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Glacial–interglacial rain ratio changes: Implications for atmospheric CO_2 and ocean–sediment interaction

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Abstract

A reduction of the carbonate-carbon to organic-carbon export rain ratio during glacial times has been advanced to explain the glacial–interglacial atmospheric CO_2 variations. This hypothesis is tested and implications for the dynamics of sedimentary carbonate preservation and dissolution are explored with a multi-box model (MBM) of the ocean carbon cycle, fully coupled to a new transient early diagenesis model (called MEDUSA).

A peak reduction of the rain ratio by 40% at the Last Glacial Maximum (LGM) was found to produce a net atmospheric pCO_2 reduction of about 40 ppm. Changing shelf carbonate accumulation rates and continental weathering inputs produced a 55–60 ppm reduction. The combination of the two mechanisms generates a pCO_2 change of 90–95 ppm, which compares well with the observed data. However, the resulting model sedimentary record does not conform to actual sedimentary records. The changes related to continental shelf processes and variable weathering flux depress the calcite saturation horizon (CSH) by about 1 km at the LGM; if rain ratio variations are also considered, that depression increases by another km. In addition to this large amplitude for the CSH, possibly due to the adopted box-model approach, the changing rain ratio also leads to transition zone changes in the model sedimentary record that are opposite in phase with data-based reconstructions. Realistic changes in the aragonite fraction of the carbonate rain were found to have only a minimal impact on atmospheric pCO_2. Finally, chemical erosion of deep-sea sediment was shown to reduce the amplitude of variation of the sedimentary CCD by about 10–20%. It may provide a mechanism to improve the model-data agreement.

Keywords: Glacial–interglacial; Sedimentary carbonate; Dissolution; CCD; Chemical erosion

1. Introduction

The Vostok ice-core record (Barnola et al., 1987) provided the first evidence of a close relationship between atmospheric CO_2 and climate. These observations were confirmed by the later extensions of the records back to 240 kyr BP (Jouzel et al., 1993) and 420 kyr BP (Petit et al., 1999) on subsequent cores drilled at Vostok, and to 650 kyr BP (Siegenthaler et al., 2005) with the most recent data from the core drilled at EPICA Dome-C. Of all the available records on glacial–interglacial changes of the carbon cycle, the atmospheric CO_2 signal represents the strongest constraint, because of its significance at the global scale. There is agree-

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ment that the ocean plays a major role in driving atmospheric pCO_2 at the time scales of interest. The ocean contains about 60 times more carbon than the atmosphere, and the residence time of CO_2 in the atmosphere with respect to air–sea exchange is about 10 years. On time scales of a few tens of years, the atmosphere is close to equilibrium with the average surface ocean. Accordingly, atmospheric CO_2 variations such as the observed ~90 ppm variations must to a large extent be driven by changes in the surface-ocean dissolved inorganic carbon (DIC) or total alkalinity (TA) concentrations. Low-atmospheric pCO_2 is associated with increased TA or decreased DIC concentrations in the surface ocean, or with an appropriate combination of the two. Such changes could either be due to global ocean inventory changes, or to changes in the surface to deep-sea gradients of the two quantities.

A number of mechanisms have been proposed to explain the recurrent glacial–interglacial variation in atmospheric pCO_2 (see, e.g. Broecker and Peng, 1993; Sigman and Boyle, 2000; Archer et al., 2000 for reviews). Probably the longest standing one relates to rain ratio variations. Its roots reach at least back to a discussion by Berger and Keir (1984). One might actually argue that it emerged earlier even, as Broecker (1982), and also Broecker and Peng (1982), reported sensitivity calculations on rain ratio values and corresponding pCO_2 in warm surface-ocean waters. They recognised that glacial–interglacial changes in the rain ratio would impinge on atmospheric pCO_2. However, they did not retain it as an important process for the control of glacial–interglacial atmospheric CO_2.

1.1. Rain ratio scenarios and issues: a short overview

There are actually different rain ratios that need to be distinguished: to start with, we consider here the ratio of carbonate carbon over organic carbon in the export production (denoted R_{CXP} hereafter). Another rain ratio is the sea-floor rain ratio (R_{CSD}), i.e. the ratio of carbonate carbon over organic carbon in the flux that reaches the sea floor. In this study, we furthermore consider the aragonite fraction of the carbonate export flux (r_{AXP}).

1.1.1. Carbonate export rain ratio: a first scenario

Berger and Keir (1984) considered variations of R_{CXP} in order to get a stronger net response of atmospheric pCO_2 with the nutrient-based scenarios. Nutrient-based hypotheses call upon increased organic production during glacial times, bringing reduced pCO_2 by the enhanced evacuation of DIC from the surface ocean. Unfortunately, at constant R_{CXP} the concomitant increase in the carbonate production would also increase the evacuation of TA, thus annihilating parts of the aimed pCO_2 decrease. Berger and Keir (1984) pointed out that in the present-day ocean, R_{CXP} values in the biogenic particulate rain are generally larger in low-fertility than in high-fertility areas. The atmospheric pCO_2 response would be much stronger if R_{CXP} decreased as productivity increases. The negative feedback from the enhanced carbonate rain will then be weaker.

Dymond and Lyle (1985) were the first to call upon R_{CXP} as a driver for atmospheric pCO_2 changes. (They were also the first to suggest that the glacial–interglacial pCO_2 change was not the result of a single cause, but of a chain of events.) They observed that diatoms always dominate over coccolithophorids in cold nutrient-rich waters, which should have been more wide-spread during glacial times. Dymond and Lyle (1985) then proposed that the phytoplankton community restructured when glacial climate conditions were brought to an end by changes in insolation, decreasing the relative importance of diatoms in the assemblage in favour of calcite-secreting organisms, essentially coccolithophorids (thus increasing R_{CXP}). The alkalinity decrease in the surface ocean resulting from this ecosystem shift would then have initiated a CO_2 rise, which would have intensified warming, leading to an even larger CO_2 increase. As ice caps started to melt and sea level to rise, further CO_2 increase may have been the result of the deposition of organic carbon on the continental shelves, as proposed by Broecker (1982). The coccolithophorid:diatom ratio increase during the deglaciation, together with the organic production decrease would translate into a strong increase of the export rain ratio R_{CXP}.

Nutrient-based hypotheses later fell out of favour (see, e.g. Broecker and Peng, 1993; Broecker and Henderson, 1998; Sigman and Boyle, 2000). The "rain ratio model," as it was initially called by Berger and Keir (1984), was stowed away at the same time.

1.1.2. Sea-floor carbonate rain ratio: background, scenario, and mechanisms

The currently known version of the rain ratio hypothesis was proposed by Archer and Maier-Reimer