Dear Dr. Masson-Delmotte,

Please find enclosed our revised manuscript (CPD 11, 3375–3424, 2015, by Colose et al.), now entitled "The influence of volcanic eruptions on the climate of tropical South America during the last millennium in an isotope-enabled GCM." We have carefully revised our manuscript and addressed all reviewer comments and criticisms in detail. Included with our resubmission is an annotated manuscript, highlighting all the changes that were made. As you know we have already submitted a point-by-point response to the reviewer's concerns. We have repeated them here, followed by an edited version of the previous manuscript.

A common concern with reviewers was the appropriateness of the model we used. We note that NASA GISS has a long history of model development and participation in CMIP5/PMIP3 (and previous iterations of these projects) and have updated our references and "historical" discussion accordingly. Proper model validation in the context of our study is difficult, however, since we only have a few "large" eruptions in the instrumental record and the regional-scale responses are still largely controlled by internal variability coincident with the eruption. Moreover, even in the modern, the radiative forcing following volcanic events (e.g., Mt. Pinatubo) is uncertain and sensitive to assumptions about particle size.

We have followed the recommendations for improvement by Reviewer 1, Raphael Neukom.

Reviewer #2 (R2) raised concerns regarding the ensemble size and experimental setup. We argue in the response to R2 that our last millennium ensemble size is in fact quite large given the large signal associated with our sampled events. Each run in a model of this complexity takes ~1-2 years of actual time to complete, so it is not possible to substantially increase the ensemble size, nor would it necessarily yield additional insight in our composite results. Furthermore, the use of mixed-forcing ensembles is irrelevant in our context as we only probe the immediate post-eruption response; for this study the multiple model realizations are just additional ensemble members. We have, however, substantially modified the text on what information can be obtained from the three late 20^{th} century eruptions. To better understand the volcanic response in this model, we have elected to examine the last millennium runs that are forced with a greater number and higher-amplitude events. Finally, R2 stressed a better statistical presentation in order to interpret the robustness of our results. We have improved several figures and now report statistical significance wherever this is possible.

We feel that Reviewer #3's (R3) criticisms did not reflect a tone appropriate for normal scientific disagreement. Indeed, R3 openly admitted to not having read the present manuscript, and instead accused us of unethical behavior. Several of the scientific concerns they raised in the last Journal of Climate review (that were uploaded without our permission to Copernicus) were either minor (such as isotopic notation issues) that have since been fixed in the Climate of the Past version, or simply incorrect (such as the timing of eruption events entering into our composite before the event occurred). Given that R3 openly admitted to not having read the latest version of our paper, there is no substantive response we could make. Since this reviewer violated the terms of review for Journal of Climate and the tone of R3 has been consistently accusatory and personal in nature, we kindly request that R3 be disqualified from a second look at our paper.

We wish to thank you again for taking the time to handle our paper. Please address all correspondence to: ccolose@albany.edu. We look forward to hearing from you at your earliest convenience.

Sincerely,

Chris Colose

Response to Dr. Raphael Neukom

We thank Dr. Neukom for his constructive comments, which we agree will help improve the manuscript. Below we respond in detail to each comment. The referee comments are italicized:

1) Capability of the model to simulate oxygen isotopes in precipitation over South America. The conclusions of the papers stand and fall with the ability of the model to simulate oxygen isotopes in precipitation (d18Op) in general, not only in response to volcanic events. This is assessed in Figure 6. While the model appears to be quite good in simulating the seasonal cycle, I am not sure whether this analysis is sufficient to be confident about the skill of the model. I am not an expert in this field but I could think of the following options: Literature: It is possible that this has been assessed the literature describing GISS ModelE2-R. If this is the case I suggest including a paragraph reviewing this

The performance of the model, at least the previous version (ModelE-R), and its capability in tracing isotopes through the hydrological cycle has indeed been tested and presented in the literature. Schmidt et al. (2007), LeGrande and Schmidt (2008, 2009), Lewis et al. (2010, 2013, 2014) and Field et al. (2014) have tested the stable isotope results from this model against observations from satellites, IAEA data and proxy records. An earlier version of the GISS model has also been also been validated specifically over tropical South America (Vuille al., 2003a,b). We have clarified this in the revised manuscript and added a more detailed discussion of this aspect.

GNIP data and volcanic events: The authors state that data availability is not sufficient to perform a reasonable composite analysis for the volcanic events. Is there not sufficient data available to at least show the response to, let's say, the most recent event (Pinatubo)? If this is not the case, which I suspect from reading page 3386, would there be a chance to analyze this based on composites from other years? For example, one could make 18Op composites for the warmest/coldest/driest/wettest years during the period of reasonable data coverage and compare to the model data. This would require composites of reasonable size, so given that I don't know about the exact data situation in the GNIP data, I cannot be sure that this is feasible. But such an analysis would also be helpful to interpret the paleo results (see next point).

This is a valid suggestion, but rather difficult to achieve, given that the GNIP data suffer from substantial temporal gaps, and that data coverage is extremely sparse during the time of the Mt. Pinatubo eruption. Given this, and also the strong unforced variability (e.g., ENSO occurrence coincident with these eruptions), assessing the GNIP post-volcanic imprint yields inconclusive results. In fact, we have tried this approach for multiple events and the spatial structure of the isotope field resembles the well-known ENSO imprint on d18O (Vuille et al., 2003a) and with substantial spread between events.

2) Similarly to the last point, it would be good to simply see how the modeled 18Op responses to climate in the study area (not only during volcanic events). This not only to assess the skill of the model, but also to better understand the results. This could be tested using the control simulation. For example, one could select years with high/low temperature (but normal precipitation) and years with high/low precipitation (and normal temperatures). How do the 18Op anomalies look like? Most probably as expected from theory and described in the text but I think nevertheless it would be helpful to have an illustration confirming this (for example in the SM). This is relevant particularly for the explanation of the seasonal asymmetry shown in Fig. 10, which I think is one of the key findings of the paper. The interpretation provided by the authors (that the strong temperature response masks the precipitation signal in some seasons and regions) could be supported by this analysis.

The suggestion to stratify the model and observations by wet/dry and warm/cold years is interesting. Given the comments here and by R2, we will give much further attention to the model validation segment of our paper for the South American climatology and isotope physics. We agree that, in addition to better citing the relevant literature (as discussed in point #1), a more thorough treatment of how the model handles the isotope field is required.

3. This is a modeling study. However from the title and abstract this does not become clear and one could still think that proxy data are also used. In the abstract it says ":::and allows for a direct comparison between GISS simulations and paleoclimate proxy archives". This comparison is not provided in the paper, so I suggest to clarify this (e.g. by saying "future comparisons") and move this statement to the end of the abstract (as kind of an outlook). Even after reading the introduction (with a specific section on reconstructions), one could still expect proxy data to be used somewhere in the text. Given proxy data are mentioned repeatedly in the paper, the reader can hardly wait to see how the anomalies of the proxy data look like following the LM eruptions :::I suspect (and hope) that the authors plan to show this and the proxy-model comparison in a subsequent study, and this should be clarified as early as possible. The importance of this paper for such future analysis can then be stressed (again) in an outlook at the end of the manuscript. I would like to emphasize that I do not think that clarifying this in the title and/or abstract will make this paper less appealing.

We agree with these recommendations. We have changed the title to: " The influence of volcanic eruptions on the climate of tropical South America during the last millennium in an isotope-enabled GCM." The abstract has also been changed to make it clear that the purpose of the study is to focus on the volcanic response over tropical South America. Finally we do indeed intend to use some of the results obtained here to inform the interpretation of isotopic signals in high-resolution isotopic proxy records from South America, where we suspect to see volcanic signals, but these analyses are beyond the scope of the study at hand.

4. The paper focuses on tropical South America. Although the entire continent is shown in the figures, the analysis and interpretation is clearly focused on the tropics (and maybe subtropics), which makes sense (e.g. given the distribution of isotopic proxy data). Again, I suggest clarifying this in title and abstract. And again I think doing so will not make the paper less attractive but help the reader to know what to expect. The authors may even consider removing the parts of the paper describing extratropical features, for example Figure 13, to make the paper more focused. Suggest to replace "South America" by "tropical South America" in many instances of the paper.

We agree. As mentioned under point 3, abstract and title have been revised to clarify that this is a modeling study and the focus is on tropical South America. We also agree with removing the discussion of the extratropical aspects. Hence we have removed section 3.2.4 from the revised manuscript.

5. *I suspect that the response to volcanic forcing in tropical South America in the instrumental data is not as clear as described in the text, particularly for temperature. None of the obs-panels in Fig. 4 shows consistent negative anomalies in the region except for Pinatubo in JJA, where the signal appears to be rather weak. A composite analysis could clarify this picture. While Figure 3 impressively shows the consistency in observational and model data in the tropical belt, I think an identical (or similar) figure for tropical South America would be more helpful for this paper (the current fig. 3 could be provided additionally or moved to the SM). The authors may also consider showing an instrumental composite anomaly map for South America to allow a good comparison with Figs 7 and 8. (see my other point regarding figure 4 below).*

We understand the reviewer's concern, but too much emphasis on the regional scale (for the instrumental record) is not helpful in this case. Focusing on tropical South America rather than the entire tropics, will amplify the issue that El Niño tends to mask the volcanic signal over the observational period, given that ENSO has an exceptionally large impact on tropical S. American climate (Garreaud et al., 2009). This problem is not alleviated by compositing events, even if the ENSO signal is removed (e.g. through linear regression). We have made such attempts to remove ENSO, but the signal-to-noise ratio remains very low and the residual signal only perpetuates a false representation of the "typical" volcanic expression and it is not suited to test model performance.

Minor points:

6. Abstract line 4: consider including "instrumental" before "observations" to clarify that
proxy data are not used in this study.
7. Abstract lines 5-9: This is a very long sentence. I suggest to split up.
8. P. 3377 line 8: Although this is described in more detail below, I think the statement "most important" should be accompanied with a literature reference (or "see below").

Thanks you; we will include all the suggested modifications in the revised manuscript.

9. P. 3377 line 17ff. Although see Zanchettin et al. (2012) for decadal-scale responses to volcanic eruptions, at least in the North Atlantic sector.

There are several hypotheses that exist for how the decadal---and---longer timescale response to volcanic eruptions manifests itself. Part of the response may be simple mixed---layer physics (McGregor et al., 2015) without the need for appealing to an anomalous circulation or sea ice feedbacks. While this is admittedly an interesting subject of research, we do not consider it very relevant for our paper, and believe that giving it too much attention would distract from the main message of our paper.

10. P. 3379 line 25. Do the authors mean "records" instead of "archives"? The number of archives offering high-resolution proxy data is not increasing that much.

We will change the word to "records."

11. P 3380 Section 1.3 does not describe the climate of the entire continent so suggest to change the title to "tropical".

We agree, and will modify this where appropriate, including the section 1.3 title.

12. Although I somehow like the expression, "rather Mars-like" does not appear to be a very scientific description. I leave it to the editor to decide whether it is appropriate. Given the point above (and point #4), the first paragraph of this subsection could also be considered to be entirely removed.

We will remove the "Mars-like" description following both yours, and Reviewer #2's suggestion. We do wish to preserve a short motivating description of the continent.

13. P. 3381 last paragraph. To be exact, the ENSO response described here is only valid for the SAMS-affected regions. There are parts of tropical SA that have a different (reverse) response (e the Pacific coast area with strong wet anomalies during El Niño events).
14. P.3382 lines 17-21. This is a long sentence, consider splitting up.
15. P. 3383 line 5: One or more References for the amount effect would be helpful.

Thank you; that is absolutely correct. We will modify all text accordingly.

16. P. 3383 line 7: is there an "at" missing after "be"? Or maybe use the word "occur" instead.

Yes, we can insert "at" in the text.

17. P. 3382 line 12 and P. 3383 line 19: I think the use of the terms "Medieval Climate Anomaly" and "Little Ice Age" is generally not appropriate and precise...

We agree; we will instead include an approximate date range for the specific claims in the text.

18. P. 3389 line 2: The linear time trend is later also subtracted from the data to remove the global warming signal or why is it included in the regression?

We do not remove a trend later, we only explain the data using a trend and ENSO as independent variables at each grid point, and remove the (lagged) ENSO effects. As it stands, if the super-posed epoch analysis were plotted for a larger number of "prior years" (e.g., year -30 to 0) the trend would be apparent.

19. P. 3390 line 7: The "cooling over much of the globe" is not really visible in the obs panels (expectations often bias our interpretation. Therefore, I showed the graph to persons not knowing what it shows and they confirmed that it does not visibly show more blue than red). Unless it can be undermined with numbers, this statement should be removed. Potentially, the signal gets clearer if the three events are combined into a composite? This could be added as an additional panel in the bottom of the figures (see also point 5 above).

We thank you for providing yours (and a number of other) eyes to keep our interpretation honest. We will add an additional plot and discuss/quantify our statement more thoroughly.

20. P. 3390 line 22: Please specify what "this" refers to.

We refer to the model simulating the state/amplitude of ENSO at the same "time" as observations. We will clarify this aspect.

21. P. 3392 line 8: What are the composites compared against in the t-test?

At each grid point, we create two lists ("non---eruption" and "post---eruption") values following the definition in the methodology section of our manuscript. Values for each event are expressed as anomalies relative to the local non---eruption climatology to remove the possibility of low---frequency variations, and the list includes data for all events and all ensemble members to maximize the number of values to perform the t---test.

22. P. 3394 line 1: Although see Greve et al. (2014) regarding the (non)validity of the "dry gets drier" hypothesis.

It is true "dry gets drier" is not applicable everywhere, especially over land. We will clarify this in our manuscript. However, the statement referred to the large-scale tropical/subtropical atmosphere including the ocean, where it tends to be a useful first-order description of the large-scale net precipitation changes under global warming.

23. P. 3396, last paragraph: I think Figure 12 could be moved to the SM. I was missing confidence intervals in Figure 9. These could be inserted by shading the 95% range of the distribution from the random composites in Fig. 12. This would make Fig. 9 much stronger and the additional information in Fig. 12 would then be minor so that it could, in my perspective, be removed from the main manuscript.

Figure 9 and 12 still convey different pieces of information. Figure 9 shows the ensemble spread (and mean) response in temperature/precipitation for each event (the variable plotted against AOD). Figure 12 emphasizes the composite mean (and the likelihood of the composite response being realized by chance in the control simulation). We would like to retain both figures.

24. P3397: I think section 3.2.4 could be removed…

Yes, we agree that this section can be removed, and by extension, Figure 13.

25. Figure 1. Suggest to mark the eruptions that are finally used to create the composites with a different color in the top panel.

We will do this.

26. Figure 3: I think this Figure should contain confidence intervals, so the reader can see what magnitudes of anomalies are significant. A standard approach in superimposed epoch analysis plots is to show the 95% range of years no affected by an eruption. 27. Figure 3: The positive anomalies in instrumental precipitation between ca. 1.8 and 3.5 years after the eruption appears to be about as large as the immediate drying response. Do you think this is an artifact? Is it seen in both eruptions? Any reference to this in the literature? Again, indicating the significance threshold could help here.

Reviewer 2 also raised the same point. We will modify the figure to improve the statistical presentation. There are quite different responses to both eruptions in precipitation, so the composite may amplify/ mask anomalies in ways not representative of either eruption.

28. Figures 7,8,10: Include "anomalies" to the color bar caption. I think it is worth mentioning in the caption that only significant results are shown (at least that's how I understand it from reading page 3392) 29. Figure 9. This figure should also include a significance threshold and this could be taken from Fig. 12 as mentioned above (point 23). 30. Figure 12: The blue colors are hardly visible and somehow masked by black in the print version of the manuscript.

Agreed on all points, we will modify the manuscript accordingly, thank you.

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Response to Reviewer #2

We thank Reviewer #2 (R2) for the time spent reviewing our manuscript. We feel that it has improved significantly from incorporating his/her thoughts and suggestions. We respond to the reviewer criticism as follows (Review comments italicized):

1) *To start with, an evaluation of the model performance in correctly simulating the global mean TOA SW anomalies and global mean temperature anomalies needs to be shown so that to prove the model skills is correctly capturing the first order forcing and temperature response to the historical eruptions. Same remark for the South American precipitation mean seasonal cycle at least in DJF (selecting two levels of precipitation contours as on figure 6 won't just do the trick). This should be a first order sanity check for the South American Monsoon mean climatology and for the L20 eruptions of the historical periods for which observation are available.*

Following the comments of multiple reviewers, we do plan to revisit the historical/validation section of our paper. This includes an improved figure for the seasonal cycle in South American precipitation, in addition to the isotopes that we have already done.

The GISS climate model has a long history of making comparisons of the 1991 eruption of Mt. Pinatubo to observations (Hansen et al., 1996). Global temperatures are reduced by (on order) half a degree in the months following the Mt. Pinatubo eruption. "Zero order" analyses of this sort for ModelE2-R have been performed in a number of other studies and it cannot be the point of this paper to repeat all these previous analyses. Instead we will include a discussion of these papers and include appropriate references (e.g., see list provided at end of response to reviewer 1).

The question is complicated for TOA SW. In fact, this question posed to another modeling group would be mute – some groups for CMIP5 represent volcanic eruptions *exactly* as a TOA SW forcing. The implementation in the GISS code is more complicated – see Lacis et al 1992. – such that the TOA SW anomaly is influenced by not only the AOD of the sulfate aerosols, but also their size distribution. Although Mt. Pinatubo may widely be regarded as "well-observed" there is still considerable uncertainty regarding its forcing. The SAGE II instrument was saturated during the 1991 eruption, and the maximum AOD and size distribution have considerable uncertainty. More recent analyses of the Pinatubo aerosol forcing (e.g., Santer et al., 2014; Schmidt et al., 2014) have come to new conclusions that will lead to substantially reduced Aerosol Optical Depth and differences in particle size between CMIP5 and CMIP6. For CMIP6 (including PMIP4), the AOD of Mt. Pinatubo will likely be reduced.

The experiments presented here followed the CMIP5 / PMIP3 protocol for forcing of AOD and size distribution. For the historical eruptions, we would pass the 'first order' sanity check. For a more in depth analysis of signal-to-noise of the GISS model (and comparing to CCSM) for temperature and precipitation, please see (Marvel et al., 2015).

In general, it is worth pointing out that the main historical eruptions (e.g., Mt. Pinatubo) do not represent a useful validation target in our context. The spatial pattern of the post-eruption response is dominated by internal variability (e.g., ENSO). We did attempt to remove ENSO in our late 20th century (L20) analysis, but its expression over South America in particular is non-linear. ENSO and additional unforced variability mask the volcanic forcing at the regional level in L20 eruptions. Thus, the fact that the model does not "look like" observations following a given L20 event is not a reasonable criticism, as free-running GCM's are not built for this purpose.

For all these reasons we intended to shift focus to the larger LM composite in this study, which features a larger sample of events (larger signal-to-noise). We will improve this segway and motivation.

2) *My second comment concerns the method used to build the super-posed epoch and composite analysis. The authors compute anomalies respectively to the period three years before and 5 years after each eruption for both temperature and precipitations in observations for El Chichon and Pinatubo eruptions. By doing so the authors remove part of the volcanic signal. Why choosing this period? GISTEMP anomalies are based on the 1961-1990 climatology. Did you check the consistency between the two anomalies? I'd suggest removing the 1961-1990 climatology, for precipitation and temperatures so that to avoid removing the climatology with part of the climate response to volcanic forcing.*

We will re-visit the superposed epoch analysis, including addition of statistical analysis to improve the presentation.

With respect to the choice of base period, we will do a much better job of describing this in the manuscript. The choice we use simply shifts the entire curve up or down relative to the suggestion by Reviewer #2, but does not influence its temporal structure. What we actually did in the case of temperature was to use GISTEMP land-ocean temperature index, which is already provided as deviations from the 1951-1980 period (not 1961-1990) and the model data, where anomalies were then computed using that same long-term climatology.

However, we also subtract a constant in order to force the data in Figure 3 to have zero mean. Even though Mt. Pinatubo results in global cooling, large-scale tropical mean anomalies in the late 1980s and 1990s are still positive relative to the 1951-1980 climatology, due to the long-term warming trend. Since it may be awkward to display a plot of this sort with all positive anomalies, we subtract off the mean anomaly during years -3 to 5 from each data point. It is true that this is equivalent to using those years as our reference period. However, we do not view this as "removing the volcanic signal." The Hansen et al. (1996) publication makes a nice stack of 5 historical eruptions. Their method averages the 12-months prior to the eruption. This is the method that is used to make many epoch analysis stacks.

To better illustrate this, the following two figures show a comparison of Figure 3 in our discussion paper (only for Mt. Pinatubo here), in both cases with the same monthly-mean anomalies (fill color) using our choice of reference period.

The lines represent moving averages of the instrumental data (black), model ensemble mean (orange), and the individual ensemble members (grey dashed). The bottom figure shows how the data would look if we retained the 1951-1980 climatology. Regardless of choice, this will not affect our interpretation of the post-volcanic signal in the epoch analysis.

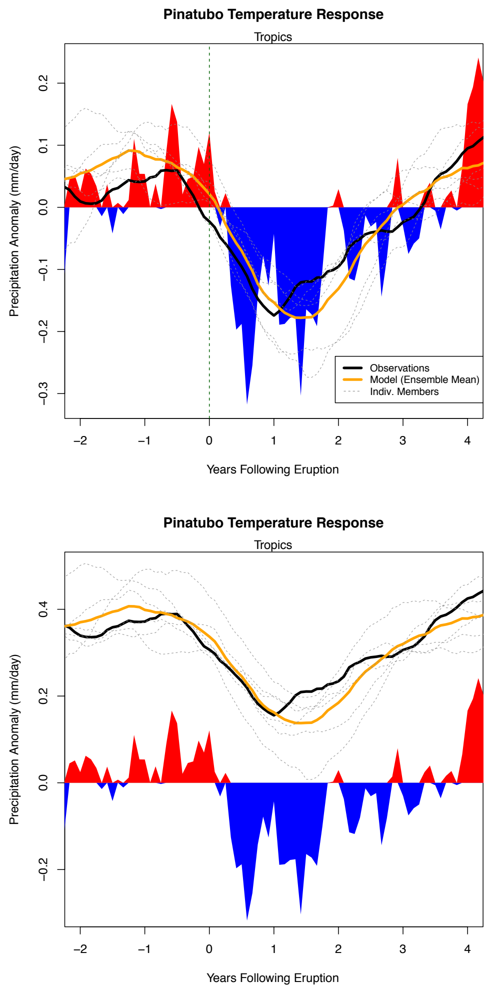

Figure 1: Tropical-mean temperature from years -3 to 5 for the Mt. Pinatubo eruption. Both panels use monthly-mean data (fill color) from GISTEMP Land-Ocean Temperature Index base-lined to give a mean of zero over displayed period. The 18 month running average in observations (solid black line), ModelE2-R ensemble mean (solid orange), and six individual ensemble members (dashed grey) are shown for the same reference period (top) and 1951-198- reference period (bottom).

3) A general comment for all the analyses displayed in the manuscript is the absence of statistical significance evaluation on each figure or plot. I suspect that two eruptions only, is not enough and most of the signal (which is very small) shown on the first figures is within the interval of internal variability. This needs to be evaluated with appropriate statistical methods used to extract the signal from the noise. Tropical South America temperature and precipitation interannual variability is high and the authors should discuss the results respectively to the background noise. No statistical confidence levels are shown. For example on Figure 4 and Figure 8, the colors map is built to be white between +/-0.1 C (mm.day-1). I really doubt that this is a real measure of significance applicable for the whole globe. The authors should address this matter seriously so that they can discuss in a convincing way the signal attributable to the volcanic forcing.

We agree that we could be more rigorous and transparent in our statistical testing. We will stress and revise for clarity in our revised manuscript that in the LM composites (Figure 7,8,10) we did actually test for significance and set any non-significant result to zero. In fact all non-significant areas in these plots were masked white, regardless of the amplitude of their signal. But in addition we also masked all areas with a very low signal (inside the -0.1 to 0.1 range) as white, which may have caused the appearance of only masking areas between -0.1 and 0.1 white. To increase clarity we will consider re-plotting these figures showing all data and use stippling for significance instead.

We will also add statistical significance levels to the historical section of our paper where appropriate (following up on point #1). We do agree that the continental-scale anomalous response is well within the bounds of natural variability, which relates to our concern on the utility of the historical analog for model validation.

4) *Why the authors did run only 6 model members for the L20 eruptions? How were they built? ENSO might be the dominant factor in the simulate response over South America so I would suggest to increase the ensemble size and sample initial states so that in the ensemble mean, the volcanic signal could be extracted from internal unforced variability without any bias toward any ENSO phase. As it is now, we can't really trust the model results as no discussions or diagnostics are shown concerning the appropriateness of the model ensemble to detect the volcanic forcing.*

Six is the number of ensemble members (with volcanic forcing) that are available as continuations of the "past1000" set of experiments with ModelE2-R (http://data.giss.nasa.gov/modelE/ar5/). Until very recently, GISS was the only model that had multiple ensemble members for the last millennium. As with any work dealing with the more complex end in the hierarchy of climate modeling, there are practical limitations in how many simulations have been performed by different modeling groups.

While it is true that averaging over a larger ensemble would improve detection of a forced signal, this does not imply that it would facilitate the ability to validate the model with observations (which itself is only one realization of an ensemble of possible realities, and largely influenced by unforced variability). Enhancing the ensemble size also would do nothing to address the issue of systematic biases in the historical forcing. It may increase the probability that a given realization of the ensemble better mimics the initial state of the atmosphere prior to observed historical eruptions, but a detailed exploration of this specific aspect is beyond the scope and intended purpose of this paper. Instead we aimed at addressing this issue by averaging over a larger sample of events (with improved signal-to-noise ratio) by focusing on the LM composite. We believe this to be the better approach than increasing the ensemble size for the L20 composite for which the average forcing is much smaller.

5) *The model results displayed on both Figure 4 and 5 show absolutely no agreement with observations (temperatures and precipitations) while the estimated robust signal attributable to any of these volcanic eruptions is not shown (signal to noise ratio). Same remark as above using a color map built to have white shade at a fixed contour is not a measure of significance. The authors can't state based on these figures that the model is able to reproduce the temperature or the precipitation responses, as the spatial patterns and amplitude are not consistent with observations. So far figure 4 and 5 suggest that the model is not able to reproduce any post-eruption signal and is not appropriate to evaluating the impact of volcanic forcing on the South American Monsoon*

The argument made that "the model results displayed on both Figure 4 and 5 show absolutely no agreement with observations," relates back to our response in #1 above, on whether one can realistically expect the model to agree with observations. Please also note that the displayed model results represent an average over several ensemble members, while observations are by definition just one realization, so we cannot compare these usefully. In general this may not have been the best choice of presentation, and we will re-visit these figures and how we can best convey the relevant information.

Below, we show the six individual ensemble members for the post El-Chichón DJF temperature anomaly (relative to the previous five years, as was done in the discussion paper). Although we showed the ensemble mean in the paper (Figure 4, in the fourth column and second row) there is still considerable spread among the ensemble members. This limits our ability to confidently validate the model by comparing the post-eruption model and instrumental response.

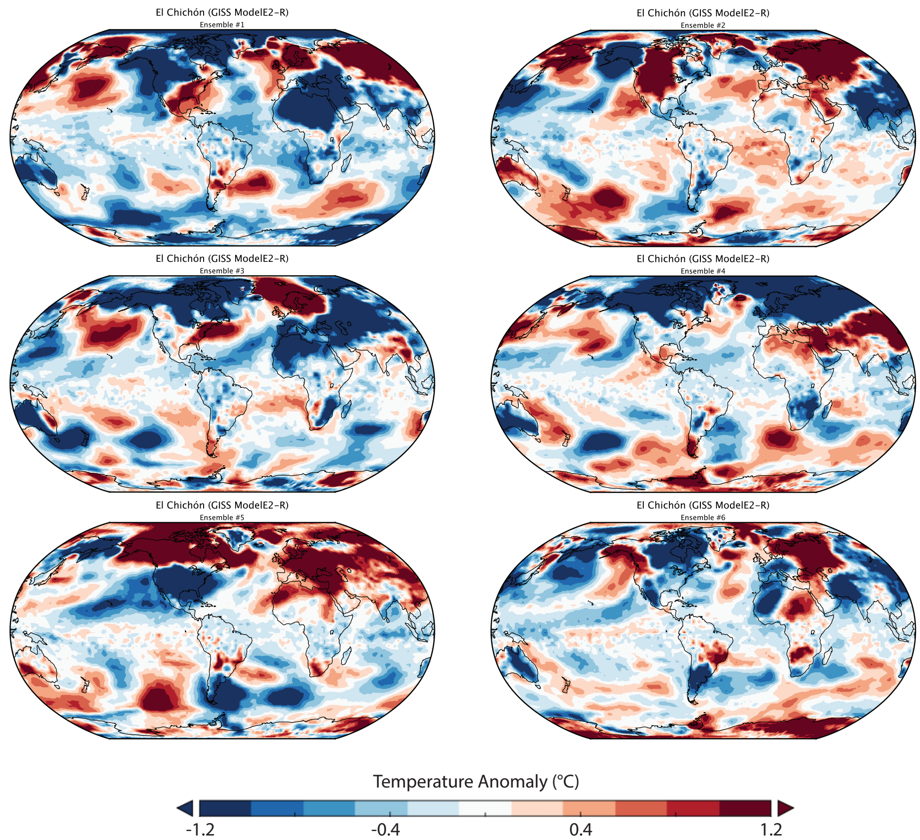

Figure 2: Temperature anomaly (°C) following El-Chich*ó*n for the six NASA GISS ModelE2-R ensemble members. Results for DJF.

6*) Last paragraph of page 3387: The authors should clarify what is the mis-scaling of the Gao forcing and why for the model composites covering the L20 eruptions, it is not an issue.*

The code to implement the Gao-derived aerosol loading (given in Tg) and convert to Aerosol Optical Depth and effective Radius (that is prescribed in ModelE2-R) did not include a constant, and thus was mis-scaled by a factor of ~0.51 and results in too large a radiative forcing. After 1850, the volcanic forcing is based on the Sato index and is correctly scaled. Thus, we omit the Gao ensemble members for the pre-industrial component of our study.

7) *First two paragraph page 3388: The authors state that the volcanic forcing should dominate the response in the LM composite. This is a very strong statement as different solar forcing scenarios have been used not to mention the two different land-use forcing*

scenarios (especially over South America) employed in the different LM member. The authors can't make such statement without providing detection-attribution analyses and other diagnostics over South America showing that the various land-use and solar irradiance forcings didn't have any impact on the post-eruption mean response (temperature and precipitations) and ensemble spread for each selected LM eruptions. Addressing this issue is not trivial and it shouldn't be overlooked. As it is, the LM composites can't be used to address specifically the volcanic response as other forcings are at play and may very well contribute significantly to the simulate response.

R2 is concerned with the use of a mixed-forcings ensemble. We first note that if a volcanic-only last millennium GISS ensemble were available in the CMIP5/PMIP3 generation, we would have used it.

We believe R2's point would certainly be important if our analysis focused on the decadal-to-centennial timescale, where volcanic forcing is competing with many other forcings during the Last Millennium (although note that Atwood et al. (2015) document that volcanic forcing dominates even at the centennial timescale, at least at the global scale).

However, we stand by the argument that since the analysis focuses on changes within just a couple of years following pinpointed eruptions (relative to surrounding years), the presence of other "slow" and much smaller-amplitude forcings simply do not matter. For example, suppose we constructed a Pinatubo composite by averaging over 48 realizations of Pinatubo, and focused on the immediate 1-3 year response in the historical simulations – no one would reasonably argue that the CO_2 increase or solar cycle coincident with that change to be an important confounding influence. The same holds here, and most of the events averaged in our paper are even larger than Pinatubo.

To highlight this aspect more clearly, we show results from several ModelE2-R experiments that had differences in the imposed solar reconstruction, but without volcanic forcing included (rows 2-3). We create composites by averaging over the same 16 eruptions (i.e., the same dates as used to create the volcanic composite). This is done separately for both the DJF and JJA season. The mean of these 2 different solar forcing composites, featuring 32 events, are shown in row 4. Results from the control simulation with no forcing are also included (row 5). The top row of this plot includes the volcanic forcing, as in the manuscript (results not masked for significance) based on 16 eruptions and three ensemble members (48 events).

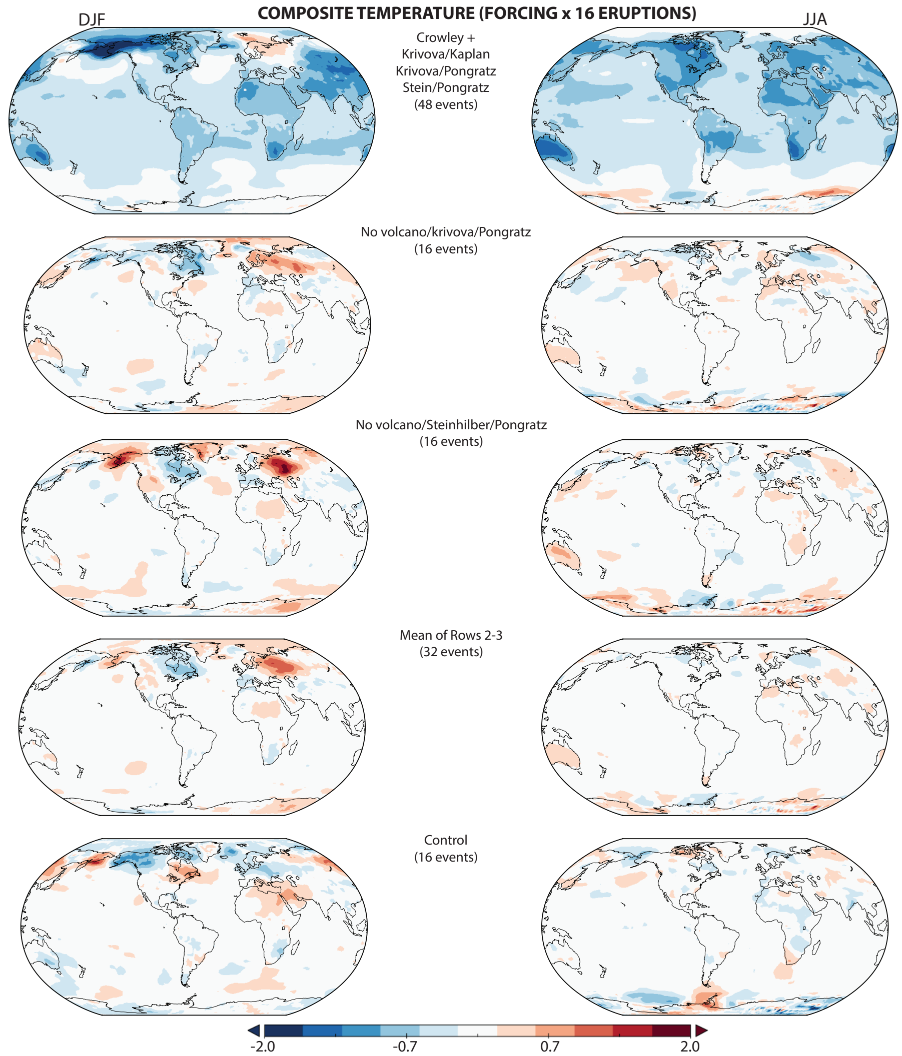

Figure 3: Composite temperature anomaly (°C) for 16 events (multiplied by number of ensembles) using the methodology in discussion paper. Row 1 with volcanic forcing (48 events) , row 2-3 with no volcanic forcing but differences in solar forcing (16 events each), row 4 is the ensemble mean of rows 2-3 (32 events). Row 5 is the 16 events from the control simulation. Results for DJF (left column) and JJA (right column).

The volcanic response stands out clearly in the ensemble, both over South America and on a global scale, even after averaging over 48 realizations of internal variability. The solar signal is just too small. There is no evidence of a coherent forced response to solar forcing, when compositing over such short random time periods (see rows 2-4). The variability in the wintertime high-latitudes still stands out, but there is no solar signal on this time scale in the tropics. Repeating this analysis for land use forcing or looking at the precipitation response instead of temperature does not change these conclusions. Hence land-use and solar irradiance forcing do not significantly affect the post-eruption mean response of temperature or precipitation in the tropics.

We will consider adding a supplemental figure to stratify our composite by times during high or low solar forcing. We expect them to look the same.

8. Section 3.2.1 first paragraph: Is -/+0.1 C statistically significant as shown on Figure 7 or is it again a color map choice? Does not look right owing to the high SST variability over land and ocean in these regions. I'd ask the author to verify this.

We have addressed this point regarding statistical significance in our response under item 3.

9) *It is difficult to believe based on the results displayed that in in the case of volcanic forcing it appears that the amplitude of the temperature-response to volcanic eruptions over tropical South America is much larger than the rather weak and spatially incoherent precipitation signal. The forcing used (Gao and Crowley) for the LM simulations are well known now to have been largely overestimated as the temperature response in CMIP5 LM simulations while the good performance of the model used in this study against Pinatubo eruption (for which plenty observation are available) for the forcing and response has not been shown. Same for the South American mean climatology.*

If we understand R2 correctly, he/she is surprised at the relative coherence of the temperature response when compared to precipitation. We have argued above that we have sampled more than enough volcanic events in our composite to isolate the signal, and the anomalous temperature field is almost always the "simplest" climate response to any global forcing. The anticipated response to elevated CO_2, for example, is relatively smooth and well characterized by a single number, with the usual caveats of polar/land amplification and minima in sub-polar regions. Precipitation is much more heterogeneous.

We are sympathetic to R2's point that the Gao/Crowley forcing datasets are virtually certain to be "wrong." However, those are the datasets that are available and which have been used in the forcing of CMIP5/PMIP3 generation last millennium simulations, and even in post-CMIP5 efforts (e.g., the CESM Last Millennium ensemble). It is not obvious that the temperature response in CMIP5 models is overly sensitive; they just may be seeing too large a forcing (e.g., because the aerosol size distribution is incorrect). The displayed temperature and precipitation (and isotope) patterns are arising from the same forcing.

Unfortunately, we are shackled to the current state of the science on paleo-volcanic forcing. Newer reconstructions such those provided by Sigl et al. (2015) have not yet been implemented in fully coupled GCMs, but even here any estimated forcing will just be a simple historical scaling and likely not robust (though Arfeuille et al., (2014) do a better calculation back to 1600 C.E.). We further would like to note that errors in the timing of the eruptions, which exist in the Gao/Crowley forcing datasets and pointed out by Sigl et al. (2015), are not relevant in our context because we know exactly when the model is forced and build our composites accordingly. Errors in the amplitude or spatial structure will potentially matter, and we have used the dataset that actually has "smaller" events. We do show a scaling against AOD for key variables in Figure 9, to lend insight into how the typical response may change if we scale the mean forcing differently.

We do agree that these mismatches have inspired proxy testing, improvements in volcanic forcing, and development of volcanic implementation in climate models. It is an exciting – and new – area of research. But, not the focus of the paper here, which looks specifically at the last millennium simulations.

Aside from this, a fully consistent emissions-based estimate of the aerosol loading, growth of particles, interaction with chemistry and clouds, release of other substances (halogens, water vapor, etc.) is at the frontier of this field and not well implemented by any group. So the model response of course needs to be viewed as a slave to the imposed forcing.

Minor comments:

- Page 3377, line 27-28 and page 3378 line 1-2. The authors state Sulfate aerosols from the Mt. Pinatubo eruption had an effective radius of up to 0.5–0.8, comparable in size to a visible wavelength and strongly scattering to incoming solar radiation. Unless the particles can reach sizes larger than 1–2, this scattering more than offsets the small increase in infrared opacity from the aerosols, and results in a cooling of Earth's surface (Turco et al., 1982; Lacis et al., 1992).

- I'd replace "of up to 0.5–0.8" by "ranging between 0.2 and 0.8 with unimodal size distribution mean radius of 0.5" As for the statement "larger than 1–2", according to theoretical calculation (Lacis et al 1992) the LW forcing would dominate for particles larger than 2.2.

We will improve our description, thank you.

-Page 3380, last paragraph: The continent spans a vast meridional extent (from 10N to 55S), contains the world's largest rainforest (the Amazon), in addition to a rather Mars-like desert (Atacama) that competes only with the dry valleys of Antarctica for the driest location on Earth. What is a "Mars-like" desert? Not really scientifically meaningful. I'd rather give the amount of precipitation per year. As for the comparison to Antarctica for the driest location on Earth, is it proven? If yes the reference is missing.

We agree that this paragraph was not well written. We have removed the anecdotal reference to Mars and Antarctica and now use actual precipitation amounts to discuss the spatial precipitation variability over the South American continent.

- Methodology section: Line 14: The authors need to clearly define how the ensembles were built, in terms of forcings and initial conditions. How many members and how they differ exactly from each other? A table summarizing this is needed.

We will include another table in the manuscript to discuss the forcings (and other model details) for the three different ensemble members used in the LM composites, and six for L20.

- Page 3385, line 19: GPCCv6 is better and is actually what you show in the supplementary material. Please clarify.

We did use a merged satellite-land precipitation product (GPCP v2.1). We will include the most recent version (v2.2) that became available after the analysis was done, though there are no differences over South America following the eruption events targeted in our paper. GPCC v6 is a land-gauge product only. It is true that we did include in Figure S1 a representative set of examples for the number of observations that are available around each eruption point, which was a readily accessible diagnostic in the GPCC netCDF files online (but not GPCP). GPCP v2.1 uses GPCC precipitation gauge analysis as a key input. We will clarify this in the Figure S1 caption.

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Lacis, A., J. Hansen, and M. Sato, 1992: Climate forcing by stratospheric aerosols. *Geophys. Res. Lett.*, **19**, 1607-1610, doi:10.1029/92GL01620.

Marvel, K., G.A. Schmidt, D. Shindell, C. Bonfils, A.N. LeGrande, L. Nazarenko, and K. Tsigaridis, 2015: Do responses to different anthropogenic forcings add linearly in climate models? *Environ. Res. Lett.*, **10**, no. 10, 104010, doi:10.1088/1748-9326/10/10/104010.

Santer, B.D., et al., 2014: Volcanic contribution to decadal changes in tropospheric temperature. *Nature Geosci.*, **7**, no. 3, 185-189, doi:10.1038/ngeo2098.

Schmidt, G.A., D.T. Shindell, and K. Tsigaridis, 2014: Reconciling warming trends. *Nature Geosci.*, **7**, no. 3, 158-160, doi:10.1038/ngeo2105.

Sigl, M., et al. 2015: Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature*, **523**, 543-549, doi:10.1038/nature14565.

Response to Reviewer #3

This review does not pertain to the manuscript submitted. Reviewer 3 openly admits to not having carefully read our manuscript, so there is nothing substantive that we can address in this review.

To the point about resubmission, however, we wish to clarify a few aspects that have been misconstrued by reviewer 3. This paper was indeed previously submitted to J. Climate. Two reviews were fair critiques, but reviewer 3 was not constructive and the tone, unfortunately, was accusatory in nature. The editor at J. Climate offered that we resubmit the paper with different reviewers. We decided, however, that an open-format journal, where the reviews themselves undergo scrutiny would better protect the peer-review process. After making further revisions to the text, we therefore resubmitted to Climate of the Past Discussions (CPD). The editor of CPD was notified of the history of this research in our cover letter. It is completely reasonable for authors to revise and resubmit work in the same or another journal after a recommendation of moderate to major revisions.

We feel that 'anonymous reviewer 3' has violated ethical guidelines as spelled out by the publisher of J. Climate by publishing private conversations between the authors, editors, and reviewers without prior notification or permission.

https://www2.ametsoc.org/ams/index.cfm/publications/editors-and-reviewers/obligations-of-editors-and-reviewers-in-the-ams-scientific-publication-process/

"10. Reviewers should not use or disclose unpublished information, arguments, or interpretations contained in a manuscript under consideration, except with the consent of the author."

We anticipate that 'anonymous reviewer 3' will be internally identified within COPERNICUS and AMS journals to avoid further such violations.

Changes to Manuscript

The revised manuscript has gone through a large number of major revisions. We have since added or removed sections, changed methodology/datasets, different references, new figures/captions, or included scattered clarifications and improvements. The presentation of the historical (L20) eruption section is much different.

We have done our best to ensure consistency between the track-changed manuscript below, and the final product submitted under the "Manuscript" upload section. However, our edits have went through several circulations among authors and a "no track change" version eventually had to be created for a clean template in order to proceed without mistakes. We apologize for any inconsistency- the final product submitted under the "Manuscript" tab is the most up-to-date version.

Please contact ccolose@albany.edu if there are any questions/clarifications required on the history of this paper.

Thank You.

Previous (Edited) Manuscript

The influence of volcanic eruptions on the climate of tropical South America during the last millennium in an isotope-enabled GCM

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Abstract

Currently, little is known on how volcanic eruptions impact large-scale climate phenomena such as paleo-ITCZ position or South American summer monsoon behavior. In this paper, an analysis of observations and model simulations is employed to assess the influence of large volcanic eruptions on the climate of tropical South America. This problem is considered both for historically recent volcanic episodes, for which more comprehensive global observations exist, as well as reconstructed volcanic events for the period 850 C.E. to present that are incorporated into the NASA GISS ModelE2-R simulation of the Last Millennium. An advantage of this model is its ability to explicitly track water isotopologues throughout the hydrologic cycle and simulating the isotopic imprint following a large eruption. This effectively removes a degree of uncertainty associated with error-prone conversion of isotopic signals into climate variables, and allows for a direct comparison between GISS simulations and paleoclimate proxy records.

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Our analysis reveals that both precipitation and oxygen isotope variability respond with a distinct seasonal and spatial structure across tropical South America following an eruption. During austral winter, the heavy oxygen isotope in precipitation is enriched, likely due to reduced moisture convergence in the ITCZ domain and reduced rainfall over northern South America. During austral summer, however, precipitation is depleted in heavy isotopes over Amazonia, despite reductions in rainfall, suggesting that the isotopic response is not a simple function of the 'amount effect.' During the South American monsoon season, the amplitude of the temperature response to volcanic forcing is larger

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than the rather weak and spatially less coherent precipitation signal, complicating the isotopic response to changes in the hydrologic cycle.

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1. Introduction

1.1. Volcanic Forcing on Climate

Plinian (large, explosive) volcanic eruptions are a dominant driver of naturally forced climate variability during the Last Millennium (LM, taken here to be 850 C.E. to present; e.g., Stothers and Rampino, 1983; Hansen et al., 1992; Crowley et al., 2000; Robock et al., 2000; Robock, 2003; Goosse et al., 2005; Yoshimori et al., 2005; Emile-Geay et al., 2008; Cole-Dai, 2010; Timmreck, 2012; Iles et al., 2013; Schurer et al., 2014). In addition to their importance for 20th century climate, they are the largest magnitude external forcing during last 1000 years of the pre-industrial period, the most recent key interval identified by the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3). As such, these eruptions serve as a natural testbed to assess the skill of climate models in simulating how climate responds to external perturbations.

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Although the most significant climate impacts of eruptions are realized over just a few years following the eruption, they provide the source of the largest amplitude perturbations to Earth's energy budget during the LM. For example, the eruption of Mt. Pinatubo in June 1991, although transitory, exerted a radiative forcing comparable to an instantaneous halving of atmospheric CO_2 [Hansen et al., 1992; Minnis et al., 1993; see also Driscoll et al. (2012) for models in the Coupled Model Intercomparison Project Phase 5 (CMIP5)]; several paleo-eruptions during the LM likely had an even larger global impact (Figure 1).

The principle climate impact from volcanic eruptions results from the liberation of sub-surface sulfur-containing gases such as sulfur dioxide and hydrogen sulfide, which are injected into the stratosphere and react with water to form sulfate aerosols (e.g., Harshvardhan and Cess, 1976; Coakley and Grams, 1976; Pollack et al., 1976, 1981; Lacis et al., 1992). The most pronounced impact of large tropical eruptions includes a radiatively cooled troposphere and heated stratosphere (e.g., Lacis et al., 1992; Robock and Mao, 1995; Stenchikov et al., 1998). Sulfate aerosols from the Mt. Pinatubo eruption grew from a background effective radius of 0.2μm up to ~0.8 μm, strongly scattering incoming solar radiation. For sulfate aerosols in this size range, this shortwave scattering is 5-10x larger than the increase in infrared opacity from the aerosols, and results in a warming stratosphere and cooling of Earth's surface (Turco et al., 1982; Lacis et al., 1992). (Turco et al., 1982; Lacis et al., 1992).

Studies on the impacts of volcanic eruptions have generally focused on global or Northern Hemisphere metrics (e.g., Lucht et al., 2002; Gillett et al., 2004; Shindell et al., 2004; Oman et al., 2005; Oman et al., 2006; Anchukaitis et al., 2010; Peng et al., 2010; Evan et al., 2012; Zhang et al., 2013; Man et al., 2014), for instance in examining responses to the East Asian monsoon system (EAMS) or the Arctic Oscillation. Comparatively little attention has been given to the Southern Hemisphere, or to South America specifically (although see Joseph and Zeng, 2011, and Wilmes et al., 2012). Some previous work has focused on the Southern Annular Mode in the ERA-40 and NCEP/NCAR reanalysis, in addition to a previous version of NASA Goddard Institute for Space Studies (GISS) Model-E (Robock et al., 2007) and in a subset of CMIP3 models (Karpechko et al., 2010) or in CMIP5 (Gillett and Fyfe, 2013).

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How volcanic forcing is expressed over South America remains an important target question for several reasons. First, recognition of the South American monsoon system (SAMS) as an actual monsoon system is less than two decades old (Zhou and Lau, 1998), and thus study of SAMS dynamics is still relatively young (section 1.3) and very little work has been done specifically focused on volcanic eruptions. For instance, should we expect to see a reduction in austral summer rainfall (during the monsoon season) as has been reported for the EAMS (Man et al., 2014)? Secondly, the largest volcanic eruptions during the late 20th century (e.g., Mt. Agung, 1963, Indonesia; El *Chichón*, 1982, Mexico; Mt. Pinatubo, 1991, Island of Luzon in the Philippines- hereafter, these three events are referred to as L20 eruptions) occur quasi-simultaneously with an anomalous *El Niño-Southern Oscillation* (ENSO) state, and in general represent a small sample size in a noisy system. This limits the prospect of robust hypothesis-testing and guidance for what impacts ought to be expected following large eruptions at the continental scale. Finally, South America offers promise for a comparatively dense network of high-resolution proxy locations relative to other tropical regions (see below), offering the potential to detect whether South American hydroclimate signals to large eruptions are borne out paleoclimatically.

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In this study, we will explore the post-volcanic response of South American climate operating through the vehicle of unique model simulations (spanning the LM) using the recently developed GISS ModelE2-R (LeGrande et al., 2015, in prep; Schmidt et al., 2014a), which allows for the sampling of a greater number of events than is possible over the instrumental period. Emphasis is placed on temperature and precipitation, but a novel part of this study extends to the response of water isotopologues (e.g., $H_2{}^{18}O$) [colloquially referred to hereafter as 'isotopes' and expressed as $\delta^{18}O$ in units per mil (‰) vs. Vienna Standard Mean Ocean Water]. The isotopic composition of precipitation ($\delta^{18}O_p$) is a key variable that is directly derived from proxy data used in tropical paleoclimate reconstructions.

The aim of this paper is to create a potentially falsifiable prediction for the isotopic imprint that a volcanic eruption should tend to produce across the South American continent. The ability to explicitly model the isotopic response allows for a less ambiguous comparison of simulations and paleoclimate records and for hypothesis testing. It is unclear whether or not the current proxy archives are suitable to test such a prediction with high confidence, given dating uncertainties (in both proxies and in the actual timing of eruptions), or the level of noise in proxy data and the real world. Additionally, the prevailing high-resolution archives in South America only feature a few tropical records (Vimeux et al., 2009; Neukom and Gergis, 2012; Vuille et al., 2012). Nonetheless, the growing number of high-resolution records offers hope that testing the modeled response to high-frequency volcanic signals will be an avenue for future research. This can also better inform debate centered on the inverse problem in interpreting isotopic signals (i.e., what do observed changes in proxy data imply about past climate changes?), which remains contentious (section 1.4).

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The structure of this article is as follows: in the remaining part of section 1, we summarize previous literature on the impact of large volcanic eruptions on paleoclimate, in addition to a discussion of South American climate. Section 2 presents data and methodology, including how volcanic forcing is implemented in ModelE2-R. Section 3 discusses our results and we end with conclusions in section 4.

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1.2. Volcanic forcing during the Last Millennium

Volcanic forcing has had a very large influence on the climate of the LM (Crowley, 2000; Hegerl et al., 2003; Shindell et al., 2004; Mann et al., 2005; Hegerl et al., 2006; Fischer et al., 2007; D'Arrigo et al., 2009; Timmreck, 2012; Esper et al., 2013; Ludlow et al., 2013; Schurer et al., 2014). Several studies (Miller et al., 2012; Schurer et al., 2014; Atwood et al., 2015, in press; McGregor et al., 2015) collectively provide a compelling case that volcanic forcing may be substantially more important than solar forcing on a hemispheric-to-global scale during the LM, in addition to driving a large portion of the inter-annual to multi-decadal variability in LM simulations (Schmidt et al., 2014b).

Two volcanic forcing datasets (Gao et al., 2008; Crowley and Unterman, 2013) relying on ice core reconstructions of volcanism are used as input in the LM ModelE2-R simulations (and are the CMIP5/PMIP3 LM standard), as discussed in Section 2.

1.3. Tropical South American Climate

South America is home to nearly 390 million people. The continent spans a vast meridional extent (from ~10 °N to 55 °S), contains the world's largest rainforest (the Amazon), in addition to one of the driest locations on Earth (the Atacama desert). The continent has diverse orography, spanning the high Andes along the Pacific to Laguna del Carbón in Argentina, the lowest point in the Southern Hemisphere. Because of this, South

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America hosts a rich diversity of climate zones and biodiversity, all of which may respond in unique ways to external forcing.

The most prominent climatic feature of tropical and subtropical South America is the South American monsoon system (Zhou and Lau, 1998; Marengo et al., 2001; Vera et al., 2006; Garreaud et al., 2009; Marengo et al., 2012). Much of South America is in a monsoon regime, with tropical/subtropical rainfall over the continent exhibiting a pronounced seasonal cycle. Unlike other monsoon systems such as that in Asia, low-level easterly winds prevail during the entire year in tropical South America, although the wind anomalies do change direction when the annual mean wind field is removed from winter and summer composites (Zhou and Lau, 1998).

During austral winter, the maximum in continental precipitation is largely restricted to north of the equator, in a band-like pattern associated with the oceanic Inter-Tropical Convergence Zone (ITCZ). During austral summer, convection is displaced from northwestern South America, and a band of heavy precipitation covers much of the continent, from the southern Amazon Basin to central Brazil and northern Argentina. A distinctive feature of the SAMS is the South Atlantic Convergence Zone (SACZ), a band of cloudiness and precipitation sourced primarily from the tropical Atlantic that extends diagonally (southeastward) from the Amazon towards southeastern Brazil (Figure 2).

The SAMS onset occurs around the end of October and the demise between the end of March and April (e.g., Nogués-Paegle et al., 2002; Vera et al., 2006; Silva and Carvalho, 2007). The dominant mode of intraseasonal precipitation variability over South America during summer exhibits a dipole pattern (Nogués-Paegle and Mo, 1997), seesawing between the SACZ region and Southeastern South America, the latter

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including the densely populated La Plata basin with local economies strongly dependent on agricultural activities.

The SAMS is strongly modulated by ENSO behavior on inter-annual timescales (Vuille and Werner, 2005; Garreaud et al., 2009). In general, SAMS-affected regions of tropical South America tend to experience drier than normal conditions during El Niño, while conditions in subtropical latitudes are anomalously humid, including the southeastern part of the continent. Surface air temperatures tend to be anomalously warm in tropical and subtropical South America during El Niño events. These relationships depend somewhat on the time of year, and during La Niña events, the pattern is essentially reversed.

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1.4. Recent South American Monsoon reconstructions from isotopic proxies

SAMS variability spanning most of the Holocene has been diagnosed from speleothem records in the Peruvian Andes (Kanner et al., 2013) and a review focused on the last 1,000-2,000 years was given in Bird et al. (2011) and Vuille et al. (2012). In all cases, a critical piece of information that is required to properly diagnose paleo-SAMS variability is the ability to translate oxygen isotope variability from natural recorders into a physical climate signal of interest.

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Early work on isotopes in ice core records from the tropical Andes detected a Little Ice Age (LIA) signal in the oxygen isotope composition of the ice, with results initially interpreted to reflect variations in local temperature due to their resemblance to ice core records from Greenland (e.g., Thompson et al., 1995, 1998) and due to their isotopic enrichment over the past 150 years, in parallel with rising global mean temperatures (Thompson et al., 2006). A temperature-dependence to oxygen isotope variability has been long known and is particularly important in mid-to-high latitudes (Dansgaard, 1964) and is most directly related to the ratio of initial and final water vapor content of a parcel that is transported horizontally, rather than the temperature-dependence of fractionation itself (Hoffman and Heimann, 1997).

This interpretation in the tropics has been challenged through a number of observational and modeling efforts (Hardy et al., 2003; Vuille and Werner 2005; Vimeux et al., 2005, 2009; Kanner et al., 2012) which suggest that isotopic signal is more closely related to the degree of rainout upstream in regions of intense convection (in the case of South America, over the Amazon basin). Additionally, since sea surface temperatures (SST) in the Pacific have a large influence on SAMS intensity on inter-annual timescales in the present, oxygen isotope variability over much of tropical South America is linked to the state of the equatorial Pacific (Bradley et al., 2003; Vuille et al., 2003).

In regimes that are highly convective in nature as in tropical South America, empirical evidence shows that the amount of precipitation (the so-called “amount effect”, Dansgaard, 1964) rather than the condensation temperature correlates most strongly with $\delta^{18}O_p$ variability, at least on seasonal to inter-annual time scales. In reality, however, the rainout most relevant for the oxygen isotope signal may be at a significant distance from the site where the proxy is derived, potentially complicating the use of local calibrations to climatology as a guide for $\delta^{18}O_p$ interpretations (Schmidt et al., 2007). Isotopic concentrations are explainable as being a function of original concentration, rainout along the moisture transport path, and mixing.

The influence of precipitation amount on $\delta^{18}O_p$, in addition to changes in the partitioning of precipitation sources, has also been identified on decadal to orbital timescales through speleothem records and lake sediments (Cruz et al., 2005; Van Breukelen et al., 2008; Bird et al., 2011; Kanner et al., 2012). These studies have also highlighted the role of latitudinal displacements of the ITCZ, which is ultimately the main moisture conduit for precipitation over the South American continent. Furthermore, many records collected throughout South America now provide evidence for enriched $\delta^{18}O_p$ values during the Medieval Climate Anomaly, which is indicative of weakened SAMS convection and rainout, followed by depleted $\delta^{18}O_p$ values, suggesting heavier rainfall during the LIA in tropical South America (Bird et al., 2011; Apaestegui et al., 2014) with an opposite response in Northeast Brazil (Novello et al., 2012). This, in turn, has been interpreted in terms of North Atlantic SST anomalies (Vuille et al., 2012; Ledru et al., 2013) and the position of the Atlantic ITCZ.

Nonetheless, oxygen isotopes respond in unique ways depending on the climate forcing of interest. Indeed, a unique, quantitative local relationship between an isotope record and any particular climate variable of interest is unlikely to hold for all timescales and prospective forcing agents (Schmidt et al., 2007) thus motivating the use of forward modeling to work in conjunction with proxy-based field data. For the remainder of this paper, we focus specifically on the volcanic forcing response.

2. Methodology

2.1. Data

The primary tool used in this study is the water isotope-enabled GISS ModelE2-R. ModelE2-R is a fully coupled atmosphere-ocean GCM (LeGrande et al., 2015, in prep; Schmidt et al., 2014a) that explicitly tracks stable water isotopes. The version used here is the same as the non-interactive atmospheric composition (NINT) physics version used in the CMIP5 experiments. The current model features 2° latitude x 2.5° longitude horizontal resolution and 40 vertical levels in the atmosphere up to 0.1 hPa, and is coupled to the Russell Ocean that conserves heat, water mass, and salt (Russell et al., 1995) at 1° x 1.25° resolution with 32 vertical levels. ModelE2-R includes stratospheric dynamics and prescribed ozone and aerosol species.

Due to uncertainties in past radiative forcing, a suite of LM simulations using ModelE2-R have been run with different combinations of plausible solar, volcanic, and anthropogenic land use histories (Schmidt et al., 2011, 2012) but with identical greenhouse gas and orbital evolution. These simulations span the period 850-2005 C.E. There are two reconstructions of past volcanic activity (Gao et al., 2008; Crowley and Unterman, 2013) that are used in six combinations of the ModelE2 simulations (see the 'past1000' experimental design at http://data.giss.nasa.gov/modelE/ar5/). We focus only on results from the Crowley reconstruction prior to 1850 CE due to a mis-scaling of the Gao forcing in the model that roughly doubled the appropriate radiative forcing. For the historical period (1850-present), the volcanic forcing history is based on Sato et al. (1993) and is equivalent among the different simulation members.

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For the LM, three forcing combinations are available in the GISS ModelE2-R simulations that use the Crowley reconstruction for volcanic perturbations. These include

Pongratz et al. (2008) [land]/ Krivova et al. (2007) [solar], Kaplan et al (2010) [land]/Krivova et al. (2007) [solar], and Pongratz et al. (2008) [land]/Steinhilber et al. (2009) [solar] (see Schmidt et al., 2011, 2012).

Water isotope tracers are incorporated into the model's atmosphere, land surface, sea ice, and ocean. These isotopes are advected and tracked through every stage of the hydrologic cycle. At each phase change (including precipitation, evaporation, ice formation or melting) an appropriate fractionation factor is applied (Schmidt et al., 2005) and all freshwater fluxes are tagged isotopically. Stable isotope results from the lineage of GISS models have a long history of being tested against observations and proxy records (e.g., Schmidt et al., 2007; LeGrande and Schmidt, 2008, 2009; Lewis et al., 2010, 2013, 2014; Field et al., 2014).

Crowley and Unterman (2013) discuss the details behind the LM Aerosol Optical Depth (AOD) reconstruction that defines the volcanic forcing time-series in ModelE2-R (Figure 1). This estimate is derived from sulfate peaks in ice cores, which are relatively well dated and referenced to the historical record during the satellite era. Crowley and Unterman (2013) provide an AOD history over 4 latitude bands (from 0-30° and 30-90° in both hemispheres). ModelE2-R uses a cubic spline to interpolate this forcing dataset over 24 latitude bands. The choice of volcanic eruptions used for the LM analysis (section 2.2 below) is based on the AOD dataset from this 24-latitude grid.

In addition to the model, we briefly explore post-L20 eruption results in the instrumental record. To do this, we take advantage of the NASA GISS Surface Temperature analysis (GISTEMP) land-ocean index (Hansen et al., 1999), and Global Precipitation Climatology Centre (GPCC) v6, a monthly precipitation dataset over land

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(Schneider et al., 2011). For figures 2 and 3 where ocean climatological data is shown, we use the Global Precipitation Climatology Project (GPCP) version 2.2 (Adler et al., 2003), a combined land station and satellite product since 1979. These datasets are called upon to gauge the tropical climate response following the three L20 eruptions. We use the 2.5° resolution GPCC dataset, as that is comparable to the GISS model and what is justified by the station coverage in this part of the world. The GPCC product offers considerably better global and South American coverage than other precipitation datasets, although observational density for rainfall is still considerably more problematic over South America than for many other regions of the globe. There is a sharp drop-off in the number of rain gauge stations used earlier in the 20th century over much of the South American continent. Figure S1 shows the station density at the time of each L20 eruption as well as the total number of land stations over South America with time.

Finally, in section 3.1 we present data from the Global Network of Isotopes in Precipitation (GNIP) accessible from the International Atomic Energy Agency (IAEA) for $\delta^{18}O_p$ as a test of the model's ability to track the seasonal hydrologic cycle in the form of its isotopic response over South America before discussing the Last Millennium results. Unfortunately, there is considerable spatial and temporal heterogeneity in the GNIP data over South America. In fact, only a few stations have data overlap with one or two eruptions and with a sufficient number of $\delta^{18}O_p$ data points to establish reasonable seasonal or annual statistics. Additionally, the post-volcanic (L20) anomalous isotope field over South America strongly resembles the ENSO expression on the isotope field (Vuille et al., 2003a) and with large spread between events (not shown. This suggests that internal variability (ENSO) dominates the forced (volcanic) response in this very small

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historical sample size, thereby leaving little hope that the prevailing network of observations is suitable for hypothesis testing and model validation in our context.

2.2 Super-posed Epoch and Composite Analysis

We present the spatial pattern of observed and simulated response for temperature and precipitation over land for two L20 eruptions (El *Chichón* and Mt. Pinatubo). Results are shown for annual-means in 1983 and 1992. We choose only two for brevity, as our argument that model validation for any specific region is difficult in a small sample of eruptions is unaffected. Because of the dominant influence of unforced variability on tropical South American climate (Garreaud et al., 2009) overriding the volcanic signal during the L20 eruptions, we instead present a superposed epoch anomaly composite of the tropical-mean temperature anomaly zonally averaged from 30°S to 30°N. Results are shown for years -3 to +5, with zero defining the eruption. This composite is formed for all three L20 eruptions. In all cases, the five years prior to the eruption were subtracted from the superposed composite. Other sensible choices for the non-eruption reference period do not significantly change the results.

For the full LM spatial composites, we use only eruptions where vertically integrated (15 to 35 km) stratospheric AOD averaged from 30°N to 30°S exceeds 0.1 for at least 12 consecutive months in the simulation (top panel in Figure 1). For the LM composites, we focus only on seasonal (DJF and JJA) composites, and a given season will enter the composite if at least 2/3 months meet the AOD threshold; this criterion yields 15 eruptions since 850 C.E. The selection of events used in the LM composite is

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very weakly sensitive to this choice of latitude band. Mt. Pinatubo is the only L20 eruption in this composite, and is actually the smallest eruption in this selection based on the maximum AOD encountered near the time of the eruption (see Table 1 for dates of each event). We believe sampling a larger number of events with greater forcing is a better way to understand the volcanic response in this model, rather than increasing the ensemble size for the L20 events. We do stress, however, that there is considerable forcing uncertainty during the LM and so the model results ought to be viewed as a slave to the imposed AOD and particle size distribution.

For the LM "non-eruption" fields, we use 15 years prior to the eruption as a reference period to calculate the anomaly for each event, unless another event occurs during that time (overlap occurs only once for eruptions in 1809 and 1815) in which case the pre-1809 climatology is used twice. The exception is for Mt. Pinatubo, which again uses the previous five years to calculate the anomaly. When constructing seasonal averages of $\delta^{18}O_p$, the oxygen isotope value for each month is weighted by the precipitation amount during that month, at each grid cell.

Since each post-eruption difference field is computed using the immediate response minus a local 15-year climatology, time is not relevant in this analysis and so we use all three ensemble members with the Crowley forcing (representing over 3,000 years of simulation time) to generate a composite that features 45 volcanic "events" (15 eruptions in each of the three members). In the historical (post-1850) extension of these runs, the coding error that resulted in a mis-implementation of the Gao forcing is not an issue, and so we use six ensemble members each (three volcanic events in six ensemble members) for the L20 results.

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$$\Delta\delta^{18}O_p = \left[\frac{\sum_{j=1}^{3}\delta^{18}O_{j,volc}P_{j,volc}}{\sum_{j=1}^{3}P_{j,volc}}\right] - \left[\frac{\sum_{j=1}^{3}\delta^{18}}{}\right.$$

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The ensemble-mean composite results displayed for the LM eruptions include contributions from three members that differ not just in the internal variability, but also in their solar and land-use forcing. Similarly, the L20 results are from model runs that also include other transient historical forcings occurring at the time of the eruption, including greenhouse gas increases throughout the duration of the event (although these forcings are the same among all ensemble members). However, in all cases we focus only on the immediate years after the eruption. Since the primary signal of interests is expected to be large compared to the impact of more slowly varying and smaller-amplitude forcings, the ensemble spread for a given eruption can be interpreted as a sampling of the model internal variability coincident with the event. We have tested our composite results using the same dates as our volcanic events in simulations with other varying forcings but with no volcanoes (there are no volcano-only runs with this model version for the LM), and the results are indistinguishable from noise (not shown). The LM composite results are discussed in section 3.2.

Finally, it is now well appreciated that any climate response under investigation will be shackled to the spatial structure of the forcing imposed on a model. For example, preferential heating/cooling of one hemisphere will induce different tropical precipitation responses than a well-mixed gas that behaves CO_2-like (**Kang et al., 2008, 2009; Frierson and Hwang, 2012; Haywood et al., 2012). Figures S2 and S3 show the latitudinal AOD distribution** structure for all eruptions used in the generation of the LM composites within ModelE2-R. The mean of all events is rather symmetric between hemispheres (though somewhat skewed toward the Southern Hemisphere tropics, which is linked to the selection criteria), and similar to the pattern expected with CO_2 change,

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the forcing is largest in the tropics. Thus, the resulting climate responses outlined in this paper ought to be viewed as a response consistent with a forcing that is relatively symmetric about the equator. Results from volcanic eruptions with emphasis on the spatial structure of forcing will be reported in a separate paper.

2.3. Influence of ENSO on the Late 20th Century (L20) eruptions

For the L20 volcanic events, El *Niño* events are occurring quasi-simultaneously with the eruption. This introduces a pervasive issue when attempting to isolate the volcanic signal (e.g., Robock, 2003; Trenberth and Dai, 2007; Joseph and Zeng, 2011) and is particularly important over South America (e.g. Garreaud et al., 2009).

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In order to remove the effects of ENSO from the super-posed epoch and spatial composite analyses described above in the GISTEMP and GPCC data, we first perform a multiple regression with the variable of interest over the period 1951-2005 using a linear time trend and the Niño 3 index as predictors (5°N-5°S, 150°W -90°W, data from http://www.cpc.ncep.noaa.gov/data/indices/) over the same period, excluding two years of data after each L20 eruption. At each grid cell, the Niño 3 index is lagged from 0-6 months and the correlation coefficient with the maximum absolute value (since a positive index can induce a negative anomaly in the variable of interest) is found. This is similar to the approach used in Joseph and Zeng (2011), allowing the maximum ENSO influence to be removed at each grid point at different times. The lagged Niño index is then regressed against the time series of each variable and the residual from this regression is retained. This approach assumes a linear relationship between ENSO and the climate

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response over South America, an assumption that appears justified on inter-annual to decadal time scales (Garreaud et al., 2009).

For each of the six ensemble members used in the model L20 composite, a similar procedure is performed in which the Niño 3 index *(consistent with the realization of the* Niño 3 *domain SSTs in that model simulation) is calculated and regressed out in the same manner*. For the full LM computations, the number of larger-amplitude events in the three-ensemble member composite should help average out the influence of Pacific SST variability, and no ENSO removal procedure is applied.

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3. Results and Discussion

3.1. L20

Figure 3 illustrates that ModelE2-R reproduces the seasonal cycle of climatological rainfall (comparing Figure 3a with 3b) and oxygen isotope distribution (comparing Figure 3c with 3d) with some fidelity over South America. This includes a meridional migration of the ITCZ toward the summer hemisphere and an intensification of the South American monsoon during DJF. Where data permit (Figure 3c) there is good agreement between model and observations, both displaying oxygen isotope DJF enrichment relative to JJA in the tropics north of the equator and the higher latitudes south of 30°S, and depletion in the continental interior south of the equator associated with the monsoon wet season. ModelE2-R (Figure 3b) tends to produce too much precipitation over northeastern Brazil although the gross features of the seasonal migration in rainfall are well captured. This ability to accurately simulate the seasonality of $\delta^{18}O_p$ over the tropical Americas has also been noted in two atmospheric GCMs with no coupled ocean (NASA-GISS II and ECHAM-4, see Vuille et al., 2003).

Figure 4 shows the ENSO-removed super-posed epoch analysis for tropical temperature associated with the recent three L20 eruptions. There is good agreement between the observed and modeled temperature response, both in amplitude and recovery timescale. The tropical-mean cooling is on the order of several tenths of a degree, and larger after Mt .Pinatuno (not shown individually).

The spatial structure of the post- El *Chichón and Pinatubo* events in land observations and the individual model realizations are shown in Figures 5 and 6, respectively. Observations exhibit cooling over much of the globe, especially after Mt. Pinatubo that is largely reproduced by the model. However, there is considerable spread among the individual ensemble members and between the two events, indicating a large role for internal variability in dictating the observed spatial pattern following these events. This is also true over South America.

In GISTEMP, the high-latitudes of South America cool more than the tropical region of the continent after Mt. Pinatubo. *There* is still a residual signal from ENSO in tropical South America following both L20 eruptions that *is not reproduced by the model. This is not unexpected, since ENSO events comparable to the magnitude of the historic realizations due not occur coincident with the volcanic forcing in the individual ensemble members. The magnitude of this signal is sensitive to the* Niño index used in the regression method described above. Without ENSO removal, tropical South America

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warms following the two eruptions *(not shown). The influence of ENSO appears minimal over the higher latitude sectors of the continent.*

The precipitation pattern following the L20 eruptions exhibits substantial variability in space and across eruptions, with a general drying pattern over land in tropical latitudes. South America experiences less precipitation near the equator after Mt. Pinatubo (see also Trenberth and Dai, 2007), a pattern reproduced in some of the ensemble realizations.

It should be noted that model-observation comparison is hindered not just by internal variability, but also by the specified historical volcanic forcing in the model. In fact, the Stratospheric Aerosol and Gas Experiment (or SAGE) II satellite sensor was saturated by the aerosol cloud after Mt. Pinatubo; subsequent work (Santer et al., 2014; Schmidt et al., 2014c) suggests that the forcing following Pinatubo is too large in the CMIP5 generation of models. It is likely that CMIP6/PMIP4 will feature a reduced AOD and different particle size.

Because of the considerable variability seen in observations (following historical eruptions) and also across ensemble members, it is evident that a larger signal-to-noise ratio than is available from the L20 eruptions alone is required to help isolate any volcanic signal. ModelE2-R is the laboratory from which we proceed to sample a larger number of events, some of which contain larger amplitude than the L20 eruptions.

3.2. Last Millennium Composites

3.2.1. Temperature and Precipitation

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Figure 7 shows the LM post-volcanic temperature composite for all 45 events. During both seasons, cooling is statistically significant over virtually the entire continent (stippling indicates significance at the 90% level using a two-sided student t-test). The temperature response is strongest in the interior of the continent, particularly during the austral winter. The enhanced high-latitude cooling exhibited in the observations after Mt. Pinatubo does not emerge in the model composite.

The precipitation anomalies for the LM composite are shown in Figure 8. As expected, there is a distinct seasonal structure in the response, with the largest anomaly concentrated in a narrow region north of the equator during austral winter, coincident with the location of climatological rainfall maxima in the region. During JJA, precipitation increases in the North Atlantic region, following volcanic eruptions, while very strong and statistically significant precipitation reductions occur just north of the equator (including over northern Brazil, Ecuador, Venezuela, Colombia, and Guyana) and encompassing the northern Amazon Basin. This signal is consistent with a weakening of the moisture flux owing to the decrease in saturation vapor pressure due to cooling that is demanded by Clausius-Clapeyron (Held and Soden, 2006). During this season, the precipitation response is significant virtually everywhere in northern South America. Supplementary Figure (S5) further illustrates that the JJA precipitation response is remarkably robust to all eruptions that enter into the composite.

Figure 9b illustrates the relationship between area-averaged precipitation from 20°S- 0° (DJF) and 0°-12°N (JJA) and the maximum AOD encountered for each eruption. These two regions were selected to reflect the seasonal migration of rainfall. 15

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Deleted: Figure 9b illustrates the relationship between area-averaged precipitation from 20°S- 0° (DJF) and 0° to 12°N (JJA, these different regions were selected to reflect the seasonal migration of rainfall) and the maximum AOD encountered for each eruption.

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eruptions are displayed with the three-member ensemble spread given for each. All data is zonally averaged from 75°W to 45°W. Precipitation only increases north of the equator during austral winter in a few model realizations. Moreover, the magnitude of the precipitation response during JJA scales with the size of the eruption, particularly for very large eruptions (e.g., comparing five eruptions with AOD > 0.3 vs. those with smaller perturbations, although the spread amongst the ensemble members is large). The spatial composite for each individual eruption (each averaged over the three ensemble members) is shown in Figure S5.

The precipitation response during austral summer is more difficult to interpret (Figure 8a). During this season, the zonally oriented Atlantic ITCZ migrates southward and the SACZ becomes more intense as it is connected with the area of convection over the central and southeastern part of the continent. It is noteworthy that the land cools substantially more than the surrounding ocean (Figure 7), which one could expect to weaken the monsoon-sourced precipitation during DJF. While precipitation is indeed reduced over the tropical continent, the response is weaker than in JJA and less spatially coherent, with many areas failing to meet statistical significance. An analysis of the individual responses reveals that the signal is more eruption-dependent during DJF than during JJA (see Figure S4), with a few events actually exhibiting modest increases in precipitation. Nonetheless, there is a clear tendency for reduced DJF precipitation within the SAMS region, although there is little to no dependence of the mean rainfall anomaly on the magnitude of the AOD perturbation, at least above the 0.1 threshold used in this study (Figure 9b), unlike for equatorial South America during JJA. Conversely, the temperature response (Figure 9a) depends on the size of the eruption in both seasons, as is expected.

3.2.2. Tropical Hydroclimate Response

Since the South American climate is intimately linked to large-scale tropical dynamics, the global precipitation composite is shown in Figure S6 to better inform the model response. The most robust signal is characterized by a reduction in tropically averaged precipitation and the tendency for wet regions to become drier, and dry regions to become wetter (see also Iles et al., 2013), in contrast to the anticipated hydrologic response in a future, higher-CO_2 world (Held and Soden, 2006).

This pattern is a thermodynamic effect linked to reduced moisture convergence within the convergence zones and to reduced moisture divergence in the descending zones of the Hadley cell, which reduces the contrast in values of precipitation minus evaporation (P-E) between moisture convergence and divergence regions (Chou et al., 2009). The complete hydrologic response of the ΔP-E field (not shown) has the same spatial structure as the ΔP field, since evaporation is decreasing nearly everywhere in the tropics. Because both P and E are decreasing on the equator-ward flank of the ITCZ the ΔP-E signal is rather weak in the deep tropics, while ΔP-E increases more rapidly than ΔP in the subtropics.

The tendency for modest precipitation anomalies over the continent during DJF appears to be part of a pattern that spans a broad swath of longitudes across the entire deep tropics in association with the seasonal cycle. Nonetheless, the response during DJF is weaker over land.

3.2.3. Oxygen Isotope Anomalies

In order to relate the responses discussed in the previous sections back to a potentially observable paleoclimate metric, we show the composite $\Delta\delta^{18}O_p$ field for the DJF and JJA seasons in South America (Figure 10). It should be cautioned that much of the isotopic variability that can be observed in proxies within the continental interior or high-elevation glacier sites will likely be seasonally biased toward the wet season months (Hardy et al., 2003).

During the JJA season, there is a strong enrichment of the $\delta^{18}O_p$ pattern that is zonally extended over equatorial South America. In addition, there is a corresponding $\delta^{18}O_p$ depletion in the adjacent North Atlantic sector. This response is inextricably coincident with the strong change in precipitation in the ITCZ domain that was assessed in Figure 8, and is broadly consistent with a "rainfall amount" control on the isotopic imprint (Dansgaard, 1964). South of approximately 15°S, the sign of the anomaly reverses to a depletion of the heavy isotope.

During the austral summer, volcanic eruptions lead to a clear negative excursion in $\delta^{18}O_p$ over virtually the entire SAMS region, including the Amazon basin, tropical Andes, and eastern Brazil. The statistical significance of the resulting isotopic anomaly extends throughout most of the landmass within the tropics and in the North Atlantic. There are small but non-significant exceptions (positive $\delta^{18}O_p$ excursions) such as in eastern Brazil. The negative excursions also include regions outside of the SAMS belt in the subtropics and mid-high latitudes of South America.

The austral summer $\delta^{18}O_p$ depletion is the opposite sign from what one would expect if the reduced precipitation were driving the isotopic response. Thus, it may well be that the strong temperature response to volcanic eruptions dominates the continent-wide oxygen isotope depletion during the DJF season and in the extratropics during JJA over the relatively weak precipitation response. Precipitation on the other hand appears to be the primary control knob of $\delta^{18}O_p$ during JJA within the ITCZ region.

The correlation between $\delta^{18}O_p$ and temperature or precipitation are reported in Figure 9, using the same domains for DJF and JJA described in section 3.2.1. In the case of volcanic forcing it appears that the amplitude of the temperature-response to volcanic eruptions over tropical South America is much larger than the rather weak and spatially incoherent precipitation signal. This may explain why the DJF isotopic signal related to volcanic eruptions seems to respond to atmospheric cooling, even in the tropics, where isotopic variability is usually more closely associated with changes in the hydrologic cycle. During JJA, the isotopic enrichment is much more associated with precipitation reduction north of the equator.

Taken together, these results suggest that the primary controls on oxygen isotope variability are forcing and event-dependent, rather than being determined inherently by the latitude of interest (e.g., "precipitation driven" in the tropics and "temperature driven" in the extratropics). This conclusion is compelled by the fact that the precipitation production and distribution in proxy records are the result of an interaction between multiple scales of motion in the atmosphere, the temperature of air in which the condensate was embedded, and exchange processes operating from source to sink of the parcel deposited at a site. Thus, a consistent description of how to interpret oxygen

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isotopes into a useful climate signal cannot be given without considering all of these processes and the target process of interest.

To further complement the spatial analysis, a composite Hovmöller diagram is utilized (Figure 11) in order to illustrate the time-evolution of the temperature, precipitation, and oxygen isotope response. For this plot, the start of each eruption is defined as the closest January to the first month in which AOD reaches 0.1 in order to illustrate the seasonal evolution (rather than compositing by "month from each eruption" as in Figure 3). Therefore, for all 45 events in the composite, the local AOD may reach this threshold within five months (before or after) of the January baseline point (eruptions in June are rounded up to the following January). The Hovmöller composites are plotted for ten years (beginning January three years prior to the eruption). The closest January point to the start of each eruption occurs in the 37th month of the Hovmöller (solid black line in Figure 11a,b,d). Results are zonally averaged from 75° to 45° W, across the SAMS region.

Figure 11a demonstrates a substantial temperature anomaly that peaks south of 10°S (compare also to Figure 7). The cooling lasts for several years following the eruption, and decays until much of the signal is lost (~4 years after the eruption at all latitudes). The zonally averaged peak reductions in South American precipitation anomalies occur over the tropical latitudes and last for a comparable period of time as the temperature response. The precipitation anomaly itself migrates synchronously with the seasonal cycle (red line in Figure 11c maps out the latitude of maximum climatological precipitation averaged over all 30 year climatologies of each 45-member event, as a function of time of year). Figure 11b indicates that the largest precipitation response is

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confined to the equatorial regions during JJA, and any protrusion into mid-latitudes (still equatorward of the storm track), although weaker in magnitude, only occurs during the summer.

Figure 12 provides additional statistical insight into the magnitude of the excursions described in this section. Here, we sampled 100 random 45-event composites in a control simulation with no external forcing (each "event" two seasons in length defined as an anomaly expressed relative to a surrounding climatology as done previously). The anomalies were averaged over the same areas as in Figure 9, with different domains for DJF and JJA. Notably, for both seasons and for all three variables examined, the single 45-event post-volcanic composite (purple square) lies outside the distribution of all sampled 45-event composites constructed with no external forcing. Nonetheless, the distribution for a smaller sample of events (black circles denote the data for each (15) eruptions, each averaged over the three ensemble members) shows considerable spread.

The $\delta^{18}O_p$ anomalies discussed above result from changes in the isotopic content of precipitation, which may be due to changes in precipitation amount or to other changes in the isotopic composition of the water vapor that condensed to form the precipitate. The changes are not determined by changes in the seasonality of the precipitation. To illustrate this (Figure S7), we decomposed the $\Delta\delta^{18}O_p$ field (see Liu and Battisti, 2015) by weighting the monthly oxygen isotope field by the pre-eruption precipitation values. The results are indistinguishable from the total $\Delta\delta^{18}O_p$ field, suggesting that any changes in monsoon seasonality are negligible in contributing to the isotopic signal, unlike the orbital case considered in Liu and Battisti (2015).

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4. Conclusions

In this study, we have analyzed the response of temperature, precipitation, and $\delta^{18}O_p$ over South America to volcanic forcing to many large tropical eruptions during the Last Millennium. It is now well known that volcanic eruptions lead to large-scale cooling throughout the tropics, and this result extends to most of the South American continent as well, except in regions that may be simultaneously affected by opposing ENSO behavior. In general, the precipitation response has been more enigmatic, though our results are in broad agreement with numerous other studies showing that there is a substantial decline in tropical-mean precipitation.

However, the immediate post-volcanic impact over South America has a complex seasonal and spatial structure. During the austral winter, the precipitation response over the continent is slaved to the response of the large-scale circulation, including a weakening of rainfall intensity within the ITCZ that is migrating northward. In the extratropics, the continent cools and exhibits slight precipitation declines nearly everywhere. Our results suggest the seasonal monsoon precipitation (during DJF) in ModelE2-R exhibits a fairly weak response that is scattered across the continent. It appears that volcanic forcing preconditions the tropical rainfall over the continent to decline during the wet season, but that this response is likely to be eruption-dependent and may be overwhelmed by internal variability.

A unique aspect of this study was to probe the $\delta^{18}O_p$ response to volcanic eruptions. During JJA, isotopes become heavily enriched in northern South America as

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convective activity produces substantially less precipitation. No such relation was found during the monsoon season, even within the tropics, where the large cooling appears to lead to more depleted $\delta^{18}O_p$, despite a weakened hydrologic cycle and reduced monsoon precipitation. In the extratropics, it appears that the temperature decline is driving isotopes toward more depleted values.

Unfortunately validation of our model results is hindered by the paucity of observational stable isotope data and by the coincidence of volcanic eruptions with ENSO events over the 20th century. Nonetheless our results may provide some guidance in the search of volcanic signals in high-resolution isotopic proxy data from South America. Given the importance of volcanic forcing for climate variability over the past millennium, and in particular the LIA period, which has been identified as a period of significant climatic perturbation in isotopic proxies from South America, a better understanding of the climatic response to volcanic forcing over this region is urgently needed.

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Table 1: Time of Eruptions and Global Aerosol Optical Depth (AOD) from Crowley and Unterman (2013). List of eruptions used in study.

Table 1. List of LM and L20 Eruptions

Start Date of Eruption[a]	Seasons in LM Composite		Max AOD[b]
	DJF[c]	JJA	
Jan 971	972	971-972	0.22
Jan 1193	1194	1193-1194	0.16
Jul 1228	1229-1251	1229-1230	0.38
Oct 1257	1258-1260	1258-1259	0.69
Jan 1286	1287-1288	1286-1287	0.28
Jul 1455	1456-1458	1456-1458	0.41
Jan 1600	1601	1600	0.17
Jan 1641	1642	1641-1642	0.24
May 1673	1674	1674	0.21
Apr 1694	1695-1697	1694-1696	0.24
Jan 1809	1810-1811	189-1810	0.30
May 1815	1816-1818	1815-1817	0.47
May 1835	1836	1835-1836	0.24
Jan 1883	1884	1884	0.20
Apr 1963[d]			0.11
Apr 1982[d]			0.12
Jun 1991	1992	1992	0.18

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[a]Start of Eruption dates based on when they can be identified in the Crowley /Sato time-series averaged over the latitude band from 30°S to 20°N. May be slightly different than actual eruption date.
[b]Maximum AOD over the 30°S to 20°N latitude band encountered in monthly time-series during the duration of each event.
[c]December in year prior to listed date.
[d] Mt. Agung and El Chichón included in L20 but not LM composites.

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List of Figure Captions

Figure. 1. Aerosol Optical Depth (AOD) used to force the NASA GISS ModelE2-R over the Last Millennium and (bottom) zoomed in on the period 1950-1999 (Crowley+Sato) as discussed in text. AOD is the vertically integrated (15-35 km) and latitudinal average from 30°S to 30°N. Note difference in vertical scale between graphs. Orange dashed line marks the AOD threshold for defining a LM eruption in the present study. Eruption events defined in text must sustain the threshold AOD for at least one year, so not all events above the orange dashed line are used in the composites.

Figure. 2. (Top) Observed Climatological Precipitation for DJF (shading, in mm day^{-1}). SAMS box is drawn over the domain from 75° to 45° W, 20° S to 0° and used for Figure 9 and 12. Data from the GPCP product, long-term climatological rainfall derived from years 1981 - 2010. (Bottom) As before, except for JJA. Box from 75° to 45° W, 0° to 10° N used in averaging for Figures 9 and 12.

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Deleted: Cartoon sketch of the South American climate system. SAMS box is drawn over the domain from 75° to 45° W, 20° S to 0° and used for Figure 9 and 12. Filled color indicates the ratio of precipitation that falls during the selected season to the entire year (December-November). Values for the precipitation ratio, and for the wind field (850 hPa, m/s), are averages from 48 selected 30-year climatologies during the Last Millennium simulations that surround volcanic eruption events (16 eruptions within three ensemble members) that are used for the Last Millennium composites.

Figure. 3. Seasonal cycle (DJF minus JJA) of precipitation in **a)** GPCP precipitation product, from data in Figure 2 **b)** in ModelE2-R c) $\delta^{18}O_p$ in GNIP data d) and $\delta^{18}O_p$ in ModelE2-R. GNIP data only shown for stations with at least 90 reported $\delta^{18}O_p$ values at a given station from 1960-present, in addition to at least ten data values for each month: December, January,February, June, July, and August. Stations with seasonal differences of less than +/- 1.0 per mil are also omitted in panel (c).

Figure. 4. Composite tropical (30°S to 30°N) response in (a) Temperature using El *Chichón and Mt. Pinatubo.* Fill color denotes observed monthly anomalies using (a) GISTEMP, with 24-month running average in observations (solid black), ModelE2-R ensemble mean (solid orange), and six individual ensemble members (dashed grey). Anomalies base-lined to give a mean of zero from years -5 to 0. Dashed purple lines encompass the 5-95% interval for monthly tropical-mean temperature anomalies (relative to the previous five-year mean) in the GISTEMP product from 1950-present. The calculation of this range omits data two years after the L20 and Mt. Agung eruptions. The range is not symmetric about zero due to the tropical warming trend during this interval. All data uses the ENSO-removal technique discussed in text.

Figure 5. Annual-mean Temperature change (°C, ocean masked) for each L20 eruption (labeled on plot) in GISTEMP (top row) and each ModelE2-R ensemble member, as discussed in text. All plots use ENSO-removal procedure described in text.

Figure. 6. As in Figure 5, except for Precipitation change (mm day^{-1}).

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Figure. 7. Last Millennium post-volcanic temperature composite (°C) averaged over all 45 events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text. Stippling indicates statistical significance at the 90% level.

Figure. 8. Last Millennium post-volcanic precipitation composite (mm day^{-1}) with all eruption events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text. Stippling indicates statistical significance at the 90% level.

Figure. 9. **a)** Average temperature anomaly during DJF within the SAMS region (red, 75° to 45°W, 20°S to 0°N) and equatorial South America during JJA (blue, 75° to 45°W, 0 to 10°N) plotted against the peak AOD for all 15 eruptions (each point averaged over three ensemble members with the three member spread shown as horizontal bars) and **b)** For precipitation. Dashed horizontal lines indicate the 5-95% range for each season's temperature or precipitation anomaly (relative to the previous 15 years averaged over the same domain) in the control simulation with no external forcing.

Figure. 10. Last Millennium post-volcanic oxygen isotope in precipitation ($\delta^{18}O_p$) composite (per mil) with all eruption events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text.

Figure. 11. Last Millennium Hovmöller diagram (10 years, time moving forward going

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Deleted: **a)** Average Temperature during DJF within the SAMS region (red, 75° to 45°W, 20°S to 0°N) and equatorial South America during JJA (blue, 75° to 45°W, 0 to 12°N) plotted against the peak AOD for all 16 eruptions (each point averaged over three ensemble members with the three member spread shown as horizontal bars) and **b)** For precipitation.

upward, with year number labeled next to each month) for **a)** temperature anomaly (°C) **b)** precipitation anomaly (mm day^{-1}) using procedure described in text. Solid black lines mark closest January to start of each eruption used in composite. **c)** Same as panel b, except zoomed in on 10 °S to 10 °N and over 3 years of time beginning with the January closest to each eruption. Red line in panel c shows latitude of maximum climatological precipitation as a function of time of year. All results zonally averaged in model from 76.25° to 46.75° W. **d)** Last Millennium Hovmöller diagrams for oxygen isotopes in precipitation (per mil).

Figure. 12. Frequency distribution of 100 random 45-event composites in LM control simulation of ModelE2-R (blue) for temperature (top row), precipitation (middle), and oxygen isotopes in precipitation (bottom) for DJF (left column) and JJA (right column). Results averaged over same domains as in Figure 9. Normal distribution with a mean and standard deviation equal to that of the data shown in red. Purple square shows the single 45-event composite used in this study, with the distribution of individual 15 volcanic eruptions (each averaged over three ensemble members) in black dots.

Figure. 13. a and b) Total $\Delta\delta^{18}O_p$ reproduced from Figure 10. Changes in to $\delta^{18}O_p$ due to changes in the seasonality of precipitation (Equation 2) during c) DJF and d) JJA. Changes in to $\delta^{18}O_p$ due to changes in the isotopic content of precipitation (Equation 3) during e) DJF and f) JJA.

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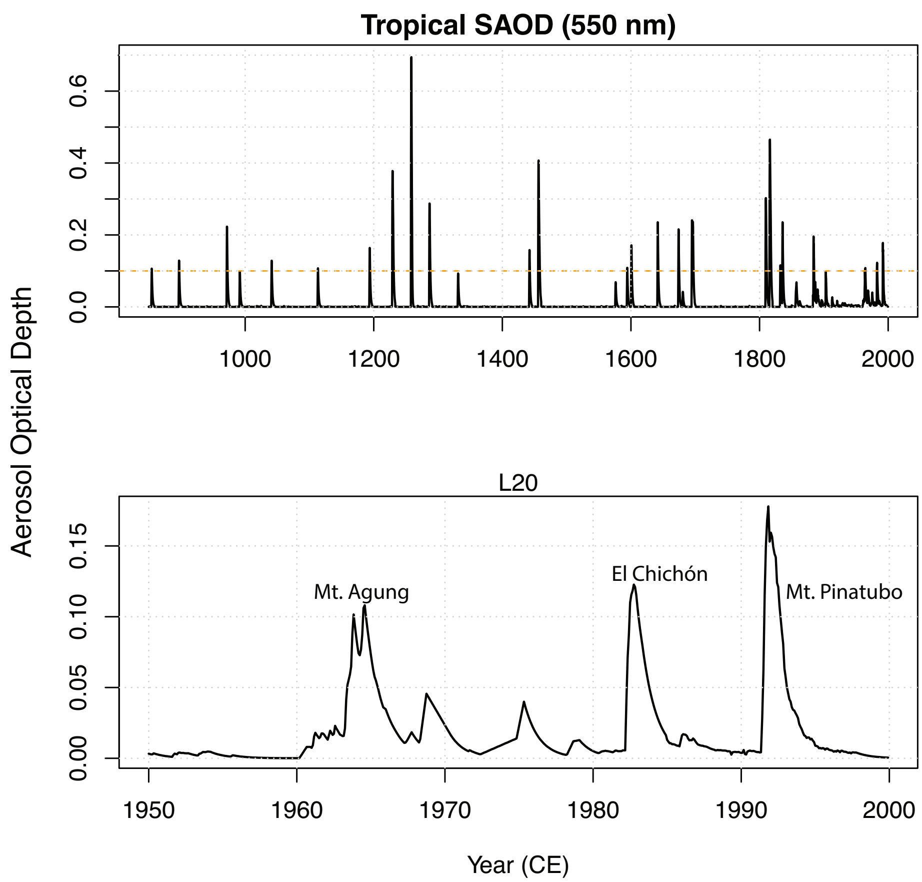

Figure. 1. Aerosol Optical Depth (AOD) used to force the NASA GISS ModelE2-R over the Last Millennium and (bottom) zoomed in on the period 1950-1999 (Crowley+Sato) as discussed in text. AOD is the vertically integrated (15-35 km) and latitudinal average from 30°S to 30°N. Note difference in vertical scale between graphs. Orange dashed line marks the AOD threshold for defining a LM eruption in the present study. Eruption events defined in text must sustain the threshold AOD for at least one year, so not all events above the orange dashed line are used in the composites.

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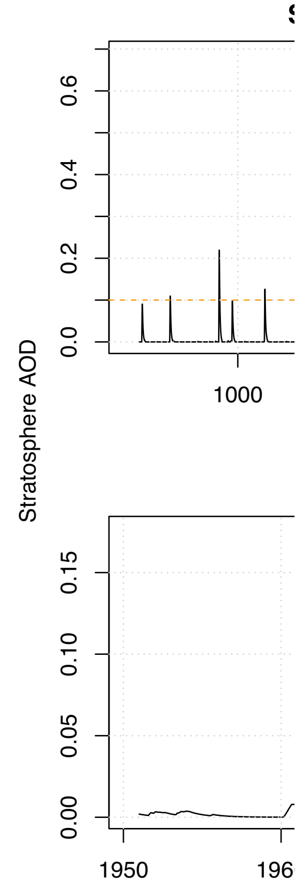

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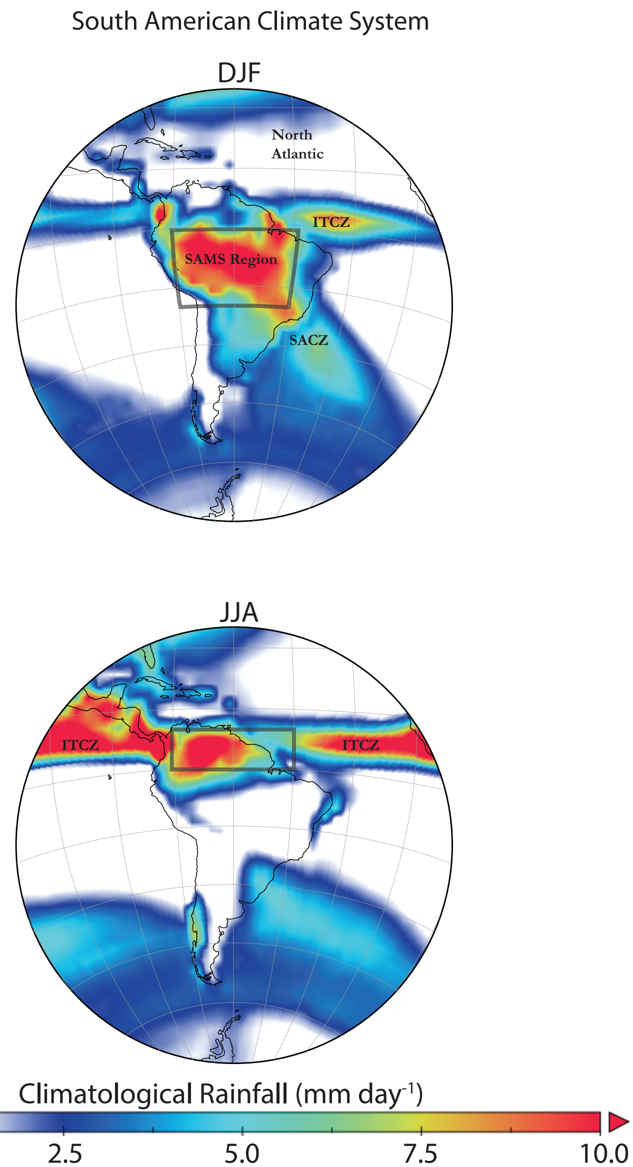

Figure. 2. (Top) Observed Climatological Precipitation for DJF (shading, in mm day^{-1}). SAMS box is drawn over the domain from 75° to 45° W, 20° S to 0° and used for Figure 9 and 12. Data from the GPCP product, long-term climatological rainfall derived from years 1981 - 2010. (Bottom) As before, except for JJA. Box from 75° to 45° W, 0° to 10° N used in averaging for Figures 9 and 12.

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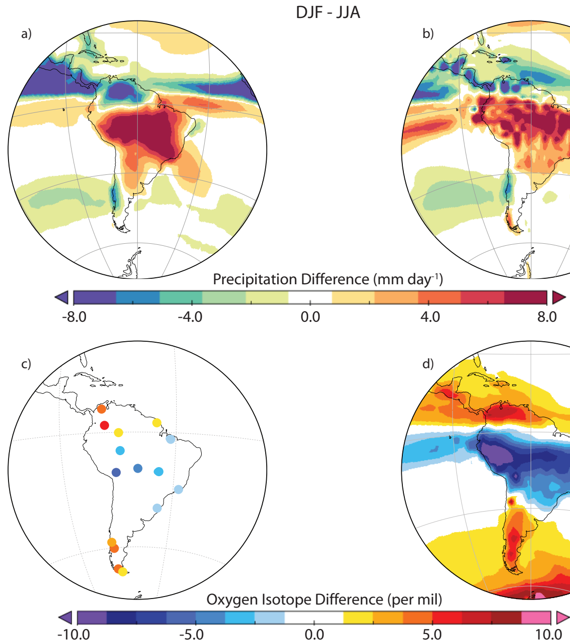

Figure. 3. Seasonal cycle (DJF minus JJA) of precipitation in **a)** GPCP precipitation product, from data in Figure 2 **b)** in ModelE2-R c) $\delta^{18}O_p$ in GNIP data d) and $\delta^{18}O_p$ in ModelE2-R. GNIP data only shown for stations with at least 90 reported $\delta^{18}O_p$ values at a given station from 1960-present, in addition to at least ten data values for each month: December, January,February, June, July, and August. Stations with seasonal differences of less than +/- 1.0 per mil are also omitted in panel (c).

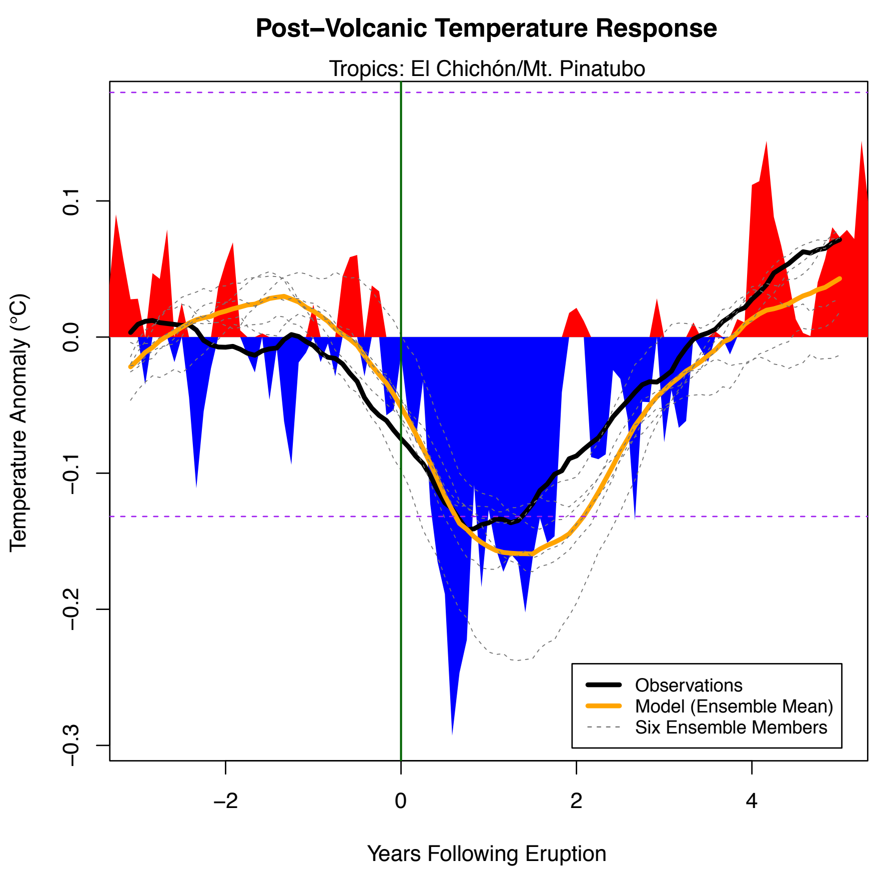

Figure. 4. Composite tropical (30°S to 30°N) response in (a) Temperature using El *Chichón and Mt. Pinatubo.* Fill color denotes monthly observed anomalies using (a) GISTEMP, with 24-month running average in observations (solid black), ModelE2-R ensemble mean (solid orange), and six individual ensemble members (dashed grey). Anomalies base-lined to give a mean of zero from years -5 to 0. Dashed purple lines encompass the 5-95% interval for monthly tropical-mean temperature anomalies (relative to the previous five-year mean) in the GISTEMP product from 1950-present. The calculation of this range omits data two years after the L20 and Mt. Agung eruptions. The range is not symmetric about zero due to the tropical warming trend during this interval. All data uses the ENSO-removal technique discussed in text.

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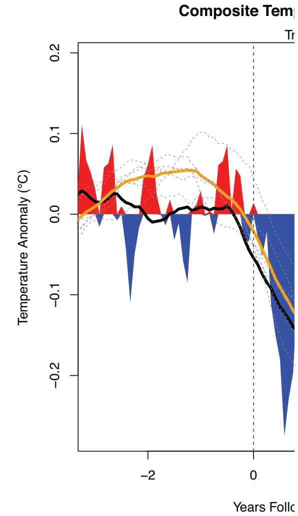

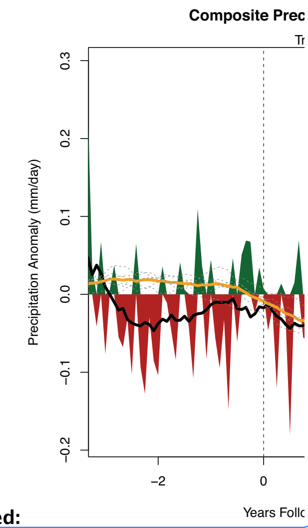

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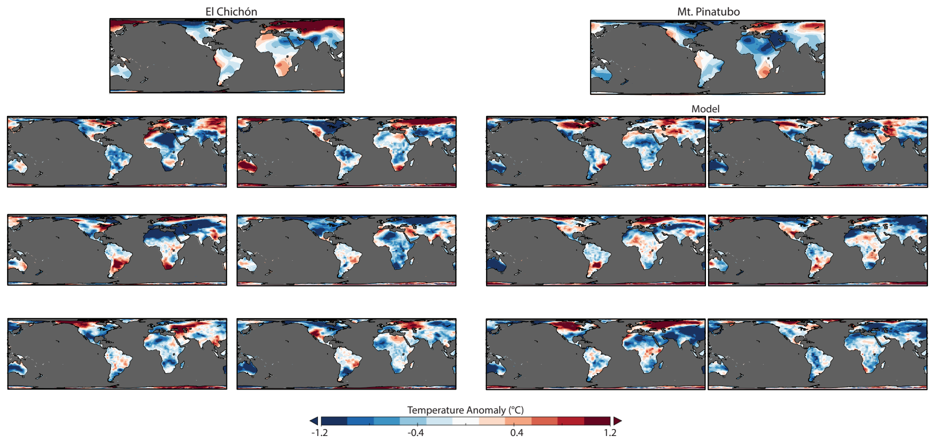

Figure. 5. Annual-mean Temperature change (°C, ocean masked) for each L20 eruption (labeled on plot) in GISTEMP (top row) and each ModelE2-R ensemble member, as discussed in text. All plots use ENSO-removal procedure described in text.

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Comment [4]: I masked out oceans to not draw un-needed focus to different "modes" (or double-ITCZ) that aren't picked up by the model . The point is the variability among events.

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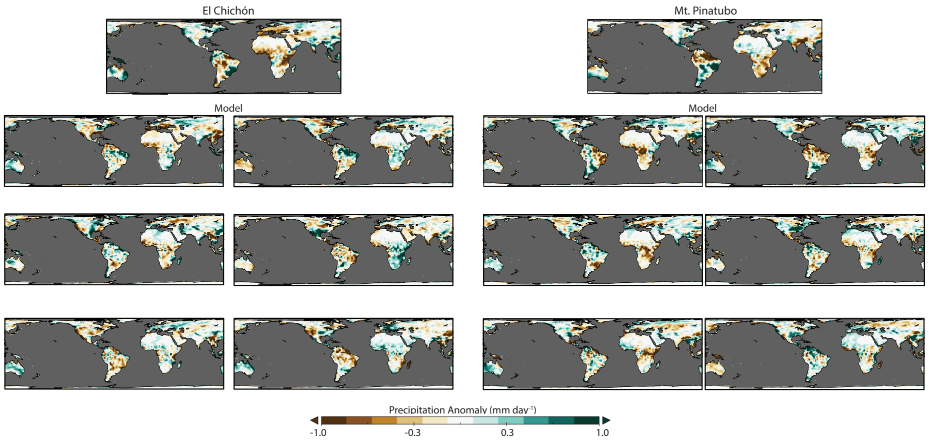

Figure. 6. As in Figure 5, except for Precipitation change (mm day^{-1}).

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Chris Colose 11/24/2015 9:06 PM
Deleted: **Figure. 6.** Seasonal cycle (DJF minus JJA) of $\delta^{18}O_p$ in **a)** GNIP and **b)** ModelE2-R (colored). Precipitation is contoured in solid at 6 mm/day and dashed at -6mm/day. GNIP data selected with a minimum of 70 reported $\delta^{18}O_p$ values at a given station from 1960-present. Model precipitation and $\delta^{18}O_p$ climatology from 1960-2005 and GPCP precipitation over the same period (1979-2005 over ocean).

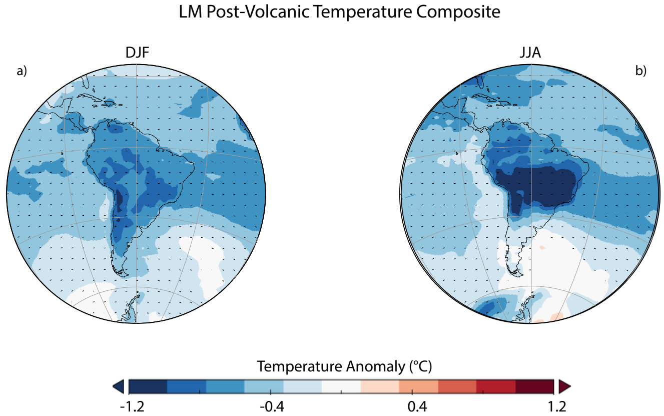

Figure. 7 Last Millennium post-volcanic temperature composite (°C) averaged over all 45 events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text. Stippling indicates statistical significance at the 90% level.

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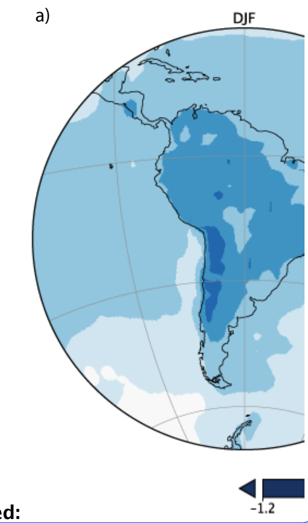

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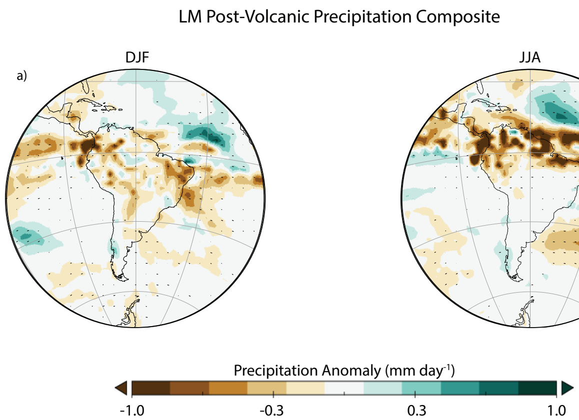

Figure. 8. Last Millennium post-volcanic precipitation composite (mm day^{-1}) with all eruption events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text. Stippling indicates statistical significance at the 90% level.

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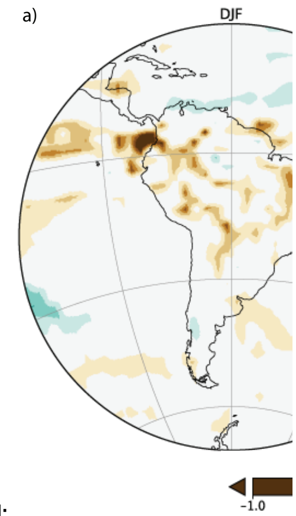

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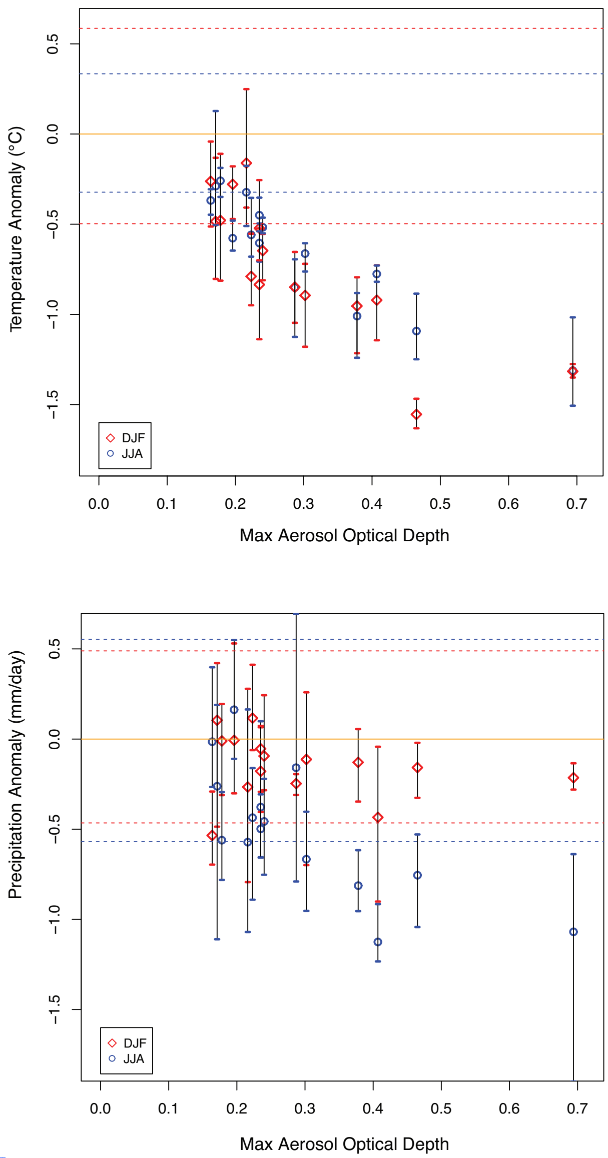

Figure. 9. **a)** Average temperature anomaly during DJF within the SAMS region (red, 75° to 45°W, 20°S to 0°N) and equatorial South America during JJA (blue, 75° to 45°W, 0 to 10°N) plotted against the peak AOD for all 15 eruptions (each point averaged over three ensemble members with the three member spread shown as horizontal bars) and **b)** For precipitation. Dashed horizontal lines indicate the 5-95% range for each season's temperature or precipitation anomaly (relative to the previous 15 years averaged over the same domain) in the control simulation with no external forcing.

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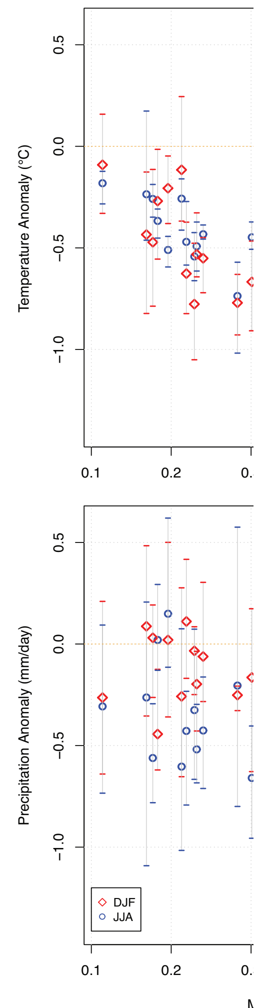

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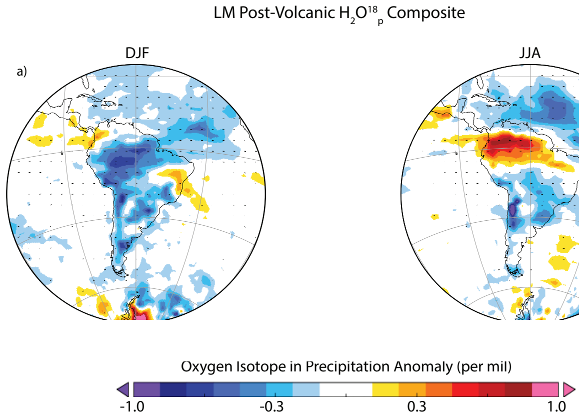

Figure. 10. Last Millennium post-volcanic oxygen isotope in precipitation ($\delta^{18}O_p$) composite (per mil) with all eruption events during **a)** DJF and **b)** JJA from GISS ModelE2-R using procedure described in text. Stippling indicates statistical significance at the 90% level.

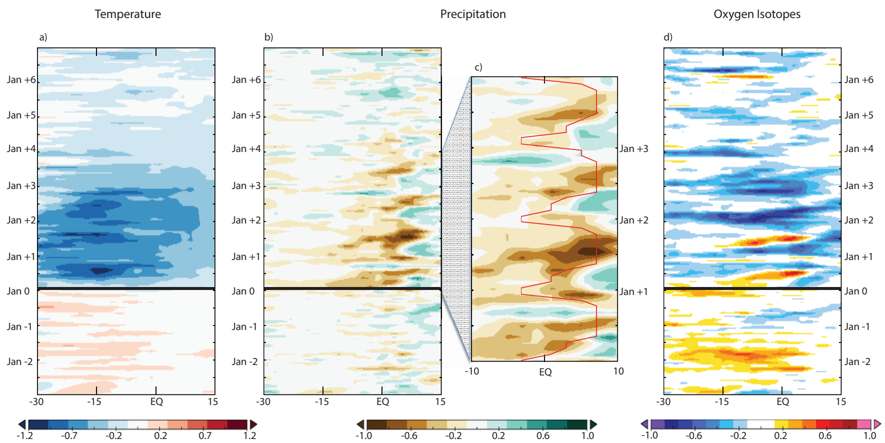

Figure. 11. Last Millennium Hovmöller diagram (10 years, time moving forward going upward, with year number labeled next to each month) for **a)** temperature anomaly (°C) **b)** precipitation anomaly (mm day^{-1}) using procedure described in text. Solid black lines mark closest January to start of each eruption used in composite. **c)** Same as panel b, except zoomed in on 10 °S to 10 °N and over 3 years of time beginning with the January closest to each eruption. Red line in panel c shows latitude of maximum climatological precipitation as a function of time of year. All results zonally averaged in model from 76.25° to 46.75° W. **d)** Last Millennium Hovmöller diagrams for oxygen isotopes in precipitation (per mil).

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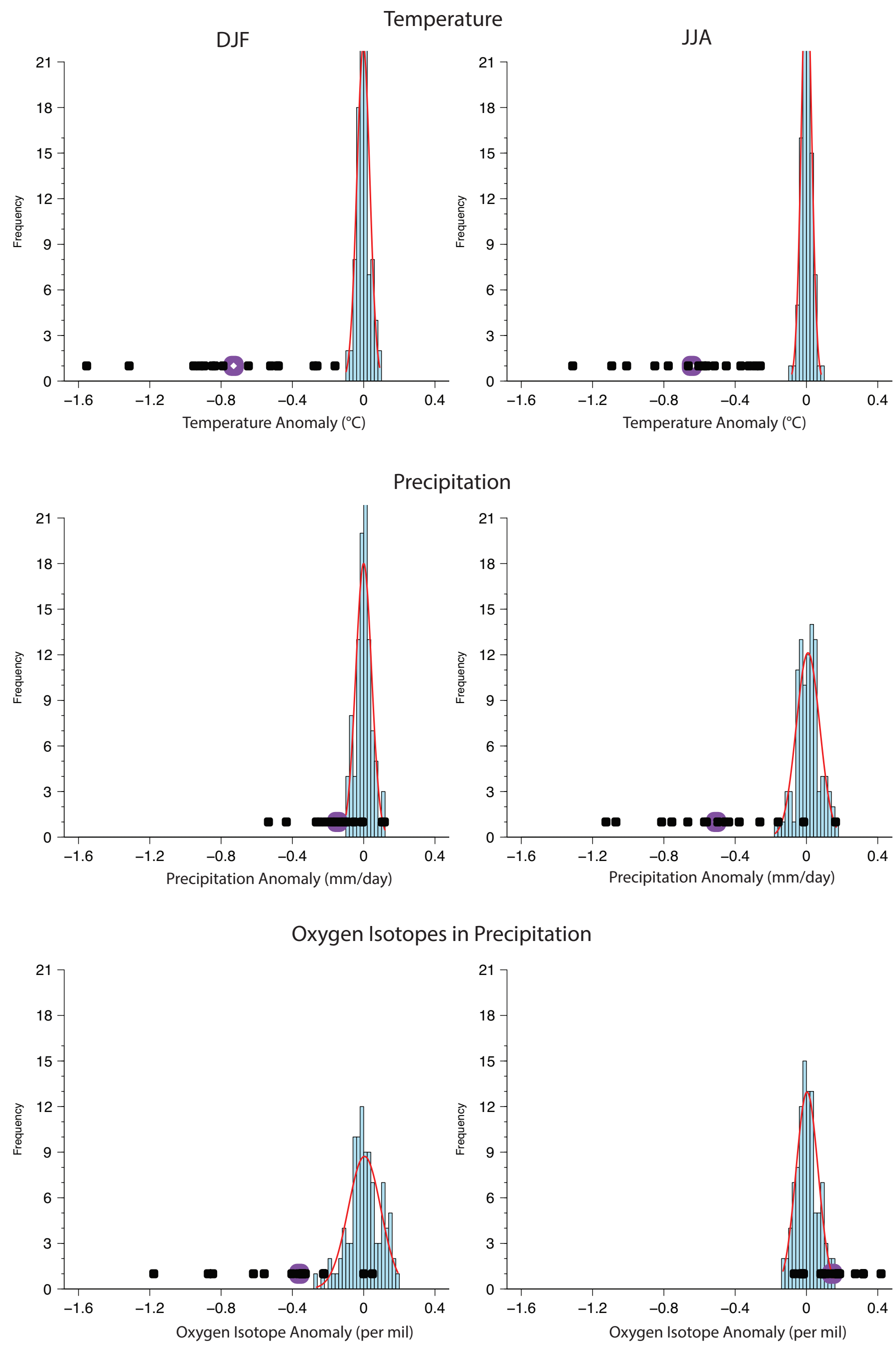

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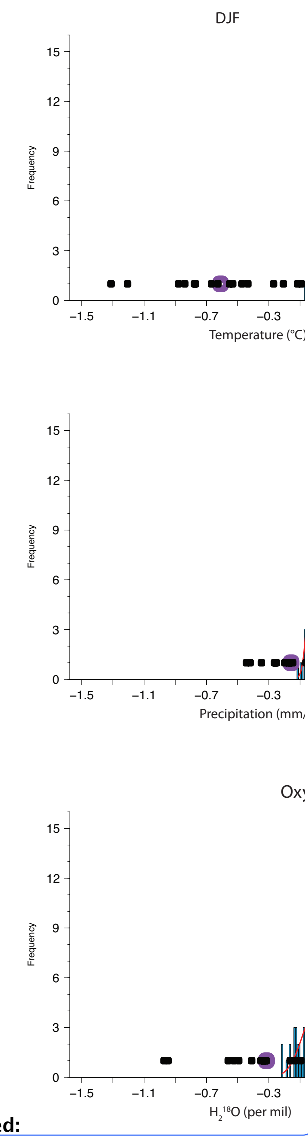

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Figure. 12. Frequency distribution of 100 random 45-event composites in LM control simulation of ModelE2-R (blue) for temperature (top row), precipitation (middle), and oxygen isotopes in precipitation (bottom) for DJF (left column) and JJA (right column). Results averaged over same domains as in Figure 9. Normal distribution with a mean and standard deviation equal to that of the data shown in red. Purple square shows the single 45-event composite used in this study, with the distribution of individual 15 volcanic eruptions (each averaged over three ensemble members) in black dots.

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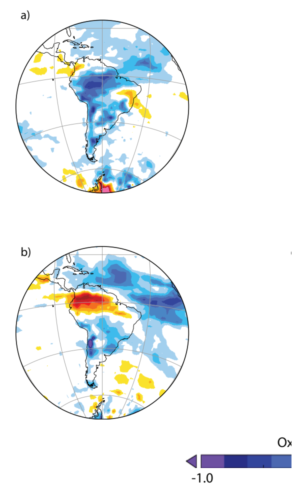

Changes in to $\delta^{18}O_p$ due to changes in the of (Equation) during) DJF and) JJA

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