Response to RC1 (1^{st} revision)

(responses in blue)

Mutz et al. look to use paleoclimate GCMs to identify drivers of past geomorphic change. This is a topic for which I hold great interest, and I feel that the authors have crafted a very useful set of model results that they leave underutilized. As such, I feel inclined to accept the paper on the basis of the useful results, but to request major revisions such that they do their own work justice.

My major concerns, which will become clear in the line-by-line comments (please feel free to respond to similar comments en masse) are as follows: 1. The paper is motivated by denudation rates and landscape evolution, but really includes this as a speculative wrapper that is not substantiated. I suggest that instead you propose testable hypotheses surrounding your findings.
2. Related to #1, much of the text is a litany of "temperature was X here ...". I find such statements of results useful only insofar as they expand upon a figure (associated with a supplementary data set) that presents the results. While these sections are written clearly, I would suggest that the authors focus on a set of geomorphic questions (if this be their motivation) and how the model-data set informs those questions.
3. Many of the discussions of model results are of ice-covered regions, yet no consideration of direct glacial erosion is given. Furthermore, no reference to the changes in the statistics of discharge or catchment area in ice-covered regions is given. This seems a disservice to this relatively high-resolution paleoclimate AGCM: the geologic setting *must* be considered, otherwise it seems that the authors' pushing on the modeling end has not been matched by a simple geological history sanity check. I would suggest that either significantly glaciated regions and the catchments that they feed be masked out, or that glacial erosion and its associated processes be included in the discussion.
4. (Discussed only here): You have not compared your models against any data. I understand that this may be simply a modeling exercise that you do compare to other models. However, I think that such a comparison could assuage skepticism about your results and lend support to your case, especially if you include it as part of a local case study (see the third point below). The core of these three points is that, with a bit more care, I think your results could say something really useful to the geomorphic community. Currently, the paper seems to be more a statement of, "this is important to geomorphology", followed by a long list of the model results. I challenge the authors to demonstrate (rather than simply stating) the importance of their work to geomorphology in a way that includes how it may impact the way scientists view Quaternary landscape evolution. Ideas include:
- Changes in means (done)
- Changes in statistical distributions of temperature and precipitation – think extreme events, frost-cracking window, etc.
- A focus on a few iconic regions while *explicitly* ignoring significantly ice-covered domains (I think this would be easiest, though obviously would be thrilled if you decided to tackle glacial processes)
- Using this focus to build a template for how to use paleoclimate GCM outputs to advance the field of geomorphology. Currently, I think that the work is acceptable following changes for internal consistency and geological accuracy (see #1 and #3), but I think that you could be selling yourselves short if you don't dig just a tiny bit deeper to investigate your forcings and their impact on geomorphology. I hope that you find these comments helpful in continuing to craft an insightful piece of work out of what seems to be a strong modeling approach.

We thank Prof. Andrew Wickert for his highly valuable review of our manuscript. Many important points were raised in the review and we hope that our appreciation for the input is sufficiently reflected in the revisions we made in response to it. We also encourage him to see our response to the second reviewer, where we provide additional geologic relevance of this study by now including a comparison of available terrestrial proxy data to our model results. We also explain throughout our response to the 2nd reviewer why an application of the predicted climate change to predict denudation rate changes is a large undertaking that can not be meaningfully conducted in this paper, but warrants more detailed applications of the models to individual areas (a topic of ongoing work/application for us). We refrain from using the model predicted runoff in the global GCM (even though it's conducted at relatively high resolution compared to previous work) to calculate changes in fluvial incision. This would be better done by mapping the predicted precipitation changes onto higher resolution (<90 m) DEMs and solving the kinematic wave equation for each fluvial erosion in each catchment, for the changes in precipitation. However, as we repeatedly mention above, this is not possible to include in this manuscript without first characterising how the precipitation has changed in each region (the current manuscript goals). Work in progress we are conducting is trying to apply the kinematic wave equation and palaeoprecipitation to selected areas, but it's proving difficult to implement meaningfully without temporally continuous (e.g. LGM to present) simulations of precipitation change. We hope this brings to the reviewers attention the complications associated with doing full erosion history calculations based on these results. We have expanded the last paragraph in the instruction to convey the above perspective better, and more clearly articulate (and justify) the scope and limitations of the manuscript.

We appreciate the importance of addressing specific sets of geomorphic questions and hypotheses (1 & 2) and we are currently taking an in-depth look at quantifying the potential for erosion by a variety of processes. These include different methods of quantifying frost cracking intensity and extreme precipitation events and how these changed over time. However, in order to include those in this manuscript, we fear that would have to seriously compromise the thoroughness with which we investigate these questions at the moment. Instead, we hope that we can convey the usefulness of our consistently set up palaeoclimate simulations as a framework for addressing any of these particular questions in detail, and have modified sections of this manuscript accordingly. This includes, but is not restricted to, extensive compilations of proxy-based precipitation reconstructions for our two larger study sites (South Asia and western South America) and comparison of this data to our model output. With this, we hope that we were also able to address the concerns raised in point 4. In order to address the important point raised about glaciated areas (3), we added an ice cover layer on all of our difference plots, included global maps of ice extent (as used for our simulations) in the supplementary material, and discussed where the large differences in temperature and precipitation we highlight in the manuscript are accompanied by changes in ice cover. Thus we hope to prevent that interpretations of the implications of our results are made without consideration of changes in ice cover (and consequently shifts in the process domain).

Line-by-line:
23. US Pacific Northwest Pacific→drop second "Pacific"
This has been corrected. Thank you for catching that.

29. future observational studies interested in quantifying→future observational studies that quantify (studies can't be interested in things, strictly speaking)
That is right of course. It has been corrected as suggested.

53. orogen scale → orogen-scale
It has been corrected as suggested.

~57. A couple of recent studies from the climate science community shed light on the impacts of the Andes (first ref below) and continents in general (second ref below). In case these are interesting to you, I'm pasting the bibliographic information here:
Maroon, E. A., D. M. W. Frierson, and D. S. Battisti (2015), The tropical precipitation response to Andes topography and ocean heat fluxes in an aquaplanet model, J. Clim., 28(1), 381–398, doi:10.1175/JCLI-D-14-00188.1.
Maroon, E. A., D. M. W. Frierson, S. M. Kang, and J. Scheff (2016), The precip itation response to an idealized subtropical continent, J. Clim., 29(12), 4543–4564, doi:10.1175/JCLI-D-15-0616.1.
Many thanks for the references. These are indeed of much interest to us and we included them in the revised manuscript.

73-75. "Furthermore, recent controversy exists concerning the spatial and temporal scales over which geologic and geochemical observations can record climate-driven changes in weathering and erosion [e.g. Whipple, 2009; von Blanckenburg et al., 2015; Braun, 2016].": I see that you do not return to this point later, so could you describe the controversy for those who are not familiar with it?
Thank you for pointing this out. We described the controversy briefly for those unfamiliar with it after the sentence quoted above.

81. I see that later you discuss a little about what an AOGCM may do, but I will be looking for justification

about how an AGCM may suffice. Is this in part because you prescribe the b.c.'s and you are running it for 17 years only? If so, could you discuss potential systematic variations between this and an AOGCM?

We prescribe sea surface temperature reconstructions (SSTs) boundary conditions, which allows us to bypass the computationally expensive coupled simulations. Because these are fixed climatologies (though with seasonality preserved), the simulation of fewer years suffices. As a consequence, however, we do not expect to see decadal scale variability as we would in case of coupled models or prescribed SSTs that vary from year to year (such as present day simulations using AMIP SST's). We discuss this in the revised manuscript.

89. "PLIO to the Last Glacial Maximum": as you include no time-slices between these, I suggest making these part of the list and dropping the "to the".

This has been corrected as suggested.

147. "This section describes the clustering method used in this study." You could drop this sentence – the section title should be enough for even an inattentive reader!

We followed this suggestion and dropped that sentence.

176-178. I was wondeirng how you picked the number of clusters: I am glad to see that you performed a thorough search.

Thank you. We added some text explaining this. We systematically increased the number of clusters from 3 to 10 and assessed the distinctiveness or similarities of resulting climate clusters. Once the increase in the number of cluster no longer resulted in the addition of another cluster that was distinctly different from the others, we used this as a cut off point and used the cluster number of the previous iteration as the optimal cluster number.

Section 3: Much of this is information that I find better communicated through figures than with text. It is clearly written, however, and I am reluctant to suggest a rewrite for brevity in a length-unconstrained journal so long as the text can be co-located with the figure.

190-192. I see you have another "This section describes..." sentence. If this is your preferred way to write, you may keep it; here, the second sentence is not such a good topic-sentence replacement.

Thank you. We kept the sentence in this instance as it also immediately draws attention to the relevant figures, which may also serve in addressing the previous point you raised.

197-198. i.e. over the ice sheets. (This applies to other regions as well, and should be important to point out if you are going to then discuss fluvial processes in orogens)

Many thanks for pointing this out. We are more mindful of this in the revised discussion.

203-paragraph: Also because of local ice loss, presumably. So I think that the two prior paragraphs could have a new summary that "The greatest changes in temperature is observed where the greatest change in local ice extent occurs."

Thank you. We followed your suggestion.

214-215. Have you considered discussions of the African Humid Period?

We had not considered discussion of precipitation changes in North Africa, since it lies outside the regions we focus on. However, we appreciate that Holocene precipitation changes in the region are important and may be of interest to many readers. We therefore included a short discussion of Holocene precipitation changes in Northern Africa in the revised manuscript.

373-374. If you are looking at the influence of temperature and precipitation on erosion, and you are not including subglacial erosion, then your preceding text must indicate where your changes really are indicative of ice extent – both as a separate process domain and as a driver of fluvial processes and potential changes in the statistics of river discharge.

Thank you. We are more mindful of this in our discussion.

Section 4.1. Your first paragraph (weathering) differs from the content (comparing your model results with those published). These should be in different subsections, and the weathering paragraph may need to be expanded. Your "weathering and erosion" paragraph also neglects direct effects of glaciers, ice caps, and ice sheets, which were globallly significant.

Thank you for this suggestion. We re-structured this section as suggested and took ice extent into consideration in the erosion section.

Section 4.2. Once again, your discussion is often of formerly (or currently) ice-covered regions without explicitly acknowledging that this is a different process domain. In addition, as with the previous section, the body paragraphs are mostly about model comparison and regional changes with sparse link to the landscape-evolution factors indicated in the topic paragraph.
As above, we restructured this section, took ice extent into account and chose a more fitting section title.

416-423. Please discuss the direct influence of glaciers on the erosion orogens in the context of changing precipitation (and therefore mass balance). Is it significant or not?
Although it is challenging to sufficiently quantify changes in glacier-related erosion due to differences in precipitation, we now include this point in our discussion.

433-434. "Coastal North America"? Doesn't look like it: seems to be most of NA south of the ice margin.
That is correct. We revised our descriptions accordingly.

Section 4.3. The authors describe the results here, but I find the connection to erosion rates to be insufficiently described compared to how they are highlighted in the topic sentence, as well as in the abstract. I would like you to go one step beyond "ought to be considered" and actually posit how you expect the erosion rates – and therefore, the balance between erosion and exhumation and perhaps the equilibrium shapes of the mountains and their rivers – to vary. Otherwise, you are suggesting future work rather than actually describing the possible geomorphic significance – and I think underutilizing your results in a paper that is clearly targeted towards geomorphologists.
As described in our response above, we believe that trying to address specific problems such as these or quantifying how differences would be expressed as erosion rates would be beyond the scope of this manuscript and come at the cost of not being able to address these as thoroughly as we are currently attempting in other ongoing work.

498. "which may favour frost driven weathering during glacial climate states" – the St. Elias range was covered by glaciers! Yes, there can be some frost-cracking around the ice, but don't you think this is important too? http://instaar.colorado.edu/groups/QGISL/ak_paleoglacier_atlas/gallery/index.html
Thank you for drawing our attention to this. We consider this in our discussion now and revised the manuscript accordingly.

508. "enhanced sediment production driven by frost processes" – same as above. Glaciers were there. Consider them.
As for the comment above, we also considered glaciers here in the revised manuscript.

Conclusions: Comparison to other models: is this match surprising or no? Did you (mostly) use the same inputs and simply increase the grid resolution? If so, could you comment on how the improved grid and possible variations in inputs and use of them ocean as a boundary condition may have affected (or not) your results as compared to those of earlier studies? This would be more useful to include in the discussion than a simple list of "Our temperature in place Y was T0 , and X et al. wrote that they found it was T1 , which is close to T0 . Think big-picture, in both process and numerics!
Due to model-specific parameterisation, deviation is possible. In the revised manuscript, we comment on this as well as on the model resolution and implications of using ocean as boundary conditions instead of an ocean model.

533. Did your 8-10 degC changes occur significantly over areas that would be affected by hillslope or fluvial processes? (i.e. unglaciated areas?)
Some unglaciated areas experience large differences in temperature, but the maxima of 8-10 degC geographically coincide with ice cover changes. We acknowledge and discuss this in the revised manuscript.

Response to RC2 (1st revision)

(responses in blue)

The authors simulate the pre-industrial, mid-Holocene, LGM, and Pliocene climates using the ECHAM5 general circulation model. The motivation is to understand how past climatic states may change regional climatologies, particularly over mountainous areas that have been the focus of much erosion and geomorphic work. The authors find that past climatic states (particularly the LGM and Pliocene) do produce changes in absolute temperature and precipitation and in the annual ranges of these two climatic variables. Overall, I did not find the manuscript to be a particularly useful addition to the literature. Though the motivation is potentially novel, the analysis is not complete and needs substantially more work. Most of the manuscript focuses on simply describing climatic changes, while neglecting novel analyses. Consequently, at this point, I recommend reject, though perhaps with substantial work (including more modeling, comparison with existing models, and/or comparison with data), it may become publishable in the future in Esurf.

We thank the reviewer for their constructive feedback on our manuscript. We found the reviewer's comment very useful in the improvement of this manuscript and hope that the modifications we made do the reviewer's thorough review justice. Most importantly, we followed the reviewer's suggestion to deepen the comparison of our model simulation results with data, specifically proxy-based reconstructions, as we believe this suggestion is of most relevance to the earth surface science community targeted by ESurf. While it was not possible to create a complete overview of all proxy-based studies everywhere and for all time periods, we included an extensive compilation of site specific reconstructions of precipitation for our largest areas (South America and Tibet). In prioritizing the compilation of precipitation reconstructions, we also hope to address the reviewer's concerns about the GCM's performance regarding this variable, and are happy to report that the model shows satisfactory to good performance in predicting the direction of changes in MH and LGM.

First, the authors need to decide what the point of the paper is. Most of the paper reads as a description of climatological changes for 3 periods in the geologic past (MH, LGM, and Plio) (indeed, most of the text is written this way). However, this work has already been done, most prominently by the PMIP and PlioMIP set of model intercomparisons. What does this manuscript offer that these model intercomparisons have not already analyzed? A case could be made that these model intercomparisons are typically of a global nature (though there has been some work on changes in the Asian Monsoon systems using both PlioMIP and PMIP results (Jiang et al., 2013; Jiang and Lang,2010; Zhang et al., 2013)), so that the analysis of the orogens in this study is useful. However, given that GCMs have difficulty simulating precipitation and in particular simulating precipitation over complex topography, the usefulness of simply describing changes over the Himalaya, Andes, Cascades, and St. Elias ranges is somewhat muted. For example, why should readers believe that ECHAM5 produces reasonable results over the St. Elias range? Why not use (or at least compare with) the exist- ing model intercomparisons to look at changes in these locations? Most of the PlioMIP simulations are of a lower resolution than the model simulations presented here, though not all (Haywood et al., 2013). Many of the newer PlioMIP2 simulations are being run at a higher resolution and permit at least some comparison with the data here (Chandan and Peltier, 2017). Having myself tried to access PlioMIP data, I understand that it can be difficult to get access to the PlioMIP output, but if the point of the paper is to quantify actual climatological change, then comparison with other models is a must (or at least a thorough treatment of possible boundary condition uncertainties and additional ECHAM5 model runs to establish the sensitivity of precipitation/temperature in these areas); otherwise, we have no reason to believe that ECHAM5 presents anything resembling a proper picture of climatic change in the past.

Summary Response: We appreciate this assessment and hope to have enhanced the usefulness of the manuscript with modifications we've made throughout the results and discussion sections. While GCM simulations for the time slices we chose already exist and individual studies were also conducted at a relatively high resolution, we believe (contrary to the reviewer's suggestion) that the usefulness of our results lies in both the high resolution combined with the consistency in model choice, resolution, output frequency (and methods of descriptive statistics). We emphasise this point in the revised manuscript. We acknowledge in the text (methods section 2.1 and introduction) the shortcomings of GCMs in predicting orographic precipitation in the discussion and in the revised text now compare the simulated precipitation with readily available proxy-based reconstructions for specific locations in Tibet and South America where we were able to compile data (this was a large undertaking). The revised manuscript now demonstrates the shortcomings of GCMs and provides an additional data compilation that ESurf readers interested in palaeoclimate effects on denudation may find useful. The changes we have made to address this reviewers suggestions are contained in the revised introduction, and extensively throughout the Discussion section (4.0), as well as the addition of two new (concluding figures).

In More Detail: While we appreciated the reviewer's comments, we note that what he/she is asking for in the above comments is a manuscript that either focuses on an inter-model comparisons, or a comparison to proxy data. We see merits in both, but both are not possible in a single manuscript. An inter-model comparison is not really well suited to the aims of this journal and our target community to bring attention to the magnitude of palaeoclimate changes that have occurred in different active orogens. Our intended audience is not the palaeoclimate modelling community (and journals associated with it), but rather the surface processes community. We specifically chose this journal to provide this community with palaeoclimate predictions that may be of interest to them. In our own experience in trying to interpret palaeodenudation rates from data we produce, our first goal is always trying to find predictions or observations of climate change for a region. Thus, we set out to write this paper to provide what we find in our research as the first, most useful, step in understanding the surface process history of a region. Furthermore, one major aspect of this study that we want to retain is the statistical analysis of the climatology of each time slice as this is what is most useful for the ESurf community in terms of knowing if a region they are working is has experienced a signal change in climate through time.

Thus, we are left with the conundrum that what the review requests and we want would normally be three full manuscripts that include: 1) a statistical analysis of climatological changes over active orogens (our previous focus of the text), or 2) a comparison of a suite of similarly set up and common code (ECHAM5) simulations of palaeoclimate time slices to other GCM models (one of the suggestions by this reviewer), or 3) a model-data comparisons for model evaluation at the time slices investigated (also suggested by this reviewer).

In an attempt to hopefully reach a compromise with this reviewer – the revised manuscript is now structured around points 1 and 3 above (statistical analysis of climatological changes, and model-data comparison where possible). These changes have been manifested in a now expanded discussion section, and through the addition of model-data comparison figures at the end of the text (see section 4.1.2 , 4.2.2, and 4.4). These changes hopefully reach a happy middle-ground between our aims and the reviewer's suggestions. The changes have significantly expanded the manuscript, and we hope that the reviewer also recognizes that implementation of all the suggested changes is not possible within a single manuscript of typical length for this journal. The revised manuscript now has 18 figures (including 1 in the supplemental section) and 21 pages of manuscript text (not including references / captions).

Some parts of the paper address actual causes for climatic change (for example, discussion of the Pacific North American Teleconnection (no citation given). Is this related to the PDO? Lines 493-495). Again, if this is the primary point of the paper, then substantially more work needs to be done to address why precipitation, for example, increases in the Himalaya in the Pliocene. If this was the point of the paper, it would obviate the need to compare with other model simulations (see paragraph above), but would then require substantially more work to identify how various atmospheric phenomenon change through time. A generalized description of changes in the past is not particularly useful (most of this information can be communicated fairly effectively with figures), so addressing the causes of these changes (or comparison with proxiesâA˘T˘ see below) is worthwhile.

Parts of the discussion showcase comparisons with terrestrial proxy data, though this is limited to citing previous work and stating that there is general agreement with previous, proxy-model work. If a proxy-model comparison is the point of the paper, then more work needs to be done actually compiling the proxies and doing a proper statistical test to see if there is agreement between modelled precip/temperature changes in each of these orogens and existing data. This would be a useful contribution to the literature, but, again, would require substantially more work.

We address the suggestions in the previous 2 paragraphs in the following ways: **First,** as was mentioned earlier, we maintain that for this journal and the community that reads it there is value in demonstrating climate change events in commonly studied active orogens where denudation studies (sensitive to climate change) are conducted. This requires that we maintain our current statistical characterisations of the climate change. With this approach, it then becomes intractable to focus on the climate dynamics associated with change in each region because typically a thorough investigation of the climate dynamics associate with change in each region could be a paper for each region in itself, and the broader picture of change in a range would be missed. We try to meet the reviewer half way in this suggestion by including additonal comments on possible causes for climatic change in different regions.

The PNA (citation now included) is related to the PDO, and Alaskan precipitation and temperature is to some degree controlled by it. In order to properly address these questions, however, further analyses looking at dominant atmospheric variability modes, trajectories and other aspects of atmosphere would have to be carried out, which are beyond the scope of this study. We have modified the manuscript in text at the end of section 2.1 to clarify (and justify) why we do not conduct an inter model comparison, as well as some of the caveats associated with our approach.

However, (**second**), we like the reviewer's suggestions of adding additional comparisons to proxy data, and we heavily invested time in compiling this information in this revised version for locations where spatially distributed data are available for the time slices available.
Unfortunately, changes from proxy studies are often reported in terms of relative changes compared to modern (e.g., wetter/drier, warmer/colder) and are sometimes contradictory for the same location, making the application of otherwise suitable statistical tests (e.g. t-test and even non-parametric tests) difficult. There are, in some cases (see final figures in paper), even contradictions between the proxy data themselves in neighbouring locations, a reality often underappreciated by the surface processes community. Furthermore, terrestrial proxy data are not available for all the time slices and locations we investigate. This is particularly true for the Pliocene time slice. **With these limitations of available proxies, we do the best we can to compare available observations to proxy data. These comparisons are now provided in revisions to the discussion section, and the addition of 2 figures at the end of the manuscript**.

We note that for the Alaska and Cascadia (NW USA) study areas, which are heavily and repeatedly glaciated, that limited - to no proxy data are available (due to poor preservation of proxies over glacial-interglacial cycles). Although some marine proxy records and records of past glaciations have been published for these regions, they are not useful for our purposes because they do not record if terrestrial locations in the regions were wetter/drier or warmer/colder during our time slices. Marine proxy records are of limited use for comparison to the terrestrial changes investigated in this study. Thus, despite the lack of terrestrial proxy comparisons available for two of the regions (Alaska, Cascadia), we maintain that presentation of the model predicted changes for these data poor regions is extremely useful because the model predictions augment existing terrestrial data gaps, and provide a starting point for future studies to formulate testable hypotheses of climate change and potential denudation impacts.

Much of the motivation for the manuscript appears to be to understand how climatic changes may change denudation/geomorphic analyses, but this is done in only a superficial way. If this is the point of the paper, then, again, much more work needs to be done, rather than simply stating that erosion depends on climate (lines 416-423 are a good example of statements that serve to motivate a paper, but don't provide any actual analysis). For example, can the authors take some of the climate model output and, given a potential 2000 mm/yr change in precipitation in the Himalaya since the Pliocene, actually re-interpret some of the existing exhumation/denudation data? If not, why not? What additional data is necessary? And if such a reanalysis isn't possible, then how does knowledge of such a change in precipitation facilitate future work?

This is a great suggestion and we are indeed doing this as ongoing work. But what the reviewer is asking for here simply cannot be included in this paper without making it an extremely long manuscript. For example, in the surface processes community, comparisons of river profiles to modern precipitation, or temperature changes to frost cracking histories for **one** catchment / study area (e.g. <100x100 km2) is typically a full manuscript in itself (e.g. Marhsall et al., 2015 Science Advances; Schaller et al. 2004 Journal of Geology). So, we respectfully disagree with the reviewer that this should be done within this manuscript. It's simply not possible to do in a way that would be convincing to the surface processes community.

I agree with the generalized statements made throughout the paper (i.e., that denudation and landscape evolution depend on climate), but these are somewhat self-evident and, as currently written, the manuscript does not make a fundamental contribution to improving our knowledge on this subject except to state that climate changed in the past. Assumptions of stationarity are indeed a problem in interpreting modern datasets that have a component of geologic history, but a really nice contribution of this paper would be to show how these assumptions can be mitigated when one knows the history of precipitation or temperature.

We agree with the reviewer that it is “self-evident” that palaeoclimate can impact the denudation history of an orogen, but how many palaeodenudation rate studies actually make a comparison to spatial distributed predictions of palaeoclimate? Very few in our experience, and we cite the robust ones in the manuscript. What most palaeodenudation rate studies do is compare some set of observation to the nearest set of proxy observations, but this approach does not provide a sense of spatial variability in terrestrial climate change that models predict (furthermore, proxy observations are often far removed from the denudation rate observations). In our manuscript, we specifically avoid picking on previous publications that follow this ‘conventional’ approach to show how this commonly used approach ignores spatial variability in climate change. We don’t think this is a productive way to advance the science. Instead, we maintain that providing spatially continuous model predictions at different time slices in a self-consistent set of simulations is extremely useful for documenting the magnitude of climate change (which is not self-evident), and for formulating testable hypotheses for future work and to identify where the best locations are in the world to investigate climate change impacts on a regions denudation history. Thus, the way in which our research group usually conducts palaeodenudation rate studies is to first run model simulations to formulate testable hypotheses, and then to investigate/test these hypotheses with field studies and geochemical observations of denudation histories. This approach to investigating palaeoclimate-palaeodenudation interactions is definitely not self-evident in the literature in our opinion.

We very much agree that in order for our simulations to ultimately be useful in actually quantifying denudation much more work needs to be done. Translating any of the changes observed here (or by other studies) to erosion rates remains a big problem in the Earth surface science community. It is one that we are actively working on and includes the application and comparison of different models for quantifying frost cracking [Anderson et al., 1998, Hales and Roering, 2007, and Andersen et al. 2015] and possible improvements on them, different measures for precipitation extremes and testing how well they are captured in modern day simulations (by comparison with indices derived from observation based datasets), etc.. However, the format and length of a typical article does not allow thorough investigation of any of these as part of this manuscript and we believe that an arbitrary selection of these efforts would ultimately be very misleading. Instead, we hope to offer these consistently set up simulations as a useful framework for the earth surface science community to build on. We added further descriptions and discussion to convey this.

Because ESurf is not a climate modeling journal, more discussion needs to be given as to the limitations of ECHAM5 in a way that Earth surface process folks can understand. For example, what are the uncertainties associated with simulating orographic precipitation? Though T159 is high-resolution, it still requires substantially smoothing topography, which presumably introduces some uncertainty in to the results. What uncertainties are associated with the PRISM reconstruction? (on a side note, which PRISM reconstruction is used? PRISM3D? PRISM2? I mention this because the topographies between different PRISM reconstructions are substantially different.)

We thank the reviewer for raising this important point. We emphasised the problem of simulating orographic precipitation, and included the recommendation for downscaling where it may be required. We used the PRISM3D reconstruction (as in Haywood et al. 2010), and commented on some of its uncertainties.

I found the use of the cluster analysis to be not intuitively helpful. If the authors want to keep using it, then the authors need to at least walk the reader through an example of how to understand Figures 6, 9, 12, and 15. Is C1 always the same climate zone in each figure and in each time-slice? If so, why are different colors used? Why don’t the authors use something more intuitive, like Köppen’s climate classification scheme (Peel et al., 2007) to classify climates? As best I understand it, the clustering analysis is used to show the spatial extent of a given climate in a given time-slice and in a given location, but it’s not clear how one should interpret these results.

We have modified the text in the results and discussion sections to help clarify this. In short, the clustering analysis essentially fulfills a similar synoptic purpose, but optimises classification and is more fine-tuned to this study’s purpose in its selection of variables. This is now reflected in text changes we made to the end of the methods section 2.2. The climate clusters do indeed show the spatial extent of a given climate (described by the mean vectors represented graphically in the raster plots and by numbers in the table included in the supplementary material). The idea is to provide an overview of regional climate without the need to study maps of individual variables, on which these patterns and the climatic homogeneity may not be seen as easily. Each plot represents an optimal classification and thus cluster 1, for example, is not always described by the same mean vector (though usually is usually very similar). The different colours are used to avoid the interpretation that cluster 1, for example, is always characterised by the exact same mean vector. We have included a more elaborate explanation in our revised manuscript to avoid confusion. While readers may be more familiar with the Köppen climate classification scheme, we are more interested in providing an overview not forcefully tied to the categories of this classification scheme. Clustering by various methods (such as this one or PCA) as a synoptic tool are not uncommon (e.g. Paeth 2004, Mannig et al. 2013), but we acknowledge that many readers may not be use to these tools and therefore elaborate explanations.

Minor Comments: Are the topographies for any of these ranges modified at all (it's unclear from the PRISM reference (Line 131), whether this has been done).

Yes, the topographies are different and we now specify the reconstruction we use (PRISM3D) in the methods section.

Lines 57-59: "Cold-temperature island" is not a climatic term in widespread use. What precisely do you mean? Also, Boos and Kuang, 2010 specifically refute the idea that Plateau surface elevation matters for the South Asian Monsoon and rather focus on the Himalaya instead.

Yes, this matters only regionally, but not for the South Asian Monsoon. We have corrected this sentence.

Line 61: Zhisheng et al. (2001) don't actually present any new geological data. Instead, it is all from cited literature. The focus of their study was GCM results. Dettman et al. (2003) is not the only study to look at this. Please see the following studies (which are just a sampling): (Caves et al., 2017; Kent-Corson et al., 2006; Lechler et al., 2013; Lechler and Niemi, 2011; Licht et al., 2016; Methner et al., 2016; Mulch et al., 2015,
2008; Pingel et al., 2016).

Thank you for pointing out this inaccuracy and pointing us to additional studies we ought to list here. We modified the text accordingly.

Lines 77 and 78: "documenting the magnitude" appears twice.

Thank you for pointing this out. We corrected this.

Lines 96-97: Though, importantly, several recent studies have run ECHAM5 at a higher resolution ((Feng et al., 2016; Feng and Poulsen, 2016).

That is true, of course. We mention these in our revised manuscript.

Lines 102-103: This statement is somewhat odd, since the authors are specifically investigating climatological changes over mountain ranges, where resolution typically tends to matter.

Thank you for noticing this apparent inconsistency. We corrected the text accordingly.

Lines 114-133: For all simulations, stating the pCO2 used in the experiment would be most helpful, particularly since it won't take up much room. Also, how is the land- surface treated? For example, the authors state that they are using vegetation reconstructions, but it's unclear if this is then being fed into a "built-in" land-surface model or if they are explicitly using JSBACH.

This is a good point. We included these values in the text. We used the built-in land surface scheme (LSS) and clarified this in the revised text.

Lines 126: "for the" used twice.

This has been corrected.

Lines 203-204: Changes in Greenland and Antarctica are almost certainly unreliable. Because PRISM uses a reconstructed ice-sheet extent, changes in temperature in Greenland and Antarctica are almost certainly reflecting the imposed boundary condition, which itself has quite a bit of uncertainty. It's hard to get around this, except to note that the change in temperature is entirely dependent upon the ice-sheet boundary condition (see discussion in and of de Boer et al. (2015)).

Thank you for pointing this out. We comment on the Pliocene uncertainty in ice sheet reconstructions in the method section of the revised manuscript.

Lines 416-423: Are runoff changes in these models coupled to precipitation changes? In all cases, does P–E (precipitation minus evaporation) scale with changes in precipitation. I'm not particularly familiar with JSBACH (presuming this is the land-surface model used), but if it has a CO2 fertilization parameterization, then runoff may be decoupled from precip. Some of these erosion processes may depend more on runoff than precip.

We use the built in LSS and the runoff is coupled to precipitation. Also, ECHAM5's runoff is not particularly useful in river discharge modelling (see Weiland et al. 2011), which would be of interest in context of erosion. Given this, we refrain from using the model predicted runoff in the global GCM (even though it's conducted at relatively high resolution compared to previous work) to calculate changes in fluvial incision. This would be better done by mapping the predicted precipitation changes onto higher resolution (<90 m) DEMs and solving the kinematic wave equation for each fluvial erosion in each catchment, for the changes in precipitation. However, as we repeatedly mention above, this is not possible to include in this manuscript without first characterising how the precipitation has changed in each region (the current manuscript goals). Work in progress we are conducting is trying to apply the kinematic wave equation and palaeoprecipitation to selected areas, but it's proving difficult to implement meaningfully without temporally continuous (e.g. LGM to present) simulations of precipitation change. We hope this brings to the readers attention the complications associated with doing full erosion history calculations based on these results. We have expanded the last paragraph in the instruction to convey the above perspective better, and more clearly articulate (and justify) the scope and limitations of the manuscript.

Figure 1: Would be nice to also plot the topography of the St. Elias range and the Cascades.

This is a good idea. We included ECHAM5 topographies for Alaska and the Pacific Northwest in Fig. 1 in the revised manuscript.

Figure 7b-Precip-PLIO: Why does precipitation appear to follow a wave-like pattern over tropical South America? Is this due to the spectral nature of ECHAM5?

This may indeed be due to the spectral nature of ECHAM5.

References used in review:

Thank you for being thoughtful enough to provide these. We have added many of them to the revised text.

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Response to RC1 (2nd revision)

(responses in blue)

The revised manuscript by Mutz et al. is a clear improvement over its predecessor, but does not sufficiently address substantial comments that I made on the last version of the manuscript. I have given more thought to specific suggestions on how to rectify this. Some of these issues are major, and I have therefore suggested "Major Revisions", though I believe that Mutz et al. may be able to complete them in short order. I will, therefore, also keep this short and to the point. Once these major issues are resolved, I will be happy to review the revised manuscript thoroughly.

The primary items of concern are:
1. A title that is not representative of the article content
2. A lack of clarity from the abstract and introduction on what the authors actually do.

We thank Andrew Wickert for the review of the revised manuscript, and for the concise and clear communication of concerns and suggestions. We hope that we managed to address these concerns adequately. Below, we describe how we addressed these concerns.

In short, the authors must communicate up-front something along the lines of:
"Motivated by the need to better understand climate impacts on the denudation of orogens, we model paleoclimate at 4 time slices, and qualitatively compare how changes in temperature and precipitation may impact fluvial and/or hillslope erosion."

After the description of the scientific background to this study in the introduction, we included a slightly modified version of the suggested sentence to begin to describe our work. We modified the sentence to be as precise as possible in our communication of what we attempt in the study (line 85): *"Motivated by the need to better understand climate impacts on Earth surface processes, especially the denudation of orogens, we model palaeoclimate for four time slices in the Late Cenozoic, use descriptive statistics to identify the extent of different regional climates, quantify changes in temperature and precipitation, and discuss the potential impacts on fluvial and/or hillslope erosion."*

Title:
"Where is Late Cenozoic climate change most likely to impact denudation?"

The authors do not answer this question. There are two issues to address here. The former can be addressed in the text. The latter will require a change in scope or title.
1. The text does not answer this question in regards to fluvial and hillslope erosion. The discussion provides some ideas on how changes in P and T may impact erosion rates in different regions, but offer no concrete proposals or answers.
2. The authors state that glacial erosion is beyond the scope of their study. There is no way to discuss late Cenozoic erosion (let alone climate change and erosion) without considering glacial erosion.

I would suggest a title that relates more closely to the authors' work, as a modeling study intended to provide environmental conditions that may impact fluvial and/or hillslope erosion. Such a title will be less broad in scope, but may be more powerful in precision.

We agree with Andrew Wickert and modified the title to more precisely describe our work. We have changed the title to *"Estimates of Late Cenozoic climate change relevant to Earth surface processes in tectonically active orogens"*. We included "at active orogens" to better communicate the regional focus of our work. Since the intention of this study is also to provide a GCM-simulation framework for studies investigating a variety of surface processes, we decided to add "relevant to Earth surface processes". This way, the title does not promise to answer questions pertaining to all types of erosional processes, but instead explains that the work presented here, specifically the simulation themselves, provides a basis for more in-depth studies of a variety of surface processes. For example, since our original submission of the manuscript, the GCM simulation framework has been used to investigate vegetation response to differences in palaeoclimate (Werner et al., in review).
We also modified part of the introduction (line 111) in order to not create false expectations, and communicate more clearly what is to be expected in the manuscript.

Abstract:
1. Do you discuss vegetation gradients in the results of your work? In other words, is it worth including here? Otherwise, the abstract is clear.

While we belief our simulations are of benefit to the vegetation modelling community, as is demonstrated by the study mentioned above, we do not discuss this much in our manuscript. We therefore omitted "vegetation gradients" in the abstract.

Introduction:
It is not clear in the introduction how you will link your model results to landscape evolution. Making clear the focus on the model and its inspiration (landscape evolution), along with the limited scope of the actual application to landscape evolution you provide here, will help the readers see the paper for what it is.

We now clarify in the introduction (line 102) that our GCM output may directly be used as boundary conditions for vegetation and landscape evolution models, such as LPJ-GUESS and Landlab respectively, to bridge the gap between palaeoclimate change and quantitative estimates for Earth surface system responses.

One specific point: you mention glacial erosion in the introduction as being important, but then note in line 434 that you will not address it. Up until this point, the reader may reasonably think that you are going to discuss glacial erosion, as it is a dominant process in the late Cenozoic.

We now clarify in the introduction (line 109) that merited discussion of glacial erosion is beyond the scope of our study to avoid readers looking for such discussion in our manuscript.

References:

Werner, C., Schmid, M., Ehlers, T. A., Fuentes-Espoz, J. P., Steinkamp, J., Forrest, M., Liakka, J., Maldonado, A., and Hickler, T.: Effect of changing vegetation on denudation (part 1): Predicted vegetation composition and cover over the last 21 thousand years along the Coastal Cordillera of Chile, Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-14, in review, 2018.

List of Major Changes (1st revision)

Overall, we found the reviewer's comments refreshingly useful. We greatly appreciate the time the editors have taken to find thoughtful reviewers, and the reviewers time in providing constructive comments. We were able to implement most of the suggested changes. However, some of the requested changes by reviewer 2 would require multiple manuscripts, and in our response to this reviewers comments we explain a (hopefully) happy middle ground between their requests and the reality of what we think can be realistically implemented in a manuscript for the ESurf community of readers. **The most extensive changes to the manuscript are in the introduction and discussion sections, as well as in the modification of previously presented figures (Fig. 1, 2, 3, 7, 10, 13)** - since modification of these sections and figures most directly addresses the reviewers concerns and they did not identify errors in our results required new simulations.

The general concern that resonated in both reviewers comments was the need to focus the manuscript more and add ‘meat’ to our arguments in one direction or another. We have taken this to heart, and **the revised manuscript presents an in-depth (and very time consuming) compilation of terrestrial proxy data observations for two of the regions (South Asia, South America)** which were not extensively glaciated and have good records available. These proxy data were compared to the model results and provide a new and focused dimension to the manuscript. **As a results of these efforts, we included two additional figures (Fig. 16, 17)**. As detailed in our response to reviewer 2 - we do not present a detailed inter-model comparison, although we have expanded our comparison to previous published work throughout the text (mostly in the discussion section). We also provide additional justification for our approach, and highlight more explicitly what is novel about our presentation of a series of experiments conducted with the same model at the same resolution.

The marked-up manuscript below highlights changes made to the manuscript in more detail.

List of Major Changes (2nd revision)

In accordance with suggestions made by the reviewer, major changes have been made to the title and parts of the introduction. Minor changes have been made to the abstract and acknowledgements.

Revised Manuscript (marked-up, 1st and 2nd revisions)

~~Where is Late Cenozoic climate change most likely to impact denudation?~~

Estimates of Late Cenozoic climate change relevant to Earth surface processes in tectonically active orogens

Sebastian G. Mutz[1], Todd A. Ehlers[1], Martin Werner[2], Gerrit Lohmann[2], Christian Stepanek[2], Jingmin Li[1,3]

[1] Department of Geosciences, University Tübingen, D-72074 Tübingen, Germany

[2] Department of Paleoclimate Dynamics, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, D-27570 Bremerhaven, Germany

[3] now at Institute for Geography and Geology, University of Würzburg, Würzburg, D-97074 Germany

Correspondence to: Sebastian G. Mutz (sebastian.mutz@uni-tuebingen.de)

Abstract

The denudation history of active orogens is often interpreted in the context of modern climate ~~and vegetation~~ gradients. Here we address the validity of this approach and ask the question: what are the spatial and temporal variations in palaeo~~-~~climate for a latitudinally diverse range of active orogens? We do this using high-resolution (T159, ca. 80 x 80 km at the equator) palaeo~~-~~climate simulations from the ECHAM5 global Atmospheric General Circulation Model and a statistical cluster analysis of climate over different orogens (Andes, Himalaya, SE Alaska, Pacific NW USA). Time periods and boundary conditions considered include the Pliocene (PLIO, ~3 Ma), the Last Glacial Maximum (LGM, ~21 ka), Mid Holocene (MH, ~6 ka) and Pre-Industrial (PI, reference year 1850). The regional simulated climates of each orogen are described by means of cluster analyses based on the variability of precipitation, 2m air temperature, the intra-annual amplitude of these values, and monsoonal wind speeds where appropriate. Results indicate the largest differences to the PI climate ~~are observed~~existed for the LGM and PLIO climates in the form of widespread cooling and reduced precipitation in the LGM and warming and enhanced precipitation during the PLIO. The LGM climate shows the largest deviation in annual precipitation from the PI climate, and shows enhanced precipitation in the temperate Andes, and coastal regions for both SE Alaska and the US Pacific Northwest ~~Pacific~~. Furthermore, LGM precipitation is reduced in the western Himalayas and enhanced in the eastern Himalayas, resulting in a shift of the wettest regional climates eastward along the orogen. The cluster-analysis results also suggest more climatic variability across latitudes east of the Andes in the PLIO climate than in other time-slice experiments conducted here. Taken together, these results highlight significant changes in Late Cenozoic regional climatology over the last ~3 Ma. Comparison of simulated climate with proxy-based reconstructions for the MH and LGM reveal satisfactory to good performance of the model in reproducing precipitation changes, although in some cases discrepancies between neighbouring proxy observations highlight contradictions between proxy observations themselves. Finally, we document regions where the largest magnitudes of Late Cenozoic changes in precipitation and temperature occur and offer the highest potential for future observational studies ~~interested in quantifying~~that quantify the impact of climate change on denudation and weathering rates.

Keywords: Cenozoic climate, ECHAM5, Last Glacial Maximum, Mid-Holocene, Pliocene, cluster analysis, Himalaya, Tibet, Andes, Alaska, Cascadia

1. Introduction

Interpretation of orogen denudation histories in the context of climate and tectonic interactions is often hampered by a paucity of terrestrial palaeo~~-~~climate proxy data needed to reconstruct spatial variations in palaeo~~-~~climate. While it is self-evident that palaeoclimate changes could influence palaeodenudation rates, it is not always self-evident what the magnitude of climate change over different geologic time scales is, or what geographic locations offer the greatest potential to investigate palaeoclimate impacts on denudation. Palaeoclimate reconstructions are particularly beneficial when denudation rates are determined using geo- and thermo-chronology techniques that integrate over timescales of 10^3-10^{6+} years (e.g. cosmogenic radionuclides or low-temperature thermochronology) [e.g., Kirchner et al., 2001; Schaller et al., 2002; Bookhagen et al., 2005; Moon et al., 2011; Thiede and Ehlers, 2013; Lease and Ehlers, 2013]. However, few studies using denudation rate determination methods that integrate over longer timescales have access to information about past climate conditions that could influence these palaeo-denudation rates. Palaeo~~-~~climate modelling offers an alternative approach to sparsely available proxy data for understanding the spatial and temporal variations in precipitation and temperature in response to changes in orography [e.g. Takahashi and Battisti, 2007a, b; Insel et al., 2010; Feng et al., 2013] and global climate change events [e.g. Salzmann, 2011; Jeffery et al., 2013]. In this study, we characteri~~z~~se the climate at different times in the Late Cenozoic, and the magnitude of climate change for a range of active orogens. Our emphasis is on identifying changes in climate parameters relevant to weathering and catchment denudation to illustrate the potential importance of various global climate change events on surface processes.

Previous studies of orogen~~-~~-scale climate change provide insight into how different tectonic or global climate change events influence regional climate change. For example, sensitivity experiments demonstrated significant changes in regional and global climate in response to landmass distribution and topography of the Andes, including changes in moisture transport, the north-south asymmetry of the Intertropical Convergence Zone ~~and the north-south asymmetry of the Inter Tropical Convergence Zone~~ [e.g. Takahashi and Battisti, 2007a, ; Insel et al., 2010] and (tropical) precipitation [Maroon et al., 2015, ; ~~Maroon et al.~~ 2016]. Another example is the regional and global climate changes induced by the Tibetan Plateau surface uplift due to its role as a ~~cold-temperature island and~~ physical obstacle to circulation [Raymo and Ruddiman, 1992; Kutzbach et al., 1993; Thomas, 1997; Bohner, 2006; Molnar et al., 2010; Boos and Kuang, 2010]. The role of tectonic uplift in long term regional and global climate change remains a focus of research and continues to be assessed with geologic datasets [e.g. ~~Zhisheng, 2001;~~ Dettman et al., 2003; Caves et al., 2017; Kent-Corson et al., 2006; Lechler et al., 2013; Lechler and Niemi, 2011; Licht et al., 2016; Methner et al., 2016; Mulch et al., 2015, 2008; Pingel et al., 2016] and climate modelling [e.g. Kutzbach et al., 1989; Kutzbach et al., 1993; Zhisheng, 2001;~~,~~ Bohner, 2006; Takahashi and Battisti, 2007a; Ehlers and Poulsen, 2009; Insel et al., 2010; Boos and Kuang, 2010]. Conversely, climate influences tectonic processes through erosion [e.g. Molnar and England, 1990; Whipple et al., 1999; Montgomery et al., 2001; Willett et al., 2006; Whipple, 2009]. Quaternary climate change between glacial and interglacial conditions [e.g. Braconnot et al., 2007; Harrison et al., 2013] resulted in not only the growth and decay of glaciers and glacial erosion [e.g. Yanites and Ehlers, 2012; Herman et al., 2013; Valla et al., 2011] but also global changes in precipitation and temperature [e.g. Otto-Bliesner et al., 2006; Li et al., 2017] that could influence catchment denudation in non-glaciated environments [e.g. Schaller and Ehlers, 2006; Glotzbach et al., 2013; Marshall et al., 2015]. These dynamics highlight the importance of investigating how much climate has changed over orogens that are the focus of studies of climate-tectonic interactions and their impact on erosion.

Despite recognition by previous studies that climate change events relevant to orogen denudation are prevalent throughout the Late Cenozoic, few studies have critically evaluated how different climate change events may, or may not, have affected the orogen climatology, weathering and erosion. Furthermore, recent controversy exists concerning the spatial and temporal scales over which geologic and geochemical observations can record climate-driven changes in weathering and erosion [e.g. Whipple, 2009; von Blanckenburg et al., 2015; Braun, 2016]. For example, the previous studies highlight that although palaeoclimate impacts on denudation rates are evident in some regions and measurable with some approaches, they are not always present (or detectable) and the spatial and temporal scale of climate change influences our ability to record climate sensitive denudation histories. This study contributes to our understanding of the interactions between climate, weathering, and erosion by bridging the gap between the palaeoclimatology and surface processes communities by documenting the magnitude and distribution of climate change over tectonically active orogens. ~~Our focus is on documenting the magnitude of paleoclimateclimate and climate change in different locations with the intent of informing past and ongoing paleodenudation studies of these regions. The application of~~

~~these results to predicted changes in denudation rates is beyond the scope of this study and the focus of future work.~~

Motivated by the need to better understand climate impacts on Earth surface processes, especially the denudation of orogens, we model palaeoclimate for four time slices in the Late Cenozoic, use descriptive statistics to identify the extent of different regional climates, quantify changes in temperature and precipitation, and discuss the potential impacts on fluvial and/or hillslope erosion. ~~We~~ In this study, we employ the ECHAM5 global Atmospheric General Circulation Model and document climate and climate change for time slices ranging between the Pliocene (PLIO, ~3 Ma) to pre-industrial (PI) times for the St. Elias Range of South East Alaska, the US Pacific Northwest (Olympic and Cascade Range), western South America (Andes) and South Asia (incl. parts of Central- and East Asia). Our approach is two-fold and includes:

1. An empirical characteri~~z~~sation of palaeo-climates in these regions based on the covariance and spatial clustering of monthly precipitation and temperature, the monthly change in precipitation and temperature magnitude, and wind speeds where appropriate.

2. Identification of changes in annual mean precipitation and temperature in selected regions ~~over in the following time, specifically from the~~ for four time periods: (PLIO, ~~to the~~ Last Glacial Maximum (LGM), the Mid-Holocene (MH) and PI)~~.~~ and subsequent validation of the simulated precipitation changes for MH and LGM.

Our focus is on documenting climate and climate change in different locations with the intent of informing past and ongoing palaeodenudation studies of these regions. The results presented here also provide a means for future work to formulate testable hypotheses and investigations into whether or not regions of large palaeoclimate change produced a measurable signal in denudation rates or other Earth surface processes. More specifically, different aspects of the simulated palaeoclimate may be used as boundary conditions for vegetation and landscape evolution models, such as LPJ-GUESS and Landlab, to bridge the gap between climate change and quantitative estimates for Earth surface system responses. In this study, we intentionally refrain from applying predicted palaeoclimate changes to predict denudation rate changes. Such a prediction is beyond the scope of this study because a convincing (and meaningful) calculation of climate-driven transients in fluvial erosion (e.g. via the kinematic wave equation), variations in frost cracking intensity, or changes in hillslope sediment production and transport at the large regional scales considered here is not tractable within a single manuscript, and instead is the focus of our ongoing work. Merited discussion of climatically induced changes in glacial erosion, as is important in the Cenozoic, is also beyond the scope of this study. Instead, our emphasis lies on providing and describing a consistently setup GCM simulation framework for future investigations of Earth surface processes, and to identify regions in which Late Cenozoic climate changes potentially have a significant impact on fluvial and hillslope erosion.

2. Methods: Climate modelling and cluster analyses for climate characteris~~z~~ation

2.1 ECHAM5 simulations

The global Atmospheric General Circulation Model ECHAM5 [Roeckner et al., 2003] has been developed at the Max Planck Institute for Meteorology and is based on the spectral weather forecast model of the ECMWF [Simmons et al., 1989]. In the context of palaeoclimate applications, the model has been used mostly at lower resolution (T31, ~~approximately~~ca. 3.75°x3.75°; T63, ca. 1.9°x1.9° in case of Feng et al. [2016] and T106 in the case of Li et al. [2016] and Feng and Poulsen [2016]) . The performed studies are not limited to the last millenium [e.g. Jungclaus et al., 2010] but also include research in the field of both warmer and colder climates, at orbital [e.g. Gong et al., 2013; Lohmann et al., 2013; Pfeiffer and Lohmann, 2016; Zhang et al., 2013a; Zhang et al., 2014; Wei and Lohmann, 2012] and tectonic time scales [e.g. Knorr et al., 2011; Stepanek and Lohmann, 2012], and under anthropogenic influence [Gierz et al., 2015].

Here, the ECHAM5 simulations were conducted at a T159 spatial resolution (horizontal grid size ca. 80 km x 80 km at the equator) with 31 vertical levels (between the surface and 10hPa). This high model resolution is admittedly not required for all of the climatological questions investigated in this study, and it should be noted that the skill of GCM's in predicting orographic precipitation remains limited at this scale [e.g. Meehl et al. 2007]. However, simulations were conducted at this resolution so that future work can apply the results in combination with different dynamical and statistical downscaling methods to quantify changes at large catchment to orogen scales. The output frequency is relatively high (1 day) to enhance the usefulness of our simulations as input for landscape evolution and other models that may benefit from daily input. The simulations were conducted for five different time periods: present-day (PD), PI, MH, LGM and PLIO.

A PD simulation (not shown here) was used to establish confidence in the model performance before conducting palaeo~~-~~simulations and has been compared with the following observation-based datasets: European Centre for Medium-Range Weather Forecasts (ECMWF) re-analyses [ERA40, Uppala et al., 2005], National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) re-analyses [Kalnay et al., 1996; Kistler et al., 2001], NCEP Regional Reanalysis (NARR) [Mesinger et al., 2006], the Climate Research Unit (CRU) TS3.21 dataset [Harris et al., 2013], High Asia Refined Analysis (HAR30) [Maussion et al., 2014] and the University of Delaware dataset (UDEL v3.01) [Legates et al., 1990]. (See Mutz et al. [2016] for a detailed comparison with a lower resolution model).

The PI climate simulation is an ECHAM5 experiment with PI (reference year 1850) boundary conditions. Sea Surface Temperatures (SST) and Sea Ice Concentration (SIC) are derived from transient coupled ocean-atmosphere simulations [Lorenz and Lohmann, 2004; Dietrich et al., 2013]. Following Dietrich et al. [2013], greenhouse gas (GHG) concentrations (CO2: 280 ppm) are taken from ice core based reconstructions of CO_2 [Etheridge et al., 1996],

CH_4 [Etheridge et al., 1998] and N2O [Sowers et al., 2003]. Sea surface boundary conditions for MH originate from a transient, low-resolution, coupled atmosphere-ocean simulation of the mid (6 ka) Holocene [Wei and Lohmann, 2012; Lohmann et al, 2013], where the GHG concentrations (CO2: 280 ppm) are taken from ice core reconstructions of GHG's by Etheridge et al. [1996], Etheridge et al. [1998] and Sowers et al. [2003]. GHG's concentrations for the LGM (CO2: 185 ppm) have been prescribed following Otto-Bliesner et al. [2006]. Orbital parameters for MH and LGM are set according to Dietrich et al. [2013] and Otto-Bliesner et al. [2006], respectively. LGM land-sea distribution and ice sheet extent and thickness are set based on the PMIP III (Palaeoclimate Modelling Intercomparison Project, phase 3) guidelines (elaborated on by Abe-Ouchi et al [2015]). Following Schäfer-Neth and Paul [2003], SST and SIC for the LGM are based on GLAMAP [Sarnthein et al. 2003] and CLIMAP [CLIMAP project members, 1981] reconstructions for the ~~for the~~ Atlantic and Pacific/Indian Ocean, respectively. Global MH and LGM vegetation are based on maps of plant functional types by the BIOME 6000 / Palaeovegetation Mapping Project [Prentice et al., 2000; Harrison et al., 2001; Bigelow et al., 2003; Pickett et al., 2004] and model predictions by Arnold et al. [2009]. Boundary conditions for the PLIO simulation, including GHG concentrations (CO2: 405), orbital parameters and surface conditions (SST, SIC, sea land mask, topography and ice cover) are taken from the PRISM (Pliocene Research, Interpretation and Synoptic Mapping) project [Haywood et al., 2010; Sohl et al., 2009; Dowsett et al., 2010], specifically PRISM3D. The PLIO vegetation boundary condition was created by converting the PRISM vegetation reconstruction to the JSBACH plant functional types as described by Stepanek and Lohmann [2012], but the built-in land surface scheme was used.~~.~~

SST reconstructions can be used as an interface between oceans and atmosphere [e.g. Li et al. 2016] instead of conducting the computationally more expensive fully coupled Atmosphere-Ocean GCM experiments. While the use of SST climatologies comes at the cost of capturing decadal-scale variability, and the results are ultimately biased towards the SST reconstructions the model is forced with, the simulated climate more quickly reaches an equilibrium state and the means of atmospheric variables used in this study do no change significantly after the relatively short spin-up period. The palaeoclimate simulations (PI, MH, LGM, PLIO) using ECHAM5 are therefore carried out for 17 model years, of which the first two years are used for model spin up. The monthly long-term averages (multi-year means for individual months) for precipitation, temperature, as well as precipitation and temperature amplitude, i.e. the mean difference between the hottest and coldest months, have been calculated from the following 15 model years for the analysis presented below.

For further comparison between the simulations, the investigated regions were subdivided (Fig. 1). Western South America was subdivided into four regions: parts of tropical South America (80°-60° W, 23.5-5° S), temperate South America (80°-60° W, 50°-23.5° S), tropical Andes (80°-60° W, 23.5-5° S; high-pass filtered), i.e. most of the Peruvian Andes, Bolivian Andes and northernmost Chilean Andes, and temperate Andes (80°-60° W, 50°-23.5° S, high-pass filtered). South Asia was subdivided into three regions: tropical South Asia (40°-120°E, 0°-23.5°N), temperate

South Asia (40°-120°E, 23.5°-60°N), and high altitude South Asia (40°-120°E, 0°-60°N; high-pass filtered).

Our approach of using a single GCM (ECHAM5) for our analysis is motivated by, and differs from, previous studies where inter-model variability exists from the use of different GCMs due to different parameterisations in each model. The variability in previous inter-model GCM comparisons exists despite the use of the same forcings [e.g. see results highlighted in IPCC AR5]. Similarities identified between these palaeoclimate simulations conducted with different GCMs using similar boundary conditions can establish confidence in the models when in agreement with proxy reconstructions. However, differences identified in inter-model GCM comparisons highlight biases by all or specific GCMs, or reveal sensitivities to one changed parameter, such as model resolution. Given these limitations of GCM modelling, we present in this study a comparison of a suite of ECHAM5 simulations to proxy-based reconstructions (where possible) and, to a lesser degree, comment on general agreement or disagreement of our ECHAM5 results with other modelling studies. A detailed inter-model comparison of our results with other GCMs is beyond the scope of this study, and better suited for a different study in a journal with a different focus and audience. Rather, by using the same GCM and identical resolution for the time slice experiments, we reduce the number of parameters (or model parameterisations) varying between simulations and thereby remove potential sources of error or uncertainty that would otherwise have to be considered when comparing output from different models with different parameterisations of processes, model resolution, and in some cases model forcings (boundary conditions). Nevertheless, the reader is advised to use these model results with the GCM's shortcoming and uncertainties in boundary condition reconstructions in mind. For example, precipitation results may require dynamical or statistical downscaling to increase accuracy where higher resolution precipitation fields are required. Furthermore, readers are advised to familiarise themselves with the palaeogeography reconstruction initiatives and associated uncertainties. For example, while Pliocene ice sheet volume can be estimated, big uncertainties pertaining to their locations remain [Haywood et al. 2010].

2.2 Cluster analysis to document temporal and spatial changes in climatology

~~This section describes the clustering method used in this study.~~ The aim of the clustering approach is to group climate model surface grid boxes together based on similarities in climate. Cluster analyses are statistical tools that allow elements (i) to be grouped by similarities in the elements' attributes. In this study, those elements are spatial units, the elements' attributes are values from different climatic variables, and the measure of similarity is given by a statistical distance. The four basic variables used as climatic attributes of these spatial elements are: near-surface (2m) air temperature, seasonal 2m air temperature amplitude, precipitation rate, and seasonal precipitation rate amplitude. Since monsoonal winds are a dominant feature of the climate in the South Asia region, near surface (10m) speeds of u-wind and v-wind (zonal and meridional wind components, respectively) during the monsoon season (July) and outside the monsoon season (January) are included as additional variables in our analysis of that region. Similarly, u-wind and v-wind speeds during (January) and outside (July) the monsoon season in South America are added to the list of considered variables to take into account the South American Monsoon System (SASM) in the cluster analysis for this region. The long-term monthly means of those variables are used in a hierarchical clustering method, followed by a non-hierarchical k-means correction with randomis~~z~~ed re-groupment [Mutz et al., 2016; Wilks, 2011; Paeth, 2004; Bahrenberg et al., 1992].

The hierarchical part of the clustering procedure starts with as many clusters as there are elements (ni), then iteratively combines the most similar clusters to form a new cluster using centroids for the linkage procedure for clusters containing multiple elements. The procedure is continued until the desired number of clusters (k) is reached. One disadvantage of a pure hierarchical approach is that elements cannot be re-categoris~~z~~ed once they are assigned to a cluster, even though the addition of new elements to existing clusters changes the clusters' defining attributes and could warrant a re-categori~~z~~sation of elements. We address this problem by implementation of a (non-hierarchical) k-means clustering correction [e.g. Paeth, 2004]. Elements are re-categorizsed based on the multivariate centroids determined by the hierarchical cluster analysis in order to minimisze the sum of deviations from the cluster centroids. The Mahalanobis distance [e.g. Wilks, 2011] is used as a measure of similarity or distance between the cluster centroids, since it is a statistical distance and thus not sensitive to different variable units. The Mahalanobis distance also accounts for possible multi-collinearity between variables.

The end results of the cluster analyses are subdivisions of the climate in the investigated regions into *k* subdomains or clusters based on multiple climate variables. The region-specific *k* has to be prescribed before the analyses. A large *k* may result in redundant additional clusters describing very similar climates, thereby defeating the purpose of the analysis to identify and describe the dominant, distinctly different climates in the region and their geographical coverage. Since it is not possible to know a priori the ideal number of clusters, *k* was varied between 3 and 10 for each region and the results presented below identify the optimal number of visibly distinctly different clusters from the analysis. Optimal *k* was determined by assessing the distinctiveness and similarities between the climate clusters in the systematic process of increasing *k* from 3 to 10. Once an increase in *k* no longer resulted in the addition of another cluster that was climatologically distinctly different from the others, and instead resulted in at least two similar clusters, *k* of the previous iteration was chosen as the optimal *k* for the region.

The cluster analysis ultimately results in a description of the geographical extent of a climate (cluster) characterised by a certain combination of mean values for each of the variables associated with the climate. For example, climate cluster 1 may be the most tropical climate in a region and thus be characterised by a high precipitation values, high temperature values and low seasonal temperature amplitude. Each of the results (consisting of the geographical extent of climates and mean vectors describing the climate) can be viewed as an optimal classification for the specific region and time. It serves primarily as a means for providing an overview of the climate in each of the regions at different times, reduces dimensionality of the raw simulation output, and identify regions of climatic homogeneity that is difficult to notice by viewing simple maps of each climate variable. Its synoptic purpose is similar to that of the widely known Köppen-Geiger classification scheme [Peel et al., 2007], but we allow for optimal classification rather than prescribe classes, and our selection of variables is more restricted and made in accordance with the focus of this study.

3. Results

Results from our analysis are first presented for general changes in global temperature and precipitation for the different time slices (Fig. 2, 3), which is then followed by an analysis of changes in the climatology of selected orogens. A more detailed description of temperature and precipitation changes in our selected orogens is presented in subsequent subsections (Fig. 4 and following). All differences in climatology are expressed relative to the PI control run. Changes relative to the PI rather than PD conditions are presented to avoid interpreting an anthropogenic bias in the results and focusing instead on pre-anthropogenic variations in climate. For brevity, near-surface (2m) air temperature and total precipitation rate are referred to as temperature and precipitation.

3.1 Global differences in mean annual temperature

This section describes the differences between simulated MH, LGM, and PLIO annual mean temperature anomalies with respect to PI shown in Fig. 2b, and PI temperature absolute values shown in Fig. 2a. Most temperature differences between the PI and MH climate are within -1°C to 1°C. Exceptions to this are the Hudson Bay, Weddell Sea and Ross Sea regions which experience warming of 1-3°C, 1-5°C and 1-9°C respectively. Continental warming is mostly restricted to low-altitude South America, Finland, western Russia, the Arabian Peninsula (1-3°C) and subtropical north Africa (1-5°C). Simulation results show that LGM and PLIO annual mean temperature deviate from the PI means the most. The global PLIO warming and LGM cooling trends are mostly uniform in direction, but the magnitude varies regionally. The strongest LGM cooling is concentrated in regions where the greatest change in ice extent occurs (as indicated on Fig. 2), i.e. Canada, Greenland, the North Atlantic, Northern Europe and Antarctica. Central Alaska shows no temperature changes, whereas coastal South Alaska experiences cooling of ≤ 9°C. Cooling in the US Pacific northwest is uniform and between 11 and 13°C. Most of high-altitude South America experiences mild cooling of 1-3°C, 3-5°C in the central Andes and ≤ 9°C in the south. Along the Himalayan orogen, LGM temperature values are 5-7°C below PI values. Much of central Asia and the Tibetan plateau cools by 3-5°C, and most of India, low-altitude China and southeast Asia by 1-3°C.

In the PLIO climate, parts of Antarctica, Greenland and the Greenland Sea experience the greatest temperature increase (≤ 19°C). Most of southern Alaska warms by 1-5°C and ≤ 9°C near McCarthy, Alaska. The US Pacific northwest warms by 1-5°C. The strongest warming in South America is concentrated at the Pacific west coast and the Andes (1-9°C), specifically between Lima and Chiclayo, and along the Chilean-Argentinian Andes south of Bolivia (≤ 9°C). Parts of low-altitude South America to the immediate east of the Andes experience cooling of 1-5°C. The Himalayan orogen warms by 3-9°C, whereas Myanmar, Bangladesh, Nepal, northern India and northeast Pakistan cool by 1-9°C.

3.2 Global differences in mean annual precipitation

Notable differences occur between simulated MH, LGM, PLIO annual mean precipitation anomalies with respect to PI shown in Fig. 3b, and the PI precipitation absolute values shown in Fig. 3a. Of these, MH precipitation deviates the least from PI values. The differences between MH and PI precipitation on land appear to be largest in northern tropical Africa (increase ≤1200 mm/a) and along the Himalayan orogen (increase ≤2000 mm/a) and in central Indian states (decrease) ≤500mm. The biggest differences in western South America are precipitation increases in central Chile between Santiago and Puerto Montt. The LGM climate shows the largest deviation in annual precipitation from the PI climate, and precipitation on land mostly decreases. Exceptions are increases in precipitation rates in North American coastal regions, especially in coastal South Alaska (≤2300 mm/a) and the US Pacific Northwest (≤1700 mm/a). Further exceptions are precipitation increases in low-altitude regions immediately east of the Peruvian Andes (≤1800 mm/a), central Bolivia (≤1000 mm/a), most of Chile (≤1000 mm/a) and northeast India (≤1900 mm/a). Regions of notable precipitation decrease are northern Brazil (≤1700 mm/a), southernmost Chile and Argentina (≤1900 mm/a), coastal south Peru (≤700 mm/a), central India (≤2300 mm/a) and Nepal (≤1600 mm/a).

Most of the precipitation on land in the PLIO climate is higher than those in the PI climate. Precipitation is enhanced by ca. 100-200 mm/a in most of the Atacama desert, by ≤1700 mm/a south of the Himalayan orogen and by ≤1400 mm/a in tropical South America. Precipitation significantly decreases in central Peru (≤2600mm), southernmost Chile (≤2600mm) and from eastern Nepal to northernmost northeast India (≤2500mm).

3.3 Palaeoclimate characteri~~z~~sation from the cluster analysis and changes in regional climatology

In addition to the above described global changes, the PLIO to PI regional climatology changes substantially in the four investigated regions of: South Asia (section 3.3.1), the Andes (section 3.3.2), South Alaska (section 3.3.3) and the Cascade Range (section 3.3.4). Each climate cluster defines separate distinct climate that is characterized by the mean values of the different climate variables used in the analysis. The clusters are calculated by taking the arithmetic means of all the values (climatic means) calculated for the grid boxes within each region. The regional climates are referred to by their cluster number C_1, C_2, …, C_k, where k is the number of clusters specified for the region. The clusters for specific palaeo-climates are mentioned in the text as $C_{i(t)}$, where i corresponds to the cluster number (i=1, …, k) and t to the simulation time period (t=PI, MH, LGM, PLIO). The descriptions first highlight the similarities and then the differences in regional climate. The cluster means of seasonal near-surface temperature amplitude and seasonal precipitation amplitude are referred to as temperature and precipitation amplitude. The median, 25th percentile, 75th percentile, minimum and maximum values for annual mean precipitation are referred to as P_{md}, P_{25}, P_{75}, P_{min} and P_{max} respectively. Likewise, the same statistics for temperature are referred to as T_{md}, T_{25}, T_{75}, T_{min} and T_{max}. These are presented as boxplots of climate variables in different time periods. When the character of a climate cluster is described as “high”, “moderate” and “low”, the climatic attribute’s values are described relative to the value range of the specific region in time, thus high PLIO precipitation rates may be higher than high LGM precipitation rates. The character is presented a raster plots, to allow compact visual representation of it. The actual mean values for each variable in every time-slice and region-specific cluster are included in tables in the supplementary material.

3.3.1 Climate change and palaeoclimate characteri~~z~~sation in South Asia, Central- and East Asia

This section describes the regional climatology of the four investigated Cenozoic time slices and how precipitation and temperature changes from PLIO to PI times in tropical, temperate and high altitude regions. LGM and PLIO simulations show the largest simulated temperature and precipitation deviations (Fig. 4b) from PI temperature and precipitation (Fig. 4a) in the South Asia region. LGM temperatures are 1-7°C below PI temperatures and the direction of deviation is uniform across the study region. PLIO temperature is mostly above PI temperatures by 1-7°C. The cooling of 3-5°C in the region immediately south of the Himalayan orogen represents one of the few exceptions. Deviations of MH precipitation from PI precipitation in the region are greatest along the eastern Himalayan orogeny, which experiences an increase in precipitation (≤2000 mm/a). The same region experiences a notable decrease in precipitation in the LGM simulation, which is consistent in direction with the prevailing precipitation trend on land during the LGM. PLIO precipitation on land is typically higher than PI precipitation.

Annual means of precipitation and temperature spatially averaged for the regional subdivisions and the different time slice simulations have been compared. The value range P_{25} to P_{75} of precipitation is higher for tropical South Asia than for temperate and high altitude South Asia (Fig. 5 a-c). The LGM values for P_{25}, P_{md} and P_{75} are lower than for the other time slice simulations, most visibly for tropical South Asia (ca. 100 mm/a). The temperature range (both T_{75}-T_{25} and T_{max}- T_{min}) is smallest in the hot (ca. 21°C) tropical South Asia, wider in the high altitude (ca. -8°C) South Asia, and widest in the temperate (ca. 2°C) South Asia region (Fig. 5 d-f). T_{md}, T_{25} and T_{75} values for the LGM are ca. 1°C, 1-2°C and 2°C below PI and MH temperatures in tropical, temperate and high altitude South Asia respectively, whereas the same temperature statistics for the PLIO simulation are ca. 1°C above PI and MH values in all regional subdivisions (Fig. 5 d-f). With respect to PI and MH values, precipitation and temperature are generally lower in the LGM and higher in the PLIO in tropical, temperate and high altitude South Asia.

In all time periods, the wettest climate cluster C_1 covers an area along the southeastern Himalayan orogen (Fig. 6 a-d) and is defined by the highest precipitation amplitude (dark blue, Fig. 6 e-h). $C_{5(PI)}$, $C_{3(MH)}$, $C_{4(LGM)}$ and $C_{5(PLIO)}$ are characterized by (dark blue, Fig. 6e-h) the highest temperatures, u-wind and v-wind speeds during the summer monsoon in their respective time periods, whereas $C_{4(PI)}$, $C_{5(MH)}$, and $C_{6(LGM)}$ are defined by low temperatures and highest temperature amplitude, u-wind and v-wind speeds outside the monsoon season (in January) in their respective time periods (Fig. 6 e-h). The latter 3 climate classes cover much of the more continental, northern landmass in their respective time periods and represents a cooler climate affected more by seasonal temperature fluctuations (Fig. 6 a-d). The two wettest climate clusters C_1 and C_2 are more restricted to the eastern end of the Himalayan orogen in the LGM than during other times, indicating that the LGM precipitation distribution over the South Asia landmass is more concentrated in this region than in other time slice experiments.

3.3.2 Climate change and palaeoclimate characteri~~z~~sation in the Andes, Western South America

This section describes the cluster analysis based regional climatology of the four investigated Late Cenozoic time slices and illustrates how precipitation and temperature changes from PLIO to PI in tropical and temperate low- and high altitude (i.e. Andes) regions in western South America (Fig. 7-9).

LGM and PLIO simulations show the largest simulated deviations (Fig. 7b) from PI temperature and precipitation (Fig. 7a) in western South America. The direction of LGM temperature deviations from PI temperatures is negative and uniform across the region. LGM temperatures are typically 1-3°C below PI temperatures across the region, and 1-7°C below PI values in the Peruvian Andes, which also experience the strongest and most widespread increase in precipitation during the LGM (≤1800 mm/a). Other regions, such as much of the northern Andes and tropical South America, experience a decrease of precipitation in the same experiment. PLIO temperature is mostly elevated above PI temperatures by 1-5°C. The Peruvian Andes experience a decrease in precipitation (≤2600mm), while the northern Andes are wetter in the PLIO simulation compared to the PI control simulation.

PI, MH, LGM and PLIO precipitation and temperature means for regional subdivisions have been compared. The P_{25} to P_{75} range is smallest for the relatively dry temperate Andes and largest for tropical South America and the tropical Andes (Fig. 8 a-d). P_{max} is lowest in the PLIO in all four regional subdivisions even though P_{md}, P_{25} and P_{75} in the PLIO simulation are similar to the same statistics calculated for PI and MH time slices. P_{md}, P_{25} and P_{75} for the LGM are ca. 50 mm/a lower in tropical South America and ca. 50 mm/a higher in the temperate Andes. Average PLIO temperatures are slightly warmer and LGM temperatures are slightly colder than PI and MH temperatures in tropical and temperate South America (Fig. 8 e and f). These differences are more pronounced in the Andes, however. T_{md}, T_{25} and T_{75} are ca. 5°C higher in the PLIO climate than in PI and MH climates in both temperate and tropical Andes, whereas the same temperatures for the LGM are ca. 2-4°C below PI and MH values (Fig. 8 g and h).

For the LGM, the model computes drier-than-PI conditions in tropical South America and tropical Andes, enhanced precipitation in the temperate Andes, and a decrease in temperature that is most pronounced in the Andes. For the PLIO, the model predicts precipitation similar to PI, but with lower precipitation maxima. PLIO temperatures generally increase from PI temperatures, and this increase is most pronounced in the Andes.

The climate variability in the region is described by six different clusters (Fig. 9 a-d), which have similar attributes in all time periods. The wettest climate C_1 is also defined by moderate to high precipitation amplitudes, low temperatures and moderate to high u-wind speeds in summer and winter in all time periods (dark blue, Fig. 9 e-h). $C_{2(PI)}$, $C_{2(MH)}$, $C_{3(LGM)}$ and $C_{2(PLIO)}$ are characterized by high temperatures and low seasonal temperature amplitude (dark blue, Fig. 9 e-h), geographically cover the north of the investigated region, and represent a more tropical climate. $C5_{(PI)}$, $C5_{(MH)}$, $C6_{(LGM)}$ and $C6_{(PLIO)}$ are defined by low precipitation and precipitation amplitude, high temperature amplitude and high u-wind speeds in winter (Fig. 9 e-h), cover the low-altitude south of the investigated region (Fig. 9 a-d) and represent dry, extra-tropical climates with more pronounced seasonality. In the PLIO simulation, the lower-altitude east of the region has four distinct climates, whereas the analysis for the other time slice experiments only yield three distinct climates for the same region.

3.3.3 Climate change and palaeoclimate characteris~~z~~ation in the St. Elias Range, Southeast Alaska

This section describes the changes in climate and the results from the cluster analysis for South Alaska (Fig. 10-12). As is the case for the other study areas, LGM and PLIO simulations show the largest simulated deviations (Fig. 10b) from PI temperature and precipitation (Fig. 10a). The sign of LGM temperature deviations from PI temperatures is negative and uniform across the region. LGM temperatures are typically 1-9°C below PI temperatures, with the east of the study area experiencing largest cooling. PLIO temperatures are typically 1-5°C above PI temperatures and the warming is uniform for the region. In comparison to the PI simulation, LGM precipitation is lower on land, but higher (≤2300mm) in much of the coastal regions of South Alaska. Annual PLIO precipitation is mostly higher (≤800mm) than for PI.

P_{md}, P_{25}, P_{75}, P_{min} and P_{max} for South Alaskan mean annual precipitation do not differ much between PI, MH and PLIO climates, while P_{md}, P_{25}, P_{75} and P_{min} decrease by ca. 20-40 mm/a and P_{max} increases during the LGM (Fig. 11a). The Alaskan PLIO climate is distinguished from the PI and MH climates by its higher (ca. 2°C) regional temperature means, T_{25}, T_{75} and T_{md} (Fig. 11b). Mean annual temperatures, T_{25}, T_{75}, T_{min} and T_{max} are lower in the LGM than in any other considered time period (Fig. 11b), and about 3-5°C lower than during the PI and MH.

Distinct climates are present in the PLIO to PI simulations for Southeast Alaska. Climate cluster C_1 is always geographically restricted to coastal southeast Alaska (Fig. 12 a-d) and characterized by the highest precipitation, precipitation amplitude, temperature, and by relatively low temperature amplitude (dark blue, Fig. 12 e-h). Climate C_2 is characterized by moderate to low precipitation, precipitation amplitude, temperature, and by low temperature amplitude. C_2 is either restricted to coastal southeast Alaska (in MH and LGM climates) or coastal southern Alaska (in PI and PLIO climates). Climate C_3 is described by low precipitation, precipitation amplitude, temperature, and moderate temperature amplitude in all simulations. It covers coastal western Alaska and separates climate C_1 and C_2 from the northern C_4 climate. Climate C_4 is distinguished by the highest mean temperature amplitude, by low temperature and precipitation amplitude, and by lowest precipitation.

The geographical ranges of PI climates C_1- C_4 and PLIO climates C_1- C_4 are similar. $C_{1(PI/PLIO)}$ and $C_{2(PI/PLIO)}$ spread over a larger area than $C_{1(MH/LGM)}$ and $C_{2(MH/LGM)}$. $C_{2(PI/PLIO)}$ are not restricted to coastal southeast Alaska, but also cover the coastal southwest of Alaska. The main difference in characterization between PI and PLIO climates C_1- C_4 lies in the greater difference (towards lower values) in precipitation, precipitation amplitude and temperature from $C_{1(PLIO)}$ to $C_{2(PLIO)}$ compared to the relatively moderate decrease in those means from $C_{1(PI)}$ to $C_{2(PI)}$.

3.3.4 Climate change and palaeoclimate characteri~~z~~sation in the Cascade Range, US Pacific Northwest

This section describes the character of regional climatology in the US Pacific Northwest and its change over time (Fig. 13-15). The region experiences cooling of typically 9-11°C on land during the LGM, and warming of 1-5°C during the PLIO (Fig. 13b) when compared to PI temperatures (Fig. 13a). LGM precipitation increases over water, decreases on land by ≤800 mm/a in the North and in the vicinity of Seattle and increases on land by ≤1400 mm/a on Vancouver Island, around Portland and the Olympic Mountains, whereas PLIO precipitation does not deviate much from PI values over water and varies in the direction of deviation on land. MH temperature and precipitation deviation from PI values are negligible.

P_{md}, P_{25}, P_{75}, P_{min} and P_{max} for the Cascade Range do not notably differ between the four time periods (Fig. 14a). The LGM range of precipitation values is slightly larger than that of the PI and MH with slightly increased P_{md}, while the respective range is smaller for simulation PLIO. The T_{md}, T_{25}, T_{75} and T_{max} values for the PLIO climate are ca. 2°C higher than those values for PI and MH (Fig. 14b). All temperature statistics for the LGM are notably (ca. 13°C) below their analogues in the other time periods (Fig. 14b).

PI, LGM and PLIO clusters are similar in both their geographical patterns (Fig. 15 a, c, d) and their characterization by mean values (Fig. 15 e, g, h). C_1 is the wettest cluster and shows the highest amplitude in precipitation. The common characteristics of the C_2 cluster are moderate to high precipitation and precipitation amplitude. C_4 is characterized by the lowest precipitation and precipitation amplitudes, and the highest temperature amplitudes. Regions assigned to clusters C_1 and C_2 are in proximity to the coast, whereas C_4 is geographically restricted to more continental settings.

In the PI and LGM climates, the wettest cluster C_1 is also characterized by high temperatures (Fig 10 e, g).

However, virtually no grid boxes were assigned to $C_{1(LGM)}$. $C_{1(MH)}$ differs from other climate state's C_1 clusters in that it is also described by moderate to high near surface temperature and temperature amplitude (Fig 10 f), and in that it is geographically less restricted and, covering much of Vancouver Island and the continental coastline north of it (Fig 10 b). Near surface temperatures are highest for C_2 in PI, LGM and PLIO climates (Fig 10 e, g, h) and low for $C_{2(MH)}$ (Fig 10 f). $C_{2(MH)}$ is also geographically more restricted than C_2 clusters in PI, LGM and PLIO climates (Fig 10 a-d). $C_{2(PI)}$, $C_{2(MH)}$ and $C_{2(LGM)}$ have a low temperature amplitude (Fig 10 e-g), whereas $C_{2(PLIO)}$ is characterized by a moderate temperature amplitude (Fig 10 h).

4. Discussion

In the following, we synthesis~~z~~e our results and compare to previous studies that investigate the effects of temperature and precipitation change on erosion. Since our results do not warrant merited discussion of subglacial processes without additional work that is beyond the scope of this study, we instead advise caution in interpreting the presented precipitation and temperature results in an erosional context where the regions are covered with ice. For convenience, ice cover is indicated on figures 2,3,47,10 and 13, and a summary of ice cover used as boundary conditions for the different time slice experiments is included in the supplemental material. Where~~n~~ possible, we relate the magnitude of climate change predicted in each geographical study area with terrestrial proxy data.

4.1 Synthesis of temperature changes ~~and implications for weathering and erosion~~

4.1.1 Temperature changes and implications for weathering and erosion

Changes in temperature can affect physical weathering due to temperature-induced changes in periglacial processes and promote frost cracking and frost creep [e.g., Matsuoka, 2001; Schaller et al., 2002; Matsuoka and Murton, 2008; Delunel et al., 2010; Andersen et al., 2015; Marshall et al., 2015], and also biotic weathering and erosion [e.g. Moulton et al., 1998; Banfield et al., 1999; Dietrich and Perron, 2006]. Quantifying and understanding past changes in temperature is thus vital for our understanding of denudation histories. In the following, we highlight regions in the world where future observational studies might be able to document significant warming or cooling that would influence temperature related changes in physical and chemical weathering over the last ~3 Ma.

Simulated MH temperatures show little deviation (typically < 1°C) from PI temperatures in the investigated regions (Fig. 2b), suggesting little difference in MH temperature-related weathering. The LGM experiences widespread cooling, which is accentuated at the poles. ~~LGM cooling is accentuated at the poles, in general agreement with studies such as Otto-Bliesner et al. [2006] and Braconnot et al. [2007], and~~ , increas~~es~~in the equator-to-pole pressure gradient and consequently strengthens global atmospheric circulation. Despite this global trend, cooling in coastal South Alaska is higher (≤ 9°C) than in central Alaska (0±1°C). The larger temperature difference in South Alaska geographically coincides with ice cover (Fig. 10b), and should thus be interpreted in context of a different erosional regime. Cooling in most of the lower-latitude regions in South America and central to southeast Asia is relatively mild. The greatest temperature differences in South America are observed for western Patagonia, which was mostly covered by glaciers. The Tibetan plateau experiences more cooling (3-5°C) than adjacent low-altitude regions (1-3°C) during the LGM.

The PLIO simulation is generally warmer, and temperature differences are ~~shows little to no warming in the tropics and~~ accentuated warming at the poles.~~, as do findings of Salzmann et al. [2011] and Robinson [2009] and Ballantyne [2010] respectively. This would reduce the equator-to-pole sea and land surface temperature gradient, as also reported by Dowsett et al. [2010], and also weaken global atmospheric circulation. Agreement with proxy-based reconstructions, as is the case of the relatively little warming in lower latitudes, is not surprising given that sea surface temperature reconstructions are prescribed in this uncoupled atmosphere simulation. It should be noted that coupled ocean-atmosphere simulations do predict more low-latitude warming [e.g. Stepanek and Lohmann 2012; Zhang et al. 2013b].~~ Warming in simulation PLIO is ~~present~~greatest in parts of Canada, ~~and~~ Greenland and Antarctia~~t~~ca (up to 19°C), which geographically coincides with the presence of ice in the PI reference simulation and thus may be attributed to differences in ice cover. It should therefore also be regarded as areas in which process domain shifted from glacial to non-glacial. ~~and consistent with values based on multi-proxy studies [Ballantyne et al., 2010]. Due to a scarcity of paleo-botanical proxies in Antarctica, reconstruction-based temperature and ice-sheet extent estimates for a PLIO climate have high uncertainties [Salzmann et al., 2011], making model validation difficult. Furthermore, controversy about relatively little warming in the south polar regions compared to the north polar regions remains [e.g. Hillenbrand and Fütterer, 2002; Wilson et al., 2002]. Mid-latitude PLIO warming is mostly in the 1-3°C range with notable exceptions of cooling in the northern tropics of Africa and on the Indian subcontinent, especially south of the Himalayan orogen.~~ The warming in simulation PLIO in South Alaska and the US Pacific northwest is mostly uniform and in the range of 1-5°C. As before, changes in ice cover reveal that the greatest warming may be associated with the absence of glaciers relative to the PI simulation. ~~whereas w~~Warming in South America is concentrated at the Pacific west coast and the Andes between Lima and Chiclayo, and along the Chilean-Argentinian Andes south of Bolivia (≤ 9°C).

Overall, annual mean temperatures in the MH simulation show little deviation from PI values. The more significant temperature deviations of the colder LGM and of the warmer PLIO simulations are accentuated at the poles leading to higher and lower equator-to-pole temperature gradients respectively. The largest temperature-related changes (relative to PI conditions) in weathering and subsequent erosion, in many cases through a shift in the process domain from glacial to non-glacial or vice versa, are therefore to be expected in the LGM and PLIO climates.

4.1.2 Temperature comparison to other studies

LGM cooling is accentuated at the poles, thus increases the equator-to-pole pressure gradient and consequently strengthens global atmospheric circulation, and is in general agreement with studies such as Otto-Bliesner et al. [2006] and Braconnot et al. [2007]. The PLIO simulation shows little to no warming in the tropics and accentuated warming at the poles, as do findings of Salzmann et al. [2011] and Robinson [2009] and Ballantyne [2010] respectively. This would reduce the equator-to-pole sea and land surface temperature gradient, as also reported by Dowsett et al. [2010], and also weaken global atmospheric circulation. Agreement with proxy-based reconstructions, as is the case of the relatively little warming in lower latitudes, is not surprising given that sea surface temperature reconstructions (derived from previous coarse resolution coupled ocean-atmosphere models) are prescribed in this uncoupled atmosphere simulation. It should be noted that coupled ocean-atmosphere simulations do predict more low-latitude warming [e.g. Stepanek and Lohmann 2012; Zhang et al. 2013b]. The PLIO warming in parts of Canada and Greenland (up to 19°C) and consistent with values based on multi-proxy studies [Ballantyne et al., 2010]. Due to a scarcity of palaeobotanical proxies in Antarctica, reconstruction-based temperature and ice-sheet extent estimates for a PLIO climate have high uncertainties [Salzmann et al., 2011], making model validation difficult. Furthermore, controversy about relatively little warming in the south polar regions compared to the north polar regions remains [e.g. Hillenbrand and Fütterer, 2002; Wilson et al., 2002]. Mid-latitude PLIO warming is mostly in the 1-3°C range with notable exceptions of cooling in the northern tropics of Africa and on the Indian subcontinent, especially south of the Himalayan orogen.

4.2 Synthesis of precipitation changes ~~and implications for orogen denudation~~

4.2.1 Precipitation and implications for weathering and erosion

Changes in precipitation affects erosion through river incision, sediment transport, and erosion due to extreme precipitation events and storms [e.g. Whipple and Tucker, 1999; Hobley et al., 2010]. Furthermore, vegetation type and cover also co-evolve with variations in precipitation and with changes in geomorphology [e.g. Marston 2010; Roering et al., 2010]. These vegetation changes in turn modify hillslope erosion by increasing root mass and canopy cover, and decreasing water-induced erosion via surface runoff [e.g. Gyssels et al., 2005]. Therefore, understanding and quantifying changes in precipitation in different palaeo~~-~~climates is necessary for a more complete reconstruction of orogen denudation histories. A synthesis of predicted precipitation changes is provided below, and highlights regions where changes in river discharge and hillslope processes might be impacted by climate change over the last ~3 Ma.

Most of North Africa is notably wetter during the MH, which is characteristic of the African Humid Period [Sarnthein 1978]. This pluvial regional expression of the Holocene Climatic Optimum is attributed to sudden changes in the strength of the African monsoon caused by orbital-induced changes in summer insolation [e.g. deMenocal et al.

2000]. Southern Africa is characterised by a wetter climate to the east and drier climate to the west of the approximate location of the Congo Air Boundary (CAB), the migration of which has previously been cited as a cause for precipitation changes in East Africa [e.g. Juninger et al. 2014]. In contrast, simulated MH precipitation rates show little deviation from the PI in most of the investigated regions, suggesting little difference in MH precipitation-related erosion. The Himalayan orogen is an exception and shows a precipitation increase of ≤ up to 2000 mm/a. The climate's enhanced erosion potential, that could result from such a climatic change, should be taken into consideration when palaeo-erosion rates estimated from the geological record in this area are interpreted [e.g. Bookhagen et al., 2005]. Specifically, higher precipitation rates (along with differences in other rainfall-event parameters) could increase the probability of mass movement events on hillslopes, especially where hillslopes are close to the angle of failure [e.g. Montgomery, 2001], and modify fluxes to increase shear stresses exerted on river beds and increase stream capacity to enhance erosion on river beds (e.g. by abrasion).

Most precipitation on land is decreased during the LGM due to large-scale cooling and decreased evaporation over the tropics, resulting in an overall decrease in inland moisture transport [e.g., Braconnot et al. 2007]. ~~Coastal~~ North America, south of the continental ice sheets, is an exception and experiences increases in precipitation. ~~, t~~For example, the investigated US Pacific Northwest and the southeastern coast of Alaska ~~are exceptions in that there is~~experience experience strongly enhanced precipitation of ≤1700 mm/a and ≤2300 mm/a, respectively. These changes geographically coincide with differences in ice extent. An increase in precipitation in these regions may have had direct consequences on the glaciers' mass balance and equilibrium line altitudes, where the glaciers' effectiveness in erosion is highest [e.g. Egholm et al., 2009; Yanites and Ehlers, 2012]. The differences in the direction of precipitation changes, and accompanying changes in ice cover ~~Reduced precipitation in other parts of southern Alaska result in a stronger south-to-north drying gradient than in the PI simulation. This could~~ would likely result in more regionally differentiated variations in precipitation-specific erosional processes in the St. Elias Range rather than causing systematic offsets for the LGM. Although precipitation is significantly reduced along much of the Himalayan orogen (≤1600 mm/a), ~~which is consistent with findings by, e.g., Braconnot et al. [2007]~~, northeast India experiences strongly enhanced precipitation (≤1900 mm/a). This could have large implications for studies of uplift and erosion at orogen syntaxes, where highly localized and extreme denudation has been documented [e.g. Koons et al., 2013; Bendick and Ehlers, 2014].

Overall, the PLIO climate is wetter than the PI climate, in particular in the (northern) mid-latitudes, and possibly related to a northward shift of the northern Hadley cell boundary that is ultimately the result of a reduced equator-to-pole temperature gradient [e.g. Haywood et al. 2000, 2013; Dowsett et al. 2010]. ~~A reduction of this gradient by ca. 5°C is indeed present in the PLIO simulation of this study (Fig. 2b).~~ Most of the PLIO precipitation over land increases ~~during the PLIO. This finding agrees well with simulations performed at a lower spatial model resolution [cf. Stepanek and Lohmann, 2012]. PLIO precipitation significantly increases~~, esp. at the Himalayan orogen by ≤1400 mm/a, and decreases from eastern Nepal to Namcha Barwa (≤2500 mm/a). Most of the Atacama Desert experiences an increase in precipitation by 100-200 mm/a, which may have to be considered in erosion and uplift history reconstructions for the Andes. A significant increase (~2000 mm/a) in precipitation from simulation PLIO to modern conditions is simulated for the eastern margin of the Andean Plateau in Peru and for northern Bolivia. This is consistent with recent findings of a pulse of canyon incision in these locations in the last ~3 Ma [Lease and Ehlers, 2013].

Overall, the simulated MH precipitation varies least from PI precipitation. The LGM is generally drier than the PI simulation, even though pockets of a wetter-than-PI climate do exist, such as much of coastal North America. Extra-tropical increased precipitation of the PLIO simulation and decreased precipitation of the LGM climate may be the result of decreased and increased equator-to-pole temperature gradients, respectively.

4.2.2 Precipitation comparison to other studies

The large scale LGM precipitation decrease on land, related to cooling and decreased evaporation over the tropics, and greatly reduced precipitation along much of the Himalayan orogeny, is consistent with previous studies by, (for example) Braconnot et al. [2007]. The large scale PLIO precipitation increase due to a reduced equator-to-pole temperature gradient, has previously been pointed out by e.g. Haywood et al. [2000, 2013] and Dowsett et al. [2010]. A reduction of this gradient by ca. 5°C is indeed present in the PLIO simulation of this study (Fig. 2b). This precipitation increase over land agrees well with simulations performed at a lower spatial model resolution [cf. Stepanek and Lohmann, 2012]. Section 4.4 includes a more in-depth discussion of how simulated MH and LGM precipitation differences compare with proxy-based reconstructions in South Asia and South America.

4.3 Trends in Late Cenozoic changes in regional climatology

This section describes the major changes in regional climatology and highlights their possible implications on erosion rates.

Himalaya-Tibet, South Asia

In South Asia, cluster-analysis based categorization and description of climates (Fig. 6) remains similar throughout time. However, the two wettest climates (C_1 and C2) are geographically more restricted to the eastern Himalayan orogen in the LGM simulation. Even though precipitation over the South Asia region is generally lower, this shift indicates that rainfall on land is more concentrated in this region and that the westward drying gradient along the orogen is more accentuated than during other time periods investigated here. While there is limited confidence in the global Atmospheric General Circulation Model's abilities to accurately represent meso-scale precipitation patterns [e.g. Cohen 1990], the simulation warrants careful consideration of possible, geographically non-uniform offsets in precipitation in investigations of denudation and uplift histories.

MH precipitation and temperature in tropical, temperate and high-altitude South Asia is similar to PI precipitation and temperature, whereas LGM precipitation and temperatures are generally lower (by ca. 100 mm/a and 1-2°C respectively), possibly reducing precipitation-driven erosion and enhancing frost-driven erosion in areas pushed into a near-zero temperature range during the LGM.

Andes, South America

Clusters in South America (Fig. 9), which are somewhat reminiscent of the Köppen and Geiger classification [Kraus, 2001], remain mostly the same over the last 3 Ma. In the PLIO simulation, the lower-altitude east of the region is characterized by four distinct climates, which suggests enhanced latitudinal variability in the PLIO climate compared to PI with respect temperature and precipitation.

The largest temperature deviations from PI values are derived for the PLIO simulation in the (tropical and temperate) Andes, where temperatures exceed PI values by 5°C. On the other hand, LGM temperatures in the Andes are ca. 2-4°C below PI values in the same region (Fig 7 g and h). In the LGM simulation, tropical South America experiences ca. 50 mm/a less precipitation, the temperate Andes receive ca. 50 mm/a more precipitation than in PI and MH simulations. These latitude-specific differences in precipitation changes ought to be considered in attempts to reconstruct precipitation-specific palaeo~~-~~erosion rates in the Andes on top of longitudinal climate gradients highlighted by, e.g., Montgomery et al. [2001].

St. Elias Range, South Alaska

South Alaska is subdivided into two wetter and warmer clusters in the south, and two drier, colder clusters in the north. The latter are characteris~~z~~ed by increased seasonal temperature variability due to being located at higher latitudes (Fig. 12). The different equator-to-pole temperature gradients for LGM and PLIO may affect the intensity of the Pacific North American Teleconnection (PNA) [Barnston and Livzey, 1987], which has significant influence on temperatures and precipitation, especially in southeast Alaska, and may in turn result in changes in regional precipitation and temperature patterns and thus on glacier mass balance. Changes in the Pacific Decadal Oscillation, which is related to the PNA pattern, has previously been connected to differences in Late Holocene precipitation [Barron and Anderson, 2011]. While this climate cluster pattern appears to be a robust feature for the considered climate states, and hence over the recent geologic history, the LGM sets itself apart from PI and MH climates by generally lower precipitation (20-40 mm) and lower temperatures (3-5°C, Fig. 10, 11), which may favour frost driven weathering during glacial climate states [e.g. Andersen et al., 2015; Marshall et al. 2015] in unglaciated areas, whereas glacial processes would have dominated most of this region as it was covered by ice. Simulation PLIO is distinguished by temperatures that exceed

PI and MH conditions by ca. 2°C, and by larger temperature and precipitation value ranges, possibly modifying temperature- and precipitation-dependent erosional processes in the region of South Alaska.

Cascade Range, US Pacific Northwest

In all time slices, the geographic climate patterns, based on the cluster analysis (Fig. 15), represents an increase in the degree of continentality from the wetter coastal climates to the further inland located climates with greater seasonal temperature amplitude and lower precipitation and precipitation amplitude (Fig 15 e-h). The most notable difference between the time slices is the strong cooling during the LGM, when temperatures are ca. 13°C (Fig. 13, 14) below those of other time periods~~,~~. Given that the entire investigated region was covered by ice (Fig 13), we can assume a shift to glacially dominated processes. ~~possibly leading to enhanced sediment production driven by frost processes, as proposed for parts of the Pacific Northwest by Marshall et al. [2015].~~

4.4 Comparison of simulated and observed precipitation differences

The predicted precipitation differences reported in this study were compared with observed (proxy record) palaeoprecipitation change. Proxy based precipitation reconstructions for the MH and LGM are presented for South Asia and South America for the purpose of assessing ECHAM5 model performance, and for identifying inconsistencies between neighbouring proxy data. Due to the repeated glaciations, detailed terrestrial proxy records for the time slices investigated here are not available, to the best of our knowledge, for the Alaskan and Pacific NW USA studies. Although marine records and records of glacier extent are available in these regions, the results from them do not explicitly provide estimates of wetter/drier, or colder/warmer conditions that can be spatially compared to the simulation estimates. For these two areas with no available records, the ECHAM5 predicted results therefore provide predictions from which future studies can formulate testable hypotheses to evaluate.

The palaeoclimate changes in terrestrial proxy records compiled here are reported as “wetter than today”, “drier than today” or “the same as today” for each of the study locations, and plotted on top of the simulation-based difference maps as upward facing blue triangles, downward facing red triangles and grey circles respectively (Fig. 16, 17). The numbers listed next to those indicators are the ID numbers assigned to the studies compiled for this comparison and are associated with a citation provided in the figure captions.

In South Asia, 14/26 results from local studies agree with the model predicted precipitation changes for the MH. The model seems able to reproduce the predominantly wetter conditions on much of the Tibetan plateau, but predicts slightly drier conditions north of Chengdu, which is not reflected in local reconstructions. The modest mismatch between ECHAM5 predicted and proxy-based MH climate change in south Asia was also documented by Li et al., [2017], whose simulations were conducted at a coarser (T106) resolution. Despite these model-proxy differences, we note that there are significant discrepancies between the proxy data themselves in neighbouring locations in the MH, highlighting caution in relying solely upon these data for regional palaeoclimate reconstructions. These differences could result from either poor age-constraints in the reported values, or systematic errors in the transfer functions used to convert proxy measurements to palaeoclimate conditions. The widespread drier conditions on the Tibetan Plateau and immediately north of Laos are confirmed by 7/7 of the palaeoprecipitation reconstructions. 23/39 of the reconstructed precipitation changes agree with model predictions for South America during the MH. The model predicted wetter conditions in the central Atacama desert, as well as the drier conditions northwest of Santiago are confirmed by most of the reconstructions. The wetter conditions in southernmost Peru and the border to Bolivia and Chile cannot be confirmed by local studies. 11/17 of the precipitation reconstructions for the LGM are in agreement with model predictions. These include wetter conditions in most of Chile. The most notable disagreement can be seen in northeast Chile at the border to Argentina and Bolivia, where model predicted wetter conditions are not confirmed by reported reconstructions from local sites.

Model performance is, in general, higher for the LGM than for the MH and overall satisfactory given that it cannot be expected to resolve sub-grid scale differences in reported palaeoprecipitation reconstructions. However, as mentioned above, it should be noted that some locations (MH of south Asia, and MH of norther Chile) discrepancies exist between neighbouring proxy samples and highlight the need for caution in how these data are interpreted. Other potential sources of error resulting in disagreement of simulated and proxy-based precipitation estimates are the model's shortcomings in simulating orographic precipitation at higher resolutions, and uncertainties in palaeoclimate reconstructions at the local sites. In summary, although some differences are evident in both the model-proxy data comparison and between neighbouring proxy data themselves, the above comparison highlights an overall good agreement between the model and data for the south Asia and South American study areas. Thus, although future advances in GCM model parameterisations and new or improved palaeoclimate proxy techniques are likely, the palaeoclimate changes documented here are found to be in general robust and provide a useful framework for future studies investigating how these predicted changes in palaeoclimate impact denudation.

4.45 Conclusions

We present a statistical cluster-analysis-based description of the geographic coverage of possible distinct regional expressions of climates from four different time slices (Fig. 6, 9, 12, 15). These are determined with respect to a selection of variables that characterize the climate of the region and may be relevant to weathering and erosional processes. While the geographic distribution of climate ~~patterns~~ remains similar throughout time (as indicated by results of four different climate states representative for the climate of the last 3 Ma), results for the PLIO simulation suggests more climatic variability east of the Andes (with respect to near-surface temperature, seasonal temperature amplitude, precipitation, seasonal precipitation amplitude and seasonal u-wind and v-wind speeds). Furthermore, the wetter climates in the South Asia region retreat eastward along the Himalayan orogen for the LGM simulation, this is due to decreased precipitation along the western part of the orogen and enhanced precipitation on the eastern end, possibly signifying more localised high erosion rates.

Most global trends of the high-resolution LGM and PLIO simulations conducted here are in general agreement with previous studies [Otto-Bliesner et al., 2006; Braconnot et al., 2007; Wei and Lohmann, 2012; Lohmann et al., 2013; Zhang et al., 2013b, 2014; Stepanek and Lohmann, 2012]. The MH does not deviate notably from the PI, the LGM is relatively dry and cool, while the PLIO is comparably wet and warm. While the simulated regional changes in temperature and precipitation usually agree with the sign (or direction) of the simulated global changes, there are region-specific differences in the magnitude and direction. For example, the LGM precipitation of the Tropical Andes does not deviate significantly from PI precipitation, whereas LGM precipitation in the Temperate Andes is enhanced.

Comparisons to local, proxy-based reconstructions of MH and LGM precipitation in South Asia and South America reveal satisfactory performance of the model in simulating the reported differences. The model performs better for the LGM than the MH. We note however that compilations of proxy data such as we present here, also identify inconsistences between neighbouring proxy data themselves, warranting caution in the extent to which both proxy data and palaeoclimate models are interpreted for MH climate change in south Asia, and western South America.

The changes in regional climatology presented here are manifested, in part, by small to large magnitude changes in fluvial and hillslope relevant parameters such as precipitation and temperature. For the regions investigated here we find that precipitation differences between the PI, MH, LGM, and PLIO are in many areas around +/- 200-600 mm/yr, and locally can reach maximums of +/- 1000-2000 mm/yr (Figs. 4, 7, 10, 13). In areas where significant precipitation increases are accompanied by changes in ice extent, such as parts of southern Alaska during the LGM, we would expect a shift in the erosional regime to glacier dominated processes. Temperature differences between these same time periods are around 1-4 °C in many places, but reach maximum values of 8-10 °C. Many of these maxima in the temperature differences geographically coincide with changes in ice sheet extent and must therefore be interpreted as part of a different erosional process domains. However, we also observe large temperature differences (~5°C) in unglaciated areas that would be affected by hillslope, frost cracking, and fluvial processes. The magnitude of these differences are not trival, and will likely impact fluvial and hillslope erosion and sediment transport, as well as biotic and abiotic weathering. The regions of large magnitude changes in precipitation and temperature documented here (Figs. 4, 7, 10, 13) offer the highest potential for future observational studies interested in quantifying the impact of climate change on denudation and weathering rates.

Acknowledgements

The model simulations presented in this study are freely available to interested persons by contacting S. Mutz or T. Ehlers. We note however that the data files are very large (~4 TB, and too large to archive in journal supplementary material) and require familiarity in reading/plotting NetCDF formatted files. ~~Support from~~ European Research Council (ERC) Consolidator Grant number 615703 provided support for S. Mutz. Additional support is acknowledged from the German science foundation (DFG) priority research program 1803 (EarthShape: Earth Surface Shaping by Biota; grants EH329/14-1 and EH329/17-1). We thank B. Adams and J. Starke for constructive discussions. We also thank the reviewers (incl. A. Wickert) for their constructive feedback on this manuscript, which helped to significantly improve it. The DKRZ is thanked for computer time used for some of the simulations presented here. C. Stepanek, M. Werner, and G. Lohmann acknowledge funding by the Helmholtz Climate Initiative Reklim and the Alfred Wegener Institute's research programme Marine, Coastal and Polar Systems.

Figure Captions

Figure 1 Topography for regions (a) tropical South Asia, (b) temperate South Asia, (c) high altitude South Asia, (d) temperate South America, (e) tropical South America, (f) temperate Andes, (g) tropical Andes~~.~~, SE Alaska and Cascadia.

Figure 2 Global PI annual mean near-surface temperatures (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b). Units are °C and insignificant ($p < 99\%$) differences (as determined by a t-test) are greyed out.

Figure 3 Global PI annual mean precipitation (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b). Units are mm/yr.

Figure 4 PI annual mean near-surface temperatures (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b) for the South Asia region. Insignificant ($p < 99\%$) differences (as determined by a t-test) are greyed out.

Figure 5 PI, MH, LGM and PLIO annual mean precipitation in (a) tropical South Asia, (b) temperate South Asia, and (c) high-altitude South Asia; PI, MH, LGM and PLIO annual mean temperatures in (d) tropical South Asia, (e) temperate South Asia, and (f) high-altitude South Asia. For each time slice, the minimum, lower 25th percentile, median, upper 75th percentile and maximum are plotted.

Figure 6 Geographical coverage and characterization of climate classes C_1- C_6 based on cluster-analysis of 8 variables (near surface temperature, seasonal near surface temperature amplitude, total precipitation, seasonal precipitation amplitude, u-wind in January and July, v-wind in January and July) in the South Asia region. The geographical coverage of the climates C_1- C_6 is shown on the left for PI (a), MH (b), LGM (c) and PLIO (d); the complementary, time-slice specific characterization of C_1- C_6 for PI (e), MH (f), LGM (g) and PLIO (h) is shown on the right.

Figure 7 PI annual mean near-surface temperatures (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b) for western South America. Insignificant ($p < 99\%$) differences (as determined by a t-test) are greyed out.

Figure 8 PI, MH, LGM and PLIO annual mean precipitation in (a) tropical South America, (b) temperate South America, (c) tropical Andes, and (d) temperate Andes; PI, MH, LGM and PLIO annual mean temperatures in (e) tropical South America, (f) temperate South America, (g) tropical Andes, and (h) temperate Andes. For each time slice, the minimum, lower 25th percentile, median, upper 75th percentile and maximum are plotted.

Figure 9 Geographical coverage and characterization of climate classes C_1- C_6 based on cluster-analysis of 8 variables (near surface temperature, seasonal near surface temperature amplitude, precipitation, seasonal precipitation amplitude, u-wind in January and July, v-wind in January and July) in western South America. The geographical coverage of the climates C_1- C_6 is shown on the left for PI (a), MH (b), LGM (c) and PLIO (d); the complementary, time-slice specific characterization of C_1- C_6 for PI (e), MH (f), LGM (g) and PLIO (h) is shown on the right.

Figure 10 PI annual mean near-surface temperatures (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b) for the South Alaska region. Insignificant ($p < 99\%$) differences (as determined by a t-test) are greyed out.

Figure 11 PI, MH, LGM and PLIO annual mean precipitation (a), and mean annual temperatures (b) in South Alaska. For each time slice, the minimum, lower 25th percentile, median, upper 75th percentile and maximum are plotted.

Figure 12 Geographical coverage of climate classes C_1- C_4 based on cluster-analysis of 4 variables (near surface temperature, seasonal near surface temperature amplitude, total precipitation, seasonal total precipitation amplitude) in southern Alaska. The geographical coverage of the climates C_1- C_4 is shown on the left for PI (a,), MH (b), LGM (c) and PLIO (d); the complementary, time-slice specific characterization of C_1- C_6 for PI (e), MH (f), LGM (g) and PLIO (h) is shown on the right.

Figure 13 PI annual mean near-surface temperatures (a), and deviations of MH, LGM and PLIO annual mean near-surface temperatures from PI values (b) for the US Pacific Northwest. Insignificant ($p < 99\%$) differences (as determined by a t-test) are greyed out.

Figure 14 PI, MH, LGM and PLIO annual mean precipitation (a), and annual mean temperatures (b) in the Cascades, US Pacific Northwest. For each time slice, the minimum, lower 25th percentile, median, upper 75th percentile and maximum are plotted.

Figure 15 Geographical coverage and characterization of climate classes C_1- C_4 based on cluster-analysis of 4 variables (near surface temperature, seasonal near surface temperature amplitude, total precipitation, seasonal total precipitation amplitude) in the Cascades, US Pacific Northwest. The geographical coverage of the climates C_1- C_4 is shown on the left for PI (a), MH (b), LGM (c) and PLIO (d); the complementary, time-slice specific characterization of C_1- C_6 for PI (e), MH (f), LGM (g) and PLIO (h) is shown on the right.

Figure 16 Simulated annual mean precipitation deviations of MH (left) and LGM (right) from PI values in South Asia, and temporally corresponding proxy-based reconstructions, indicating wetter (upward facing blue triangles), drier (downward facing red triangles) or similar (grey circles) conditions in comparison with modern climate. MH proxy-based precipitation differences are taken from Mügler et al. (2010) (**66**), Wischnewski et al. (2011) (**67**), Mischke et al. (2008), Wischnewski et al. (2011), Herzschuh et al. (2009) (**68**), Yanhong et al. (2006) (**69**), Morrill et al. (2006) (**70**), Wang et al. (2002) (**71**), Wuennemann et al. (2006) (**72**), Zhang et al. (2011), Morinaga et al. (1993), Kashiwaya et al. (1995) (**73**), Shen et al. (2005) (**74**), Liu et al. (2014) (**75**), Herzschuh et al. (2006) (**76**), Zhang and Mischke (2009) (**77**), Nishimura et al. (2014) (**78**), Yu and Lai (2014) (**79**), Gasse et al. (1991) (**80**), Van Campo et al. (1996) (**81**), Demske et al. (2009) (**82**), Kramer et al. (2010) (**83**), Herzschuh et al. (2006) (**84**), Hodell et al. (1999)(**85**), Hodell et al. (1999) (**86**), Shen et al. (2006) (**87**), Tang et al. (2000) (**88**), Tang et al. (2000) (**89**), Zhou et al. (2002) (**90**), Liu et al. (1998) (**91**), Asashi (2010)(**92**), Kotila et al. (2009) (**93**), Kotila et al. (2000) (**94**), Wang et al. (2002) (**95**), Hu et al. (2014) (**96**), Hodell et al. (1999) (**97**), Hodell et al. (1999) (**98**).

Figure 17 Simulated annual mean precipitation deviations of MH (left) and LGM (right) from PI values in South America, and temporally corresponding proxy-based reconstructions, indicating wetter (upward facing blue triangles), drier (downward facing red triangles) or similar (grey circles) conditions in comparison with modern climate. MH proxy-based precipitation differences are taken from Bird et al. (2011) (**1**), Hansen et al (1994) (**2**), Hansen et al (1994) (**3**), Hansen et al (1994) (**4**), Hansen et al (1994) (**5**), Hansen et al (1994) (**6**), Hillyer et al. (2009) (**7**), D'Agostino et al. (2002) (**8**), Baker et al. (2001) (**9**), Schwalb et al (1999) (**10**), Schwalb et al (1999) (**11**), Schwalb et al (1999) (**12**), Schwalb et al (1999) (**13**), Moreno et al (2009) (**14**), Pueyo et al (2011) (**15**), Mujica et al (2015) (**16**), Fritz et al. (2004) (**17**), Gayo et al. (2012) (**18**), Latorre et al. (2006) (**19**), Latorre et al. (2003) (**20**), Quade et al (2008) (**21**), Bobst et al. (2001) (**22**), Grosjean et al. (2001) (**23**), Betancourt et al. (2000) (**24**), Latorre et al. (2002) (**25**), Rech et al. (2003) (**26**), Diaz et al. (2012) (**27**), Maldonado et al (2005) (**28**), Diaz et al. (2012) (**29**), Lamy et al. (2000) (**30**), Kaiser et al. (2008) (**31**), Maldonado et al. (2010) (**32**), Villagrán et al. (1990) (**33**), Méndez et al. (2015) (**34**), Maldonado et al. (2006) (**35**), Lamy et al. (1999) (**36**), Jenny et al. (2002) (**37**), Jenny et al. (2002b) (**38**), Villa-Martínez et al. (2003) (**39**), Bertrand et al. (2008) (**40**), De Basti et al. (2008) (**41**), Lamy et al. (2009) (**42**), Lamy et al. (2002) (**43**), Szeicz et al. (2003) (**44**), de Porras et al. (2012) (**45**), de Porras et al. (2014) (**46**), Markgraf et al. (2007) (**47**), Siani et al. (2010) (**48**), Gilli et al. (2001) (**49**), Markgraf et al. (2003) (**50**), Stine et al. (1990) (**51**).

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