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Climate of the Past Discussions

Interactive comment on "Modulation of Late Cretaceous and Cenozoic climate by variable drawdown of atmospheric $p\mathrm{CO}_2$ from weathering of basaltic provinces on continents drifting through the equatorial humid belt" *by* D. V. Kent and G. Muttoni

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We are grateful for the comments of Referee #3, which in conjunction with those from Referee #2, resulted in a substantive reorganization of the latter part of the manuscript including the deferral of one section (Mg/Ca implications) to further work elsewhere, the inclusion of a new list section with a listing of main results, and condensation of the section on organic carbon burial and placing it in a more subsidiary position, all

with the aim of keeping the paper better focused on the main theme, the efficacy of weathering in the equatorial humid belt as a major and variable sink of CO2. We were also reminded again to explicitly differentiate the important distinction between total and net CO2 consumption rate from silicate weathering. The overall message of our paper remains the same although hopefully better reasoned.

** The section 6 presents no new results. A compilation of carbonates data and d13C record is presented. The authors propose an interpretation of these records in term of organic fraction of the total carbon burial flux. I am not sure to understand the interest of this long (too long: 4 pages) discussion.

The section on organic carbon burial has been modified/shortened and will be placed at end, just before list of conclusions. The point we were trying to make is that there is no evidence for greater organic carbon burial that could account for reduction in atmospheric pCO2 levels since 50 Ma.

9. Role of organic carbon burial

Net burial of organic carbon is a sink for CO2 and its potential contribution to the atmospheric pCO2 budget for the Cenozoic is briefly considered here. The relative fractions of carbonate and organic carbon buried in sediments are reflected in carbon isotopes of carbonate produced in surface waters (Broecker and Woodruff, 1992; Kump, 1991), for example, the bulk sediment record compiled by Katz et al. (2005) which mainly reflects calcareous plankton. A comparison between this (δ13Ccarb) dataset and the benthic foraminifera δ13CBF record compiled by Cramer et al. (2009), which reasonably continuous from $\sim$77 Ma to Present (Fig. 7) also provides insight into the evolving role of the biological pump, the transfer of carbon from the shallow to deep water reservoirs. The organic fraction (forg) of the total carbon burial flux at steady state can be estimated according to Kump and Arthur (1999):

forg = (δ'w - δcarb) / ΔB

where δ'w is the average carbon isotopic composition of the riverine flux (assumed to be -5‰, δcarb is the isotopic composition of carbonate sediments that reflect the oceanic carbon reservoir, and ΔB represents the isotopic difference between organic matter and carbonate deposited from the ocean. If ΔB is assumed to be constant (say -29‰ from 77 Ma to 15 Ma, the mean δcarb of 2.3‰ would imply a typical average forg of 0.25; a dependence of ΔB on ambient pCO2 (Kump and Arthur, 1999) would tend to slightly increase the average organic burial fraction with declining atmospheric pCO2 levels since $\sim$35 Ma, for example, forg would be 0.27 for pCO2 of $\sim$350 ppm. The large (up to $\sim$2.5‰ decrease in the bulk sediment (and benthic) records from 15 Ma to Present (Fig. 7B, C) was interpreted by Shackleton (1987) as due to a decreasing fraction of organic carbon burial although its origin has remained enigmatic (Broecker and Woodruff, 1992). Katz et al. (2005) suggested that about 1.1‰ of the decrease could be accounted for by the rise of C4 photosynthetic pathways with the remaining $\sim$1.4‰ decrease due to weathering of organic-rich shales. In any case, there is no evidence for increasing net organic carbon burial over the past 15 Myr even though climate has cooled from the Middle Miocene climate optimum (Flower and Kennett, 1994; Miller et al., 1987; Wright et al., 1992; You et al., 2009).

The other prominent feature in the bulk (and benthic) sediment carbon isotope record is the 1.5‰ increase starting at around 62.5 Ma that peaks at 57 Ma and followed by a 2‰ decrease to a prominent trough at 52 Ma (Fig. 7B). The run-up to the peak at 57 Ma implies an increasing fraction of organic carbon burial (forg up to 0.3), which may be related to burial of organic-rich sediments, whereas the subsequent large decrease in carbon isotope values (implying forg decreased to $\sim$0.22) starting at around 57 Ma may mark the exhumation and oxidation of organic carbon-rich Tethyan marine sediments during the early stages of the India-Asia collision according to Beck et al. (1995), who suggested that this may have increased atmospheric pCO2 sufficiently to have contributed to global warming in the early Cenozoic (albeit somewhat prior to peak warmth at the EECO.

A comparison between the bulk sediment and benthic carbonate δ13C records (Fig. 7B, C) shows that the average value for benthic data between 77 Ma to just before the Cretaceous–Paleogene boundary perturbation at 65 Ma (D'Hondt et al., 1998) is 1.2‰ about 1.1‰ lighter than the bulk sediment δ13C mean of 2.3‰.From 50 Ma, just after the Paleocene–Eocene boundary perturbation (Hilting et al., 2008), to 35 Ma, just before Oi-1 at around the Eocene–Oligocene boundary, as well as from 33 Ma, just after Oi-1, to 18 Ma, just before the Middle Miocene Climate Optimum, the benthic means are 0.7‰ or about 1.6‰ lighter compared to the corresponding bulk sediment means of 2.3‰.It would thus appear that the biological pump spun-up soon after EECO ($\sim$50 Ma), well before the inception of large Antarctic ice sheets and the strengthening of ocean circulation at Oi-1 at around 34 Ma (e.g, Cramer et al., 2009; Kennett, 1977), and stayed relatively constant from 35–50 Ma to 18–33 Ma. A sustained higher input of nutrients, notably phosphates (Schrag et al., 2002), from enhanced weathering of continental silicates starting with the arrival of the Deccan in the equatorial humid belt at $\sim$50 Ma may have spurred biological even though the fraction of organic carbon burial hardly varied in concert.

** The section 7 should be included into the discussion of section 5 (or removed). The section 8: again, without modeling of carbon cycle (with for example an oceanic sub-model with carbonate speciation), it seems hazardous to discuss precipitation of calcite and aragonite.

A thoroughly revised Section 7 (Uplift) is now placed as Section 6, followed by Section 7 (Transport limited, previously Section 9) with Section 8 (Calcite seas) taken out, and previous Section 10 (Concluding remarks) is now Section 8 (Temperate safety valves) followed by a shortened Section 9 (Organic carbon burial, previously Section 6).

** A conclusion with the main results is missing.

A list of main results is now included as new Section 10 (Conclusions), as requested also by Referee #2 (see Response to Referee #2).

** Specific comments: Section 5 : The study of dessert et al. 2003 shows that basalt weathering is also important into the temperate humid belts (5° to 30°). It would be interesting to present CO2 flux resulting from this climatic zone in fig 5 and 6.

We estimate that basalts (plus mixed crust) just in the narrow equatorial belt (5°S to 5°N) constitute about 35% of global CO2 outgassing if CO2 consumption of equatorial basalts is adjusted for carbonate deposition in the oceans. This would suggest that basalt weathering outside the equatorial humid belt, e.g. up to 30° N-S as suggested by the Reviewer, makes a relatively small overall contribution to CO2 consumption at the scale of our investigation. The narrow belt of high temperatures and humidity closely centered on the equator seems to be where most of the action regarding long-term consumption of CO2 takes place whereas chemical weathering (and CO2 consumption) is expected to be strongly inhibited by the shortage of water in the arid belts extending up to 30° in both hemispheres.

** Section 5: The authors cannot compare directly the CO2 consumption flux with the CO2 outgassing flux. Only one half of "this riverine CO2" is sequestrated into carbonate at geological scale.

We agree with this comment and modified Chapter 5 (P4532 lines 10-15) and Figure 6 (caption) to take into account that half of the CO2 consumed by silicate weathering is returned to the atmosphere-ocean during associated carbonate precipitation (see Response to Reviewer#2). Moreoever, feedback mechanisms are likely to be more important and tehse would be better considered in a more comprehensive carbon cycling-climate model, which is beyond the scope of this study. It is nonetheless still remarkable that the net CO2 consumption of 95 Mton CO2/yr from silicate weathering of basaltic and mixed crust provinces currently residing just in the narrow equatorial humid belt (i.e., the total CO2 consumption flux of 190 Mton CO2/yr from Figure 6 [to become Figure 7] divided by 2 to compensate for carbonate precipitation in the oceans) may balance a substantial fraction (∼35%) of the estimated present-day global volcanic CO2 emission rate of 260 Mton CO2 /yr.

** Section 8: The authors compared the volume of Deccan Traps with riverine Mg flux. We cannot compare a volume of Mg with a flux. I suggest using the paper of Tipper et al. 2006 (EPSL) for the oceanic Mg budget.

We mean to to imply a flux (volume of Deccan weathered over ∼10 Myr while transiting through equatorial humid belt) but should have been explicit. Although we suspect that basalt weathering plays an important role in Mg/Ca ocean chemistry, we take the reviewer's advice and drop this section of the paper pending more complete modeling of the carbon cycle and now simply mention the possible role of basalt weathering in caption to the last figure.

We appreciate the perceptive and very pertinent comments of the Referee, which have been instrumental in our efforts to clarify the ideas expressed in our paper.

Happy New Year to all!

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