Onset of Greenland Glaciation in the Late Pliocene:

The role of Panama Closure, ENSO, Rockies Uplift, and CO_2

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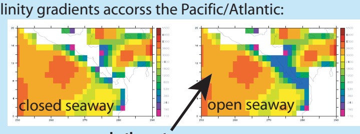
(1) INTRODUCTION

Loss of mass from the Greenland ice sheet (GrIS), and in particular the associated sea level rise, is one possible impact of anthropogenic global warming which is of fundamental concern. Therefore, significant effort has recently been applied to modelling the future response of the GrIS to elevated greenhouse gas concentrations. However, many current theories for the growth of the Greenland ice sheet in the Late Pliocene (around 3 million years ago, 3 Ma) suggest that tectonic forcing factors or changes to ENSO (El Nino-Southern Oscillation), rather than direct greenhouse gas forcing, have been the primary controller of GrIS volume in the past. Here we show, contrary to these ideas, that the growth of the GrIS was intimately linked to a decline in atmospheric CO_2. The work indicates that future stabilisation of atmospheric CO_2 at elevated Late Pliocene levels (around 400ppmv) will lead to significant loss of mass from the GrIS in the long term.

(2) EXPERIMENTAL DESIGN

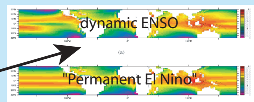
We use the HadCM3 GCM and the GLIMMER ice sheet model to test 4 hypotheses for the Pliocene growth of the GrIS. We carry out 5 simulations: a control and one for each hypothesis. Here we show the boundary condition changes which we apply for each hypothesis, relative to the Pliocene control.

(1) The closure of the Panama Seaway, as indicated by e.g. salinity gradients accross the Pacific/Atlantic:



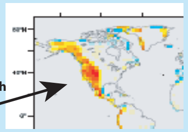
bathymetry

(2) Termination of a 'permanent ENSO' state, as indicated by Mg/Ca and d[18]O records accross the Pacific



Tropical SSTs

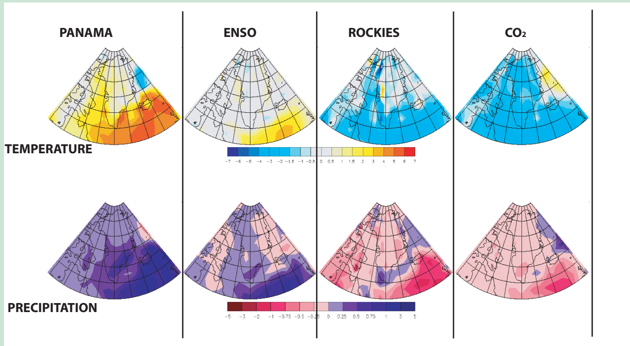
(3) Uplift of the Rockies, as indicated by fission track dating.



orography change, "High Rockies" minus control

(4) decrease in atmospheric CO_2 from 400ppmv to 280 ppmv, as indicated from stomatal density of fossil leaves and carbon isotope data.

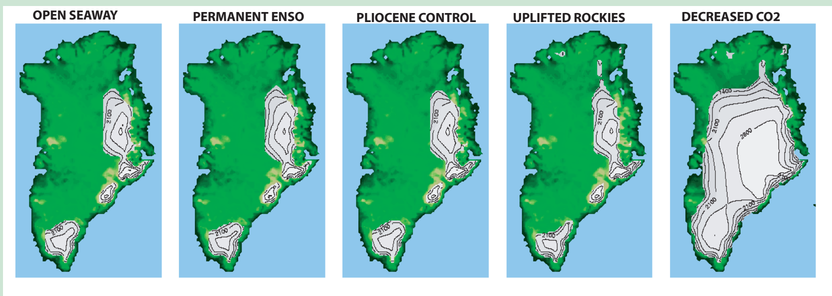
(3) GCM RESULTS



The plots on the right show the temperature and precipitation anomalies predicted by the GCM, for each hypothesis.
As expected, the closure of the Panama Isthmus leads to increased northward oceanic heat transport, greater evaporation, and increased precipitation over Greenland.
The termination of the Permanent ENSO leads to cooling in the tropics but teleconnections lead to a slight warming in the North Atlantic, and increased precipitation over Greenland.
The uplift of the Rockies leads to local cooling, enhanced by the snow-albedo feedback, which is advected downstream over Greenland. The decrease in CO_2 leads to global cooling, enhanced at high latitudes by positive feedbacks. **In each case, there is a strong correlation between temperature change and precipitation. As such, some support can be found for each hypothesis, either in terms of a 'snowgun' effect (Panama and ENSO) or a temperature effect (Rockies and CO_2).**

(4) ICE SHEET MODEL RESULTS

In order to assess the likelihood of each hypothesis, and the relative importance of temperture versus precipitation changes, we use an ice sheet model. This takes into account ice sheet flow dynamics, and the effects of sub-gridscale ororgraphy, not resolved in the GCM. The results are shown below.
It is clear that the decrease in CO_2 is the only hypothesis which leads to enhanced glaciation over Greenland.



(5) DISCUSSION

Although we have not fully coupled the ice sheet model and GCM, and relied instead on a single coupling step, further confidence in our results can be gained by noting that the equilibrium ice sheets simulated in the Panama, ENSO and Uplift simulations are all smaller than the ice sheet originally prescribed in the GCM, whereas the equilibrium ice sheet simulated in the CO_2 simulation is larger then the ice sheet prescribed in the GCM. This indicates that two-way coupling of the ice sheet model to the GCM would not affect our conclusions, and would be likely to result in even larger differences between ice sheets predicted by the CO_2 Hypothesis compared to the other hypotheses. However, future work should aim to asyncronously couple the GCM and ice sheet model. This will also provide a framework in which orbital controls on Pliocene glaciation could be analysed.

Given that we have shown the prescribed tectonic uplift to be a minor effect, the difference between the 'CO_2' ice sheet and the modern ice sheet is primarily a result of climate/ice sheet/vegetation feedbacks. These fall into two categories. Firstly, the increased area of ice sheet (high albedo) relative to vegetation (low albedo) prescribed in the driving pre-industrial GCM relative to the Pliocene leads to colder summer surface temperatures, decreased ablation, and further increase in ice volume. Secondly, the higher altitude ice sheet prescribed in the pre-industrial GCM also leads to colder summer surface temperatures. The combination of these two effects results in an ice sheet configuration similar to that observed for the modern. Future work should analyse these feedbacks in more detail, and also investigate the synergy and non-linear feedbacks between the different processes analysed in this work.

(6) CONCLUSIONS

This study indicates that the decrease in atmospheric CO_2, from the elevated values of the mid-Pliocene to lower values of the Quaternary, drove a significant enhancement of Greenland glaciation, which was further increased by climate/ice sheet/vegetation feedbacks, resulting in the GrIS observed today. It shows that neither climatic shifts associated with the tectonically-driven closure of the Panama Seaway, the termination of a permanent El Nino state, or the uplift of the Rocky Mountains, were large enough to contribute significantly to enhanced Greenland glaciation. The work highlights the need for detailed multiproxy CO_2 reconstructions through the Cenozoic, and expansion of the IRD record from the North Atlantic.

The implied strong dependence of ice sheet volume on atmospheric CO_2 concentration in the recent geological record supports previous work suggesting that future stabilisation of atmospheric CO_2 at levels substantially higher than pre-industrial could result in significant loss of mass from the GrIS in the long term.