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Could the Pliocene constrain the Equilibrium Climate Sensitivity?

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Abstract. The mid-Pliocene Warm Period (mPWP) is the most recent interval in which atmospheric carbon dioxide was substantially higher than in modern pre-industrial times. It is, therefore, a potentially valuable target for testing the ability of climate models to simulate climates warmer than the pre-industrial state. The recent Pliocene model inter-comparison Project (PlioMIP) presented boundary conditions for the mPWP, and a protocol for climate model experiments. Here we analyse results from the PlioMIP and, for the first time, discuss the potential for this interval to usefully constrain the equilibrium climate sensitivity. We present an estimate of 1.8–3.6^{o}C, but there are considerable uncertainties surrounding the analysis. We consider the extent to which these uncertainties may be lessened in the next few years.

1 Introduction

One important motivation for the study of paleoclimates is that they may provide information as to how the climate will change in the future. The temperature response to changes in radiative forcing provides one simple way to summarise this through the equilibrium or Charney climate sensitivity, S. This is defined as the equilibrium response of the globally averaged surface air temperature (SAT) to a doubling of atmospheric CO_2 concentration. As a key measure of climate changes, this is one of the principal parameters by which we understand and interpret climate system behaviours.

There is evidence of both warmer and colder climates in the past. As we look increasingly further back in time, the evidence available in the paleorecord generally becomes both more sparse and less certain, and for this reason it is usually advantageous to focus research on the more recent past where possible. The most recent periods with climates that are substantially different to the present on the global scale have typically been colder than present with large ice sheets over northern continents (i.e., the ice ages). While the Last Glacial Maximum (LGM, 21ka BP) has been extensively studied, it is challenging to draw inferences from colder climates regarding our warmer future, in part because of the ice sheets that strongly affect the climate system over large areas of the Northern Hemisphere. Thus increased attention has recently been given to warmer periods (Lunt et al., 2013). These are generally more distant in time, and data are less certain, but the inference from past to future is potentially more robust as changes in ice sheets are relatively smaller. It is this inference that the current paper explores. We focus on the mid-Pliocene warm period (mPWP), 2.97–3.29 million years before the present, as this represents the most recent time that the atmospheric $\mathrm{CO_2}$ level was substantially higher than in pre-industrial times and data from the interval also suggest that the mPWP climate was warmer than the pre-industrial.

Researchers have previously explored the mPWP as a constraint on the Earth System Sensitivity (ESS), a broader concept than Equilibrium Climate Sensitivity S which also considers the longer-term feedbacks involved in the evolution of the ice sheets, and also changes in vegetation (Lunt et al., 2010). The aim of this paper is to explore the possibility that the mPWP may inform directly on the equilibrium climate sensitivity. The methodology adopted is similar to that of Hargreaves et al. (2012) who used simulations of the LGM. The underlying hypothesis is that the models with higher response to past radiative forcing changes, will also have a higher response to current and future radiative forcing changes. If this hypothesis is correct, it should be evident as a relationship (most simply, a linear correlation) between past and future warming across the ensemble. If a correlation is indeed observed, then data relating to the past warming should, in principle, be able to help constrain the future (Schmidt et al., 2014a).

In the next section we consider some technical aspects of the method employed in the context of previous work on the LGM. Then in the Analysis section we introduce the models, the results from the correlation, the data, and then the estimate of climate sensitivity. In the following section we test the sensitivity of the result to uncertainties inherent in the calculation. Finally we discuss the results and the prospect for decreasing some uncertainties in the future.

2 Methodology

The basic idea is that, if the past behaviour of the models is indicative of their future behaviour in some relevant manner, then it should be possible in principle to use observations of the past to deduce which models are more reliable and hence generate a constrained forecast of the future. Boé et al. (2009) provides an example of this idea, using recent changes in sea ice extent to predict the future decline. In principle it is possible to exhaustively explore an ensemble of climate model simulations for all possible relationships between past and future climate changes in variables of interest. For any cases where such a relationship is found (and for which we can also estimate the past change through some observation or climate reconstruction) we could in theory generate a forecast of the future change. However, there is a strong risk that this data mining process will generate spurious results that will not be borne out in reality (Caldwell et al., 2014). More immediately, the relationship may not be supported by the next generation of climate models (Fasullo and Trenberth, 2012; Grise et al., 2015). Thus, it is also important to ensure that the relationship is a physically meaningful one

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that represents our understanding of the climate system, and is not merely a spurious correlation arising through chance.

The methodology employed here is essentially the same as that used in Hargreaves et al. (2012). They found a significant correlation in the ensemble from PMIP2 (the second phase of the Paleoclimate Modelling Inter-comparison Project Braconnot et al. (2007)) between the modelled cooling in the tropical ocean during the LGM, and the equilibrium climate sensitivity. This is a physically plausible result, as the temperature anomaly in the tropical region at the LGM is expected to be strongly dominated by greenhouse gas (GHG) forcing, and the tropical region (representing 50% of the globe) contributes substantially to global mean temperature changes. Furthermore, the response to CO_2 forcing is, at least in models, close to linear over this range of positive and negative forcing changes. Based on the correlation that Hargreaves et al. (2012) obtained, they created a simple linear regression model which used the LGM tropical temperature anomaly to predict the equilibrium sensitivity, and applied this to estimate the Earth's equilibrium sensitivity from a reconstruction of the actual LGM tropical temperature anomaly. However, it must also be noted that the correlation for the LGM, although statistically significant, was not overwhelmingly strong. Moreover, the PMIP3 ensemble gave much more equivocal results (Harrison et al., 2015; Hopcroft and Valdes, 2015). Thus, it remains challenging to use the LGM to quantitatively constrain S.

One issue that Hargreaves et al. (2012) did not discuss, was whether the relationship should be considered in terms of S regressed on the tropical paleoclimate temperature anomaly, or vice versa. An intermediate method like total least squares could also in principle be applied. The implicit assumption for the choice made in Hargreaves et al. (2012), of regressing S on LGM tropical temperature, is that the deviations in sensitivity value from the regression line are predominantly due to factors which are independent of the LGM tropical response. Further consideration supports this choice according to the following argument. Uncertainty in the equilibrium sensitivity S can be considered as being decomposed into various physical processes and feedbacks, including the response of clouds at both low and high latitudes, snow and ice albedo feedbacks at high latitudes, and various other factors. Therefore, looking at the response in the tropics alone is unlikely to give a precise indication of S. The uncertainties arising from the additional factors at higher latitudes are conceptually independent of the tropical response, and thus we can reasonably try to use the linear model

$$S = \alpha T_P + C + \epsilon$$

where T_P is here the tropical temperature response, α and C are *a priori* unknown constants and the error term ϵ includes the uncertainties due to factors such as the uncertainties in the high latitude feedbacks discussed above. In the inverse regression, where we would try to use the equilibrium sensitivity to predict tropical temperature changes, the uncertainties over and above the underlying linear relationship would have to be assumed independent of S, which does not seem so appropriate.

3 Analysis

3.1 The models

The Pliocene Model Inter-comparison Project (PlioMIP, Haywood et al. (2010, 2011)) has presented boundary conditions in order for climate models to simulate the mPWP. This was not a true "time slice" experiment such as the LGM simulations, which represented the climatic average over an interval of 19–23ka BP. The much longer mid-Pliocene interval contained multiple ice age cycles, and the mPWP experiments were designed to represent a typical or average interglacial within this period. There were two experiments conducted in PlioMIP. Experiment 1 (Haywood et al., 2010) used atmosphere-only climate models, with the sea surface temperature boundary condition prescribed from a reconstruction which is discussed further in the next section. For these simulations, we expect the SAT anomaly to be tightly constrained by the imposed boundary conditions (especially over the ocean) and therefore to bear little relationship with the model's sensitivity. The model results bear this out, and thus we do not consider these simulations further. There were 10 models that performed Experiment 2, in which coupled atmosphere-ocean general circulation models were forced with a suite of boundary conditions including a land-sea mask, topography, ice-sheet, vegetation, and green house gas concentration (see Haywood et al. (2011) for details). For these models, we expect their mPWP simulations (and in particular their SAT response) to be related to their climate sensitivities, since the greenhouse gas boundary condition forms a large part of the total forcing. In order to relate past to future, however, we can only use models for which both the mPWP simulation results and an estimate of the model's sensitivity is available. The GENISIS model is mentioned in Haywood et al. (2013) but results are not available in the PlioMIP database, so this condition reduces the ensemble to the 9 models which are listed in Table 1. The ensemble size, while smaller than might be hoped for given that more than 20 models contributed to the Climate Model Intercomparison Project, CMIP5, is of very similar size to that available for the LGM, where there are 8 models in PMIP2 and 9 models in PMIP3 satisfying equivalent criteria. For most models, the values of climate sensitivity are taken from the estimates published in Table 1 of Haywood et al. (2013). The relevant sensitivity value for the FGOALS model was not included in that paper, but has since been published elsewhere (Zheng et al., 2013).

Raised atmospheric CO_2 is one of the more significant changes in boundary conditions for the mPWP, so it seems *a priori* reasonable to hope for a correlation in the climate model ensemble between their equilibrium sensitivities and their SAT changes at the mPWP. However, the other boundary condition changes are not negligible and if the models respond very differently to these (or nonlinearly to combinations of forcings) then a correlation between global SAT anomaly at mPWP and equilibrium sensitivity may not be observed.

Model	Reference	S (K)
COSMOS	Kienast and Lohmann (2012)	4.1
CCSM4	Rosenbloom et al. (2013)	3.2
FGOALS-g2	Zheng et al. (2013)	3.7 [1]
GISS ModelE2-R	Chandler et al. (2013)	2.8
HadCM3	Bragg et al. (2012)	3.1
IPSLCM5A	Contoux et al. (2012)	3.4
MIROC4m	Chan et al. (2011)	4.05
MRI-CGCM2.3	Kamae and Ueda (2012)	3.2
NorESM-L	Zhang et al. (2012)	3.1

Table 1. Model data used in the analysis. [1] (Zheng et al., 2013), all other values taken from Haywood et al. (2013)

3.2 Correlation Analysis

As a first investigation, we tested for a correlation between global SAT anomaly in the mPWP simulations, vs S. As the left plot of Figure 1 shows, there is perhaps a very weak relationship between these two variables, but it is not statistically significant. As in Hargreaves et al. (2007) and Hargreaves et al. (2012), we anticipate that the relationship between S and paleoclimate changes is likely to be stronger if we focus on the tropics for the paleosimulations, since this will reduce the influence of ice sheet and vegetation changes. This is borne out by the right hand panels of Figure 1 which show both the correlations for both pointwise (on a 10 degree grid), and zonally-averaged paleosimulations versus S. The model ensemble exhibits a strong correlation between mPWP tropical SAT anomaly and S. Integrating over the entire tropical region, the correlation between tropical mPWP SAT anomaly and climate sensitivity is 0.73, significant at the 97.5% level under a one-sided t-test.

3.3 The data

While the small ensemble gives us cause for concern (compare Hargreaves et al. (2012) with Schmidt et al. (2014a) and Hopcroft and Valdes (2015)) we proceed under the assumption that it is informative regarding the real climate system. In order to test the potential for constraining the climate system using information from the mPWP, we need an estimate of typical tropical temperatures during this period. As our reconstruction of mPWP temperatures we use the PlioMIP Experiment 1 SST boundary conditions as described in Haywood et al. (2010). This is based on the PRISM3D data set, firstly processed into warm peak averages (to represent typical interglacial conditions within the "time slab" of interest) for both February and August, then converted to anomalies relative to modern conditions and finally interpolated in both time and space into complete SST anomaly fields

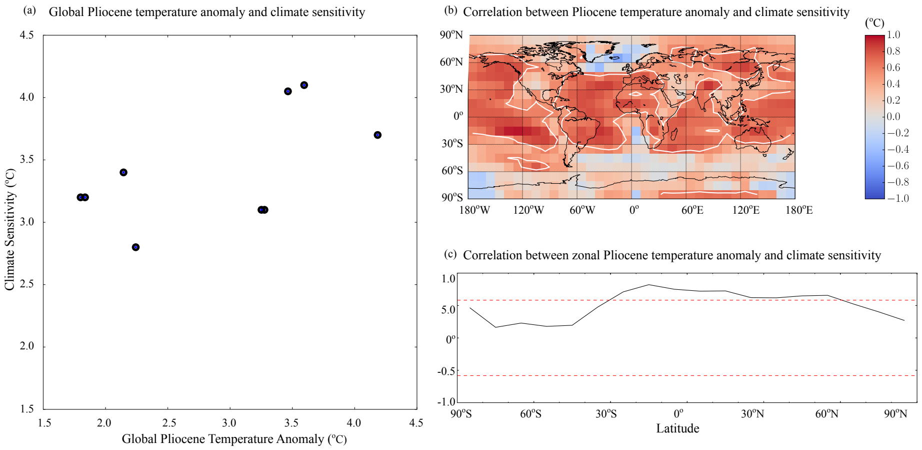

Figure 1. Correlations between the PlioMIP anomalies and climate sensitivity. For the Pliocene, the annual SAT anomalies were obtained from averaging the monthly climatology files on the PlioMIP database. For CCSM a 500 year time series is available, so the average over the last 100 years was used. (a) Globally averaged PlioMIP anomaly vs. the estimated equilibrium climate sensitivity from Table 1. (b) The Pliocene temperature anomalies were averaged onto a 10 degree grid and correlated with the global equilibrium sensitivity in each grid box. (c) Shows the zonally averaged results. The dashed lines in plot (c) indicate the 95% significance threshold for a one-sided t-test.

for use as boundary conditions for the Experiment 1 simulations, under the assumption that the spatial pattern of anomalies is the same as for the present day climate.

We use the average of these data fields for our analysis (equivalently, the annual average of the monthly fields that were generated for PlioMIP Experiment 1). More sophisticated methods could in principle be used for the SST reconstruction, such as were presented by Zammit-Mangion et al. (2014) and Bragg (2014), but this is outside the scope of this paper.

3.4 Climate sensitivity estimate

To calculate an estimate for climate sensitivity, we combine the model estimates for climate sensitivity and the warming at the mPWP, together with the PRISM3 estimate of tropical ocean temperature change, using the approach described in Hargreaves et al. (2012). In climate models, SAT over the open ocean are very close to sea surface temperatures so here we simply mask the air temperatures from the models used to produce Figure 1 (b), with the PRISM3 land-ocean mask interpolated to the same 10 degree grid, to produce a temperature over the ocean that may be directly compared to the reconstruction. The interpolated PRISM3 data indicate a warming of 0.7°C for the ocean data from 30^oS to 30^oN. The calculation of climate sensitivity involves sampling from the uncertain temper-

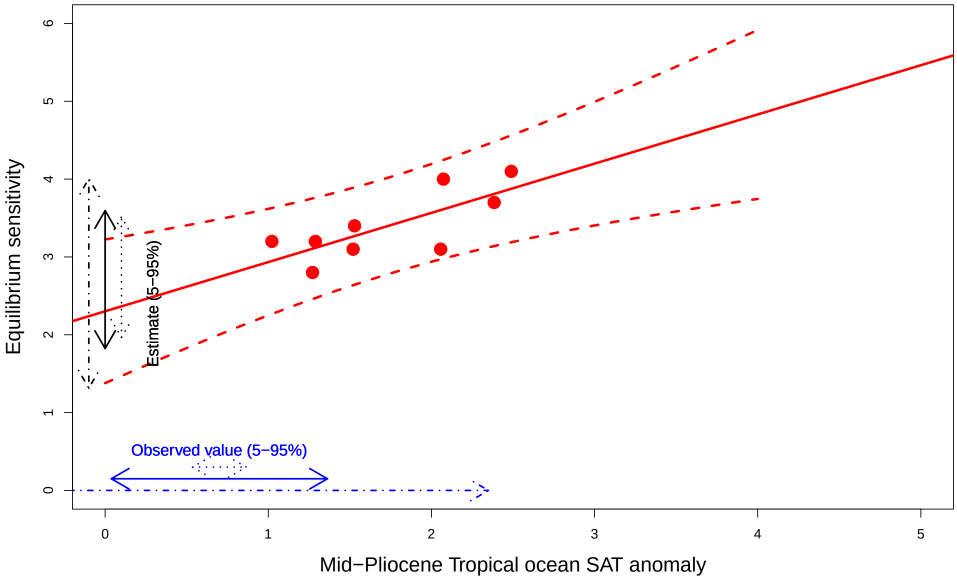

Figure 2. Estimating equilibrium climate sensitivity using the mPWP. Red dots represent model values, solid and dashed red lines indicate regression relationship and its uncertainty respectively. Blue arrows show proxy-based reconstruction of tropical temperature change over ocean, together with uncertainty of 0.1 (dashed) 0.4 (solid) and 1.0 (dot-dashed). Black arrows of the corresponding type show the resulting sensitivity estimates.

ature distribution, and for each sample, generating a prediction of the associated sensitivity taking account of the uncertainty in the linear relationship. The PRISM3 reconstruction does not include an estimate of uncertainty in the reconstruction. Initially we take a value of 0.4°C (at one standard deviation), based both on the hope that the signal was at least as large as than the noise, and that it might come close to matching the value of 0.7°C (at two standard deviations) which was obtained for a recent reconstruction of the LGM tropics (Annan and Hargreaves, 2013). It is of course essential to test the sensitivity of our result to this assumed uncertainty and we discuss this further below. Figure 2 shows the result. The regression model generates an estimate for the equilibrium climate sensitivity of 1.8–3.6°C. Only the models with weaker tropical warming are consistent with the data, and as these tend to be low sensitivity models, the resulting estimate for S is at the low end of (and outside) the full range of models that contributed to PlioMIP.

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4 Uncertainties

4.1 Data uncertainty

Proxy-based reconstructions of past climates are, of course, uncertain. As mentioned above, however, the size of the uncertainty in the PlioMIP Experiment 1 SST field has not been objectively estimated. Instead we made a first-order estimate and merely assumed the value to be similar to that obtained in a recent analysis of the LGM. It would be reasonable to assume that the Pliocene temperature estimates are in fact more uncertain, so we tested the sensitivity of our result to this. The dashed and dot-dashed blue and black lines in Figure 2 show the effect on the estimate of replacing the original estimate of 0.4°C with values of 0.1°C and 1°C (all at one standard deviation) respectively. It is apparent that reducing the uncertainty even to an extremely low value has relatively little effect on the resulting sensitivity estimate (which only narrows marginally to 2.0–3.5°C), as the spread around the regression line makes a dominant contribution to the total uncertainty. However, none of the models are consistent with this temperature estimate, as all warm more than 0.7°C, many by a substantial margin. If we increase the SST uncertainty estimate substantially to 1°C, then the uncertainty of the overall result does increase more noticeably to 1.3–4.0°C. At this point, even the models with the strongest warming are just about consistent with the data and thus the estimated sensitivity range covers the full range of model values (albeit marginally at the top end) with an extension also to lower values. Note that, at this level of uncertainty, we would no longer be confident even that the mPWP was warmer than the pre-industrial, at least in the tropics.

4.2 Forcing uncertainty

A major issue in simulating the mPWP is that the atmospheric CO_2 level corresponding to interglacial peaks is not precisely known. Furthermore, there is hypothesised to be additional forcing due to methane which cannot be directly inferred from proxy data but which has instead been assumed to be proportional to the CO_2 forcing. This was implemented within PlioMIP via an increased CO_2 concentration. That is, the imposed CO_2 forcing was selected to represent not only CO_2 but the additional effect of methane. Therefore, we have tested the sensitivity of our result to uncertainty in total GHG forcing. Our approach is rather simplistic, and makes the assumption that for each model, the tropical temperature anomaly will change in direct proportion to the net CO_2 forcing (relative to the pre-industrial control). While we do not expect this approximation to be precise, it at least allows us to perform an initial investigation into the sensitivity of our results to changes in the boundary conditions. The PlioMIP protocol imposes a value of 405ppm CO_2, but a value as low as 350ppm is possible, being at the low end of the average range considered consistent with the data proxies for CO_2 (given as "∼360-380ppmv" in Haywood et al. (2010)). When we modify the model results accordingly, we obtain the results shown in Figure 3. By downscaling the modelled results, many more of them are brought into line with the tropical SST estimate derived from the PRISM3 data

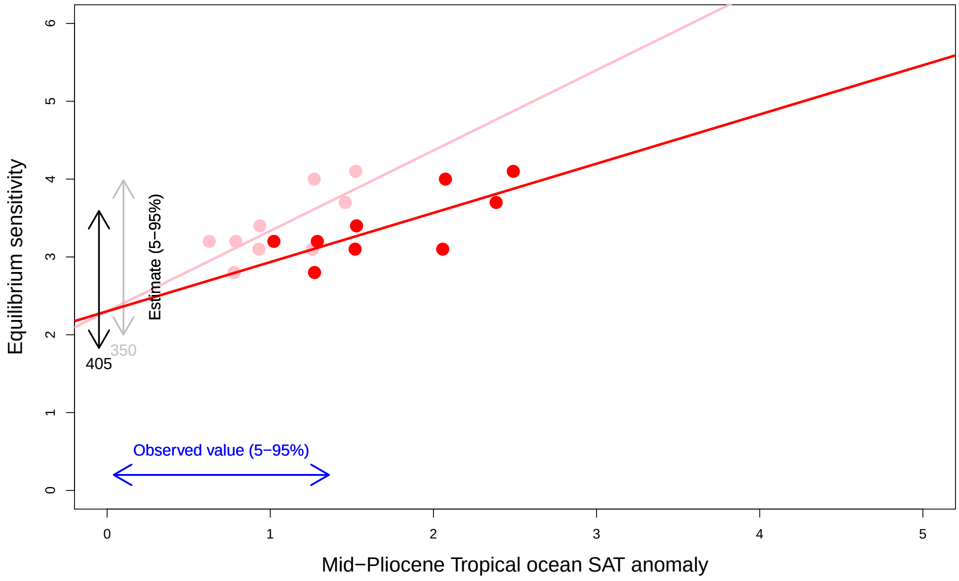

Figure 3. Investigating the sensitivity to forcing uncertainty. Bold colours show original result, pink and grey show estimate result if 350ppm CO_2 were used.

set, and the resulting sensitivity estimate increases to 2.0–4.0°C. It seems that the value of 350ppm is more consistent with the ensemble as a whole than PlioMIP's own estimate of 405ppm, though of course this cannot be taken to imply that the true value was actually this low.

4.3 Modelling uncertainties

The model results are dependent on the experimental protocols, both for the mPWP simulation, and the calculation of S. For the calculation of S, it is now commonplace to use a regression from a transient 1% pa CO_2 enrichment scenario, with this being used in the IPCC AR5 for their model sensitivity values. However, it is increasingly recognised that this regression-based estimate can significantly underestimate the true equilibrium sensitivity. One of the more extreme examples of this is the GISS model, with the sensitivity reported as 2.1°C in the IPCC AR5 but actually estimated as 2.7–2.9°C by the PlioMIP contributors, based on a long simulation (Schmidt et al., 2014b). For most other models that have done this comparison, the discrepancy is somewhat smaller (Andrews et al., 2015). For the Pliocene experiments, the computational cost of long integrations may mean that some model simulations are not fully equilibrated, which could lead to small errors in their estimates of past and present climates. Internal variability is a potential further issue. For PlioMIP the intention is that all simulations should be run for at least 500 years, which should produce a reasonably well equilibrated climate, apart from in the deep ocean. The length of the integration that is averaged into the climatology files is not stated in PlioMIP.

4.4 Methodological uncertainties

A notable point that is apparent from the figures is that the regression lines do not pass through the origin, but instead indicate that zero tropical warming at the mPWP corresponds to an equilibrium sensitivity of about 1.7 °C. This may seem a little odd, although it could be argued that even if the response in the tropics was zero, we would still expect a positive response at higher latitudes and thus also in the global average. Additionally, CO_2 is not the only forcing in the mPWP experiments (ice sheets and sea level have changed, and vegetation can also change in some if not all models), which does complicate things somewhat. In the LGM analysis, Hargreaves et al. (2012) found that the regression line derived from the PMIP2 ensemble naturally passed close to the origin, so the issue was not apparent concern there.

4.5 Time slab uncertainties

As mentioned previously, the mPWP model simulation and data collation is based on averaging the warm peaks within the mPWP interval. However, different locations may encounter peak warmth at different times, and thus the warmest peaks may not represent a historical climate state at all. Moreover, the boundary conditions for the different warm peaks would also have been somewhat different in reality. The comparison between data collected over a wide range of times, and a model snapshot with a specific set of boundary conditions, is only valid to the extent that the interglacials were in fact the same. The next iteration of PlioMIP (Haywood et al., 2015) plans to address this issue by focussing on a single interglacial for which sufficient proxy data can be obtained.

4.6 Robustness

Robustness of results is a major concern which we have discussed above and summarise here. Caldwell et al. (2014) has highlighted the risk of mining for correlations that are not robust, and there are some examples of plausible correlations in the CMIP3 ensemble which disappeared in CMIP5. Thus we focus on relationships that may be reasonably argued to represent our uncertainties in a realistic manner. In particular, it does not seem at all unreasonable to expect that a greater equilibrium response to increased CO_2 in the modern era would also imply a greater response to forcing in the past, and vice-versa, this being a simple expression of the principle of uniformitarianism. Of course in reality the sensitivity depends on underlying climate state and the nature of the forcing (Yoshimori et al., 2011) so the past is not expected to be a perfect analogue of the future, but rather a useful guide. We regard the main result presented here to be a reasonable hypothesis worthy of further investigation, rather than a confident prediction.

5 Discussion

The paleoclimate record provides the only observational evidence of large climate changes of comparable magnitude to those anticipated in the coming century. The principle of uniformitarianism implies that the past should be a useful guide to the future. Thus, paleoclimate research forms an important resource of relevance to future climate change. It is, however, not *a priori* clear that any particular paleoclimatic change is immediately informative regarding the future, as the nature of forcings and background climate state may affect the climatic response. Exploration of climate model ensembles provides one route to investigating to what extent a particular past change is in fact informative. The LGM has long been popular as the most recent period in which the climate was substantially different to the present, but as it was colder, large ice sheets were present which complicates the response.

Our results have shown that the mPWP also appears to have some potential for generating useful results. We show there is a strong correlation in the PlioMIP ensemble between tropical temperatures and climate sensitivity. Our main result is an estimate for S of 1.8–3.6°C. Major uncertainties in the experimental design and analysis cast substantial doubts over the robustness of this estimate. However, with the evolution of PlioMIP, now moving into phase 2 (Haywood et al., 2015), it seems likely that significant progress can be made on this question in the near future. For example, the data from the mPWP used here are from a number of different warm periods in the Pliocene, and in the next version of PlioMIP, this is being improved to a more traditional snap-shot of a few thousand years. As well as making the data more consistent with a model simulation, this may also help in establishing an accurate and reliable set of boundary conditions, such as increased confidence in the level of atmospheric CO_2. An improved climate reconstruction would also be helpful; the technology to produce this does exist (Annan and Hargreaves, 2013; Bragg, 2014), but has not been applied to the specific case of the mPWP. The small size of the ensemble is clearly a major concern, for which there does not seem to be an easy solution. However, PlioMIP experiments are being included as optional experiments in CMIP6, and the setup is reasonably straightforward even for non-paleoclimate experts to implement, so there are ground for optimism that the ensemble size may increase.

6 Data Availability

The PRISM3 SST reconstruction was taken from "Experiment 1 · AGCM version 1.0, Preferred Data", files PRISM3_SST_v1.1.nc and PRISM3_modern_SST.nc, available at the PRISM/PlioMIP webpage, presently located at: http://geology.er.usgs.gov/egpsc/prism/prism_1.23/prism_pliomip_data.html. The PlioMIP model output database was downloaded via sftp from holocene.ggy.bris.ac.uk. Email Alan Haywood (A.M.Haywood@leeds.ac.uk) for username and password.

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