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Conclusions

The following main conclusions can be drawn from the study presented herein;

(i) simulation of the modern carbon cycle

The framework for biogeochemical cycling developed here, when used in conjunction with a zonally-averaged representation of ocean circulation enables a reasonable simile of the modern ocean carbon cycle to be produced. However, a number of apparent deficiencies arise as a result of the simplified two dimensional circulation, particularly that of 'nutrient trapping' in equatorial up-welling zones. There are also associated problems manifested 'down-stream'; as a consequence of the strong control on total nutrient supply to mid-latitude gyre regions exerted by the equatorial zones, biogeochemical changes at the equator (such as through iron fertilization) are amplified to produce unrealistically large changes in biological productivity at higher latitudes. To retain model biogeochemical integrity, a simple topological fix is employed to lessen the degree of nutrient trapping. This has the advantage of avoiding any serious distortion of global nutrient cycles, such as might occur through the prescription of an excessive dissolved organic matter component to export production.

Despite the obvious first-order importance of the depth at which nutrients are released back into the ocean, the remineralization of biogenic particulates within the water column has been a relatively neglected area of model development. In particular, only recently has account been taken of important influences on opal remineralization such as that of ambient temperature. A new scheme for the remineralization of biogenic opal within the water column developed here, when contrasted with available opal sediment trap data, is demonstrated to offer a significant improvement on previous schemes. However, serious deficiencies in the reproduction of some observations remain, suggesting that further progress will require additional sediment trap observations to be made and the dissolution of biogenic opal more fully (experimentally) characterized. The development and inclusion of mechanistic schemes able to take into account factors determining particulate matter settling rates (including the representation of rapid export events such as those associated with phytoplankton blooms in the surface ocean) would be likely to result in a substantial improvement in overall model realism.

While indices of differential regional control exerted on atmospheric composition are difficult to interpret in terms of the underlying processes responsible, the wide range of sensitivities exhibited to perturbation in key regions (such as the Southern Ocean) amongst different models suggests that more care needs to be taken in model interpretation. Generation of a standard 'benchmark' of response, perhaps obtained through the one-off use of a state-of-the-art model could form the basis for subsequent quantitative assessment of predictions made by different model formulations.

(ii) simulation of the dynamic evolution of the system

The use of a representation of world ocean circulation derived from a zonally-averaged ocean general circulation model has important computational advantages over its three-dimensional counterpart, enabling easy access to multi-millennial time scales. Fully dynamic (i.e., 'time-stepping') model simulations made over multiple glacial-interglacial cycles provides a means for more fully utilizing the information contained within ice core records. Consideration of both the phase and amplitude of observed variability provides an important constraint on the underlying mechanisms. Ideally, model assessment would be made quantitatively via statistical and spectral methodologies, with system forcings taking into account spatial heterogeneity in the timing and magnitude of changes in boundary conditions. However, full global reconstructions are currently available only for discrete time-slices. An alternative might be to generate continuous time series of spatially-explicit boundary conditions from within a suitable Earth System Model. Forcings on the carbon cycle produced by such a model would have the advantage of being internally consistent, in contrast to paleoclimatic reconstructions made from sediment and ice cores for which there is no precise common chronology. As demonstrated here, even on a simple visual basis, it is still possible to make better use of the Vostok record, with the likely type of mechanism(s) missing from a composite scenario deduced through consideration of the timing of periods of greatest model-observation mismatch.

There is considerable interplay between the various biogeochemical cycles on glacial-interglacial time scales. Central to these is that of the ocean silicic acid cycle, which exerts important controls upon atmospheric and sediment composition through its influence upon biological productivity (particularly in determining the export ratio of calcium carbonate ($CaCO_3$) to organic carbon). With an adjustment time of order ~15 ka for the oceanic silicic acid inventory and ~9 ka for the calcite lysocline, it is not necessarily safe to rely upon steady-states when considering glacial-interglacial change. Indeed, the interaction between these two cycles produces an even slower response in the atmospheric concentration of carbon dioxide (xCO_2) with respect to perturbations of the global silicic acid cycle in the model, characterized by an e-folding time of ~23 ka. The traditional methodology of contrasting pairs of time slices made at steady state either side of the last deglacial transition (an interval of less than 18 ka) may, therefore, result in an erroneous assessment of the magnitude of the predicted change in xCO_2.

(iii) simulation of paleoceanographic proxies

Comparisons made between synthetic sediment cores and paleoceanographic proxy records can provide important additional constraints in the elucidation of the processes involved in glacial-interglacial change. For example, although in isolation, reduced aeolian iron supply to the Southern Ocean could explain a significant fraction of the initial observed deglacial increase in xCO_2, the paleoceanographic proxy record in this region clearly indicated an important omission. The anti-phase relationship exhibited by glacial-interglacial changes in sedimentary opal content in cores located either side of the Antarctic Polar Front suggested the presence of contrasting meridional variability in boundary conditions. The substantial glacial expansion of seasonal sea ice limits south of the Antarctic Polar Front, with little change to the north, represents such a contrast. The generation of synthetic sediment records driven by this additional forcing does indeed confirm sea ice extent as a vital element of glacial-interglacial change in this region.

(iv) the role of the neritic environment in the global carbon cycle

Changes in the neritic environment have the potential to account for much of the amplitude of observed xCO_2 variability, particularly through changes in the accumulation rate of $CaCO_3$ and of organic matter (including its associated nutrients). There is, therefore, a compelling need to understand the role that the coastal system plays in the global carbon cycle. Mechanistic descriptions need to be developed for this environment and coupled with existing carbon cycle models (which tend to represent just the open ocean system).

(v) the role of the Southern Ocean in the global carbon cycle

Results from this study suggest that changes in the surface boundary conditions of the Southern Ocean played a key role in perturbing the global carbon cycle, at least at the time of deglacial inception. Rapid reductions in aeolian iron supply and in maximum seasonal sea ice extents can, between them, explain much of the initial rise in xCO_2 together with the concurrent decrease in its stable isotopic signature. In addition, these two processes produce a response in the ocean surface consistent with the bulk of paleoceanographic observations made in this region. Crucially, even the apparently antagonistic response of the system either side of the Antarctic Polar Front can be accounted for. It is likely that changes in convective regime in the Southern Ocean (not tested here) will have enhanced the effect on the atmosphere.

(vi) glacial-interglacial perturbations in the global carbon cycle

None of the mechanisms considered in this study when considered in isolation are able to simultaneously meet all the constraints dictated by the paleoclimatic record. With the mechanisms applied in concert, though, over two thirds of the amplitude of xCO_2 variability can be explained. However, the component of xCO_2 change due to the 'Coral Reef Hypothesis' may be overstated (on the basis of deficiencies in the synthetic model paleoceanographic $CaCO_3$ record) which would reduce the effective magnitude of xCO_2 which can be accounted for consistent with paleoceanographic observations. Model results suggest that perturbations located in the Southern Ocean (aeolian Fe supply, sea ice extent) could potentially account for all of the observed glacial variability in xCO_2 together with the initial deglacial rise. However, longer-term changes in the system routed in oceanic $CaCO_3$ and silicic acid cycles probably play an important role in defining the envelope of gradual xCO_2 draw-down immediately following each interglacial period. Driving mechanisms for this probably include decreasing neritic $CaCO_3$ ('Coral Reef Hypothesis') and organic matter ('Phosphate Extraction Model') accumulation rates (as sea level falls), together with increasing dissolved Si supply. Considering the difficulties in generating a sufficient amplitude of xCO_2 variability without contravening paleoceanographic $CaCO_3$ constraints, it is not easy to reconcile deglacial increases in the carbon inventory of the terrestrial biosphere substantially more than the 500 GtC assumed here.

(vii) dust supply and the ice age cycles

Solely on the basis of its being the only boundary condition to substantially change prior to initial deglacial rise in xCO_2, variability in dust deposition rates to the world ocean would seem likely to be a key element in glacial-interglacial change. This is supported by model results presented here of the effect on xCO_2 of variable aeolian iron supply, either to the Southern Ocean or to the ocean as a whole. These results demonstrate that the apparent lag observed in ice cores between the start of declining aeolian deposition rates and initial deglacial xCO_2 rise can be accounted for as a result of non-linearities inherent in the ocean biogeochemical system. If variability in aeolian iron supply to the ocean does play such a critical role in glacial-interglacial change then it is important that processes controlling dust sources, atmospheric transport, and deposition (including issues of iron solubility) all be understood more fully. It is suggested here that the decline in aeolian deposition rates in the Antarctic towards the end of Stage 2 is inexorably linked to a maximum in global (or local) ice volume having been obtained. Understanding the determinants of dust supply could potentially reveal the reasons for the timing of deglaciation, thus unlocking the secrets of the 100 ka ice age cycles.