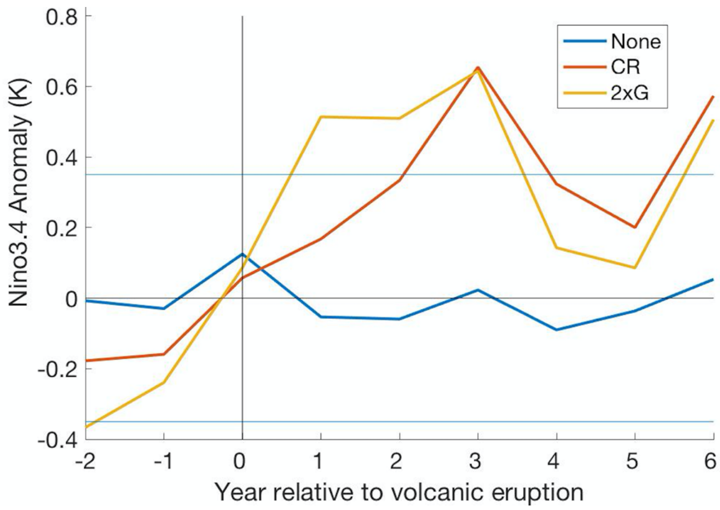

Fig 6: Multi-model and multi-volcano mean NINO3.4 response to CR and None ensemble forcing groups and multi-volcano mean DMI response to the 2xG forcing group over DJF. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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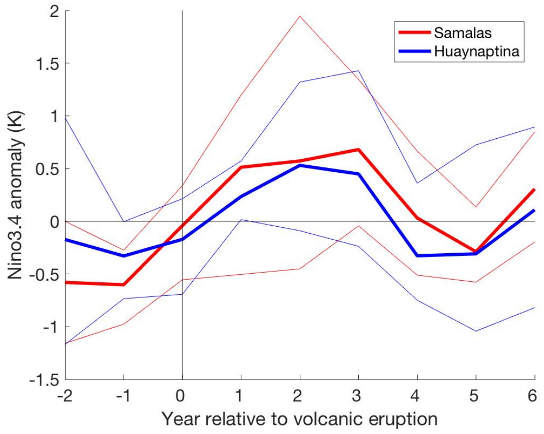

Fig 7: Mean NINO3.4 response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analyzed over DJF. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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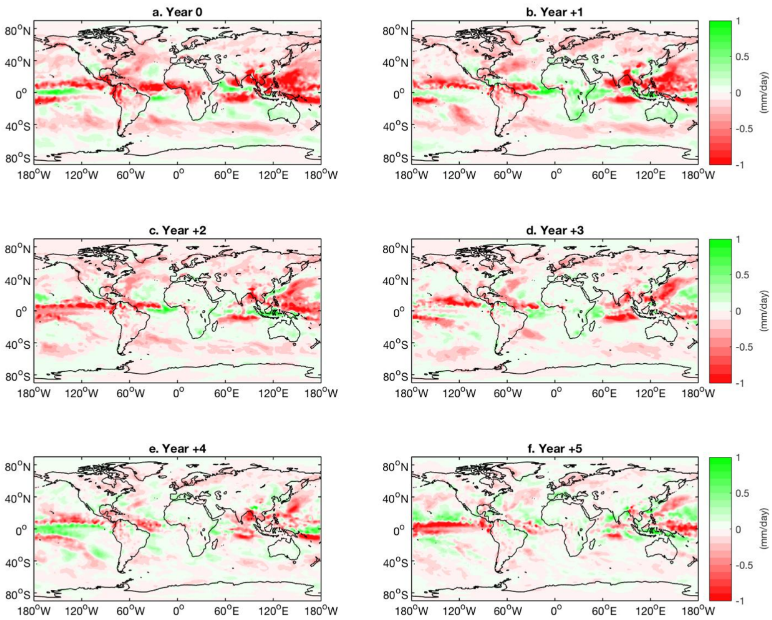

Fig 8: Global precipitation anomalies (mm/day) in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

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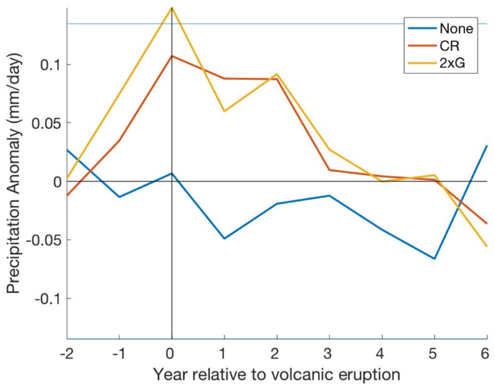

Fig 9: Mean NW Australian precipitation (mm/day) response to CR, 2xG and None forcing groups in the eight years surrounding eruption over JASON. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

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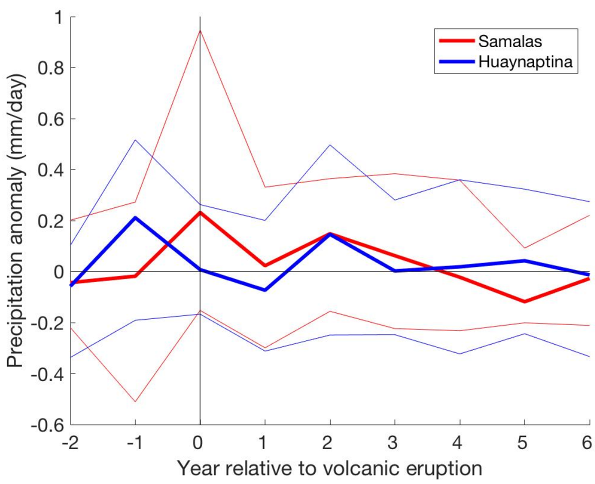

Fig 10: Mean NW Australian precipitation (mm/day) response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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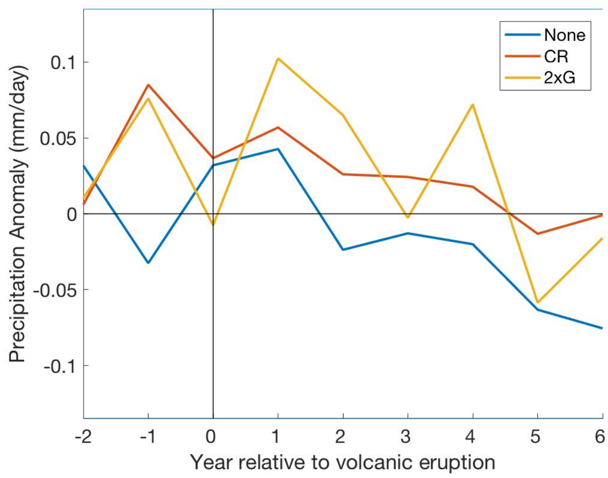

Fig 11: Mean SE Australian precipitation (mm/day) response to CR, 2xG and None forcing groups in the eight years surrounding eruption over JASON. Significance was tested using the 0.6 standard deviation threshold (horizontal blue lines), and by comparing the CR and 2xG ensembles to those without volcanic forcing.

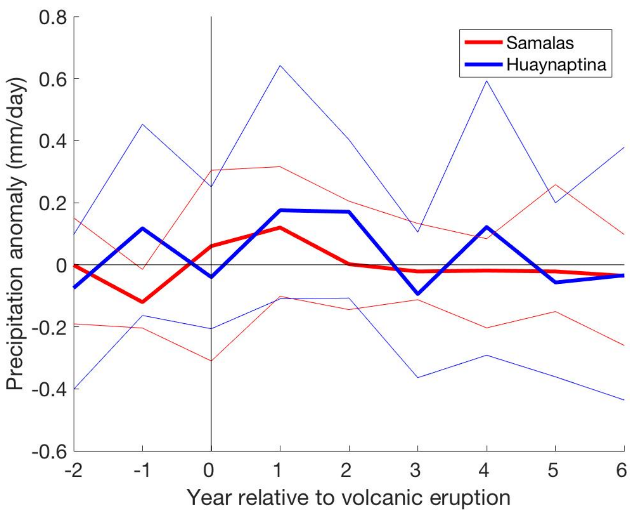

Fig 12: Mean SE Australian precipitation (mm/day) response across all volcanic ensembles to the largest (1258 Samalas) and smallest (1600 Huaynaputina) eruptions analysed over JASON. The bold lines represent the mean of all volcanic ensembles to each eruption, and the fainter lines represent the 90th and 10th percentile of the ensemble members.

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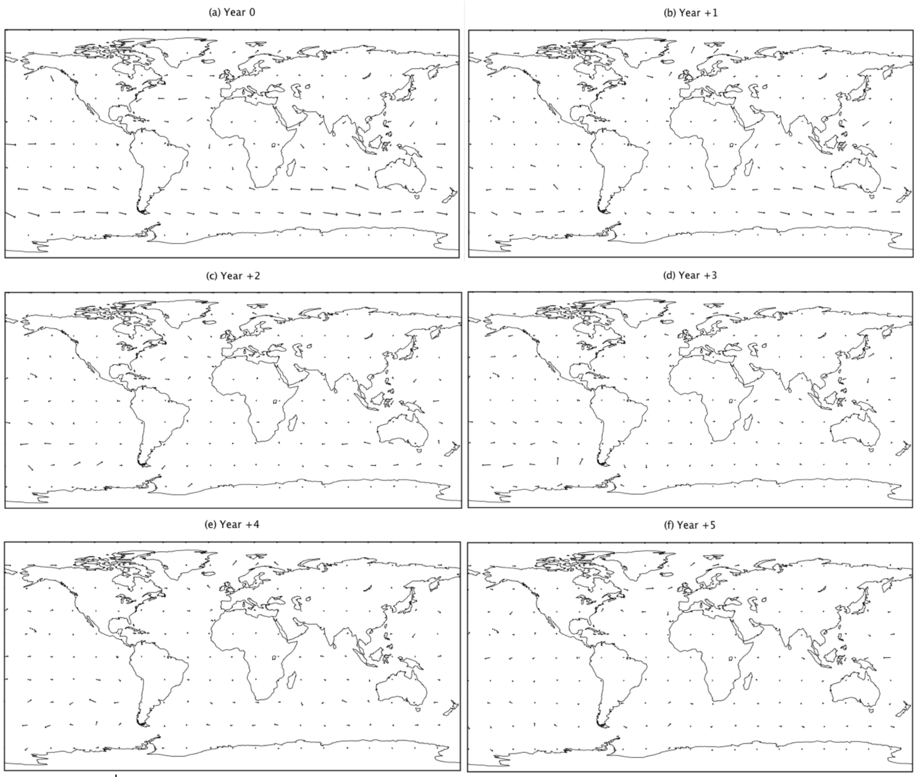

Fig 13: Global surface wind direction anomalies in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

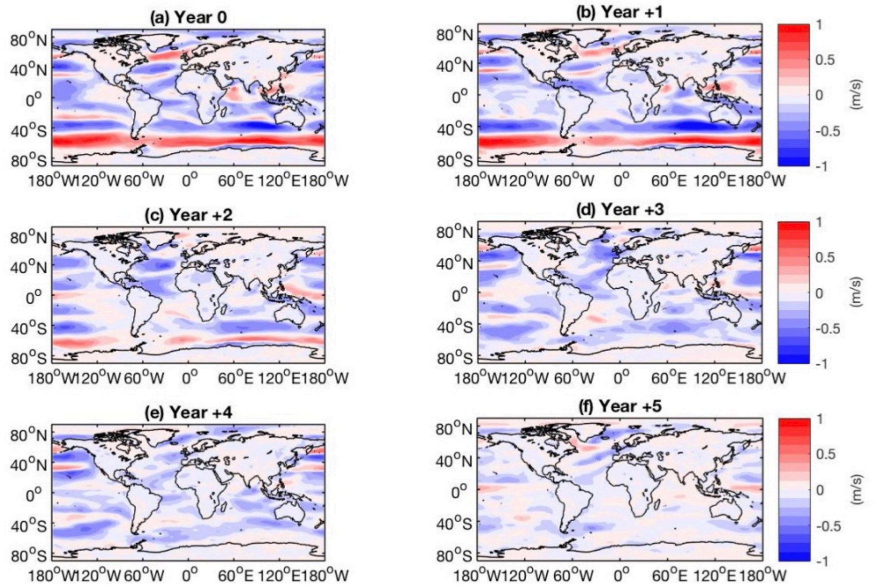

Fig 14: Global surface wind speed (m/s) anomalies in response to the Crowley and Unterman (CR) forcing, showing multi-model mean responses over JASON averaged across all analysed eruptions for years 0 to +5 after eruption.

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Australian precipitation is affected by both the IOD and ENSO. Positive IOD (pIOD) and El Nino events typically cause averaged precipitation deficits, while negative IOD (nIOD) events and La Nina cause positive precipitation anomalies (Meyers et al., 2007; Pepler et al., 2014). While ENSO is often held responsible for triggering Australian droughts, the IOD has been shown to have an equal, if not larger, impact on heavily populated areas of Australia, with all significant southeastern Australia droughts in the 20th C showing a larger response to pIOD events than El Ninos (Ummenhofer et al., 2009).

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