Clim. Past Discuss., 8, C2977–C2981, 2012
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8, C2977–C2981, 2012

Interactive Comment

# *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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Received and published: 29 December 2012

We are able respond in broad agreement to the thoughtful comments of Referee #1 (David Kidder), which have allowed us to clarify several points in the revised manuscript. Responses follow, keyed to the referee's numbered items.

General Comments:

1) A corollary implication of these calculations is that higher pCO2 and more equable climate (i.e., with much smaller than present to virtually absent polar ice sheets) during EECO and CTM were not due to presumed enhanced subduction of carbonates prior to Tethyan closure; instead, equable climate conditions over the long-term can be regarded as the norm, punctuated by times when there are unusually large subaerial exposures of highly weatherable terranes in the equatorial humid belt to draw down pCO2, allowing growth of polar ice sheets, as in the late Cenozoic.

2) Relief doesn't have to be high, just rejuvenated by uplift (exhumation) or accretion at a tempo sufficient to allow erosion to keep rocks freshly exposed to weathering processes.

3) We acknowledge that ancient climate belts may not have always been the same – the changing geographic distribution of continents alone would produce differences in monsoons and the precise loci of convergences and divergences, for example. However, to avoid a potential circular loop involving climate proxies and pCO2 levels, and the presumed silicate weathering response, we used an idealized zonal climate model [Manabe and Bryan, 1985] whose attractive feature was that it (p. 11,705) "...completely bypasses the interaction of climate and the carbon cycle itself." Yet, the models provides useful guidance on the expected global climate response to varying levels of pCO2, for example, that the subtropical null point of zonally-averaged precipitation minus evaporation moves just a few degrees of latitude higher in each hemisphere even at pCO2 concentrations that are radically much higher than today (we will include a new figure illustrating this key point), which has been corroborated in subsequent work showing that modest average poleward expansions of the subtropical dry zones with increasing pCO2 seem to be characteristic of the dynamics of Hadley circulation (e.g., Lu et al., 2007). The apparent latitudinal stability of the narrow equatorial humid belt in terms of both elevated temperatures and an excess of precipitation over evaporation (which do vary in magnitude with pCO2 although we have not taken this into account) allows us to make first-order assessments of how much silicate weathering has occurred in this

potent zone over time independent of pCO2 levels.

4) A leading indication that ancient climate belts indeed do not necessarily match modern ones is the apparent absence of polar ice sheets at various times in the past, such as most probably at the EECO and CTM. On the other hand, we wonder if broad categorizations of dry (or wet) climates always take into account the actual latitudinal distribution of relevant climate proxies, or if the climate proxies are themselves used to infer latitude and thereby generalize a given climate regime. For example, the Late Triassic (nearly 35 Myr long, more than 2/3 of the entire Triassic period) is often described as an arid world but this may be due to an observational bias of widespread proxies that formed in an inherently wide tropical arid belt and that continental drift has further smeared out and brought to our doorsteps, for example, redbed facies like the New Red and Keuper in Western Europe, eolian deposits in the Pomperaug and Fundy basins in Eastern North America, and the extensive Chinle deposits in major tourist destinations of the American Southwest. Yet some of the earliest mined coal deposits in North America (e.g., Richmond basin of Virginia) formed at the same time in the Late Triassic in the much narrower equatorial humid belt (see Kent and Tauxe 2005 Science 307:240) which also suggests that the climate belts in the Late Triassic were not that different than today's. Nonetheless, we do acknowledge that weathering in the temperate humid belt is not only possible but there is direct evidence it happened (e.g., Antrim Basalt terra rosa) but see this mainly as the operation of a safety valve that acts to absorb excess pCO2 (see renamed Section 8: Temperate Safety Valves). The idea is that the latitude crossovers of the E-P belts (and the general position of the Hadley cells with respect to the spin axis) remain stable (within a few degrees) for different pCO2 levels and with the assumption of a simple geography (Manabe and Bryan, 1985). However, the magnitude of the E-P zonal contrast is free to vary depending on pCO2 levels such that, for example, the mid-latitude temperate belt of the Early Eocene greenhouse world was probably warmer and more humid than it is in today's icehouse world, and in this respect, ancient climate belts indeed do not necessarily match modern ones.

5) We focused on calculating the amount of silicate (basaltic and granitic) weathering as a function of areal distribution with time in the context of a simple zonal climate model (see Point #3) and using published weathering rate values for such lithologies under modern conditions in the most potent venue corresponding to the equatorial humid belt. CO2 outgassing was taken to be constant with time by default. Short of invoking arbitrary changes in solar insolation or CO2 outgassing our calculations point to weathering of basaltic rocks in the equatorial humid belt as the major controlling factor for long-term changes in atmospheric pCO2. Change in albedo (e.g., proportion of land and sea, ice cover) is also likely to be an important factor in the radiative balance but we have not attempted to gauge this effect.

6) These are good and valid points but they apply to all lithologies, not just basalts. The part of the silicate weathering machine that seems understood is that given the same weathering circumstances and conditions (temperature, humidity, vegetation, exhumation, drainage, coverage etc.), basalts consume more CO2 per unit exposed area than most other lithologies. Moreover, it seems evident from climate modeling that the equatorial belt remains warm and humid (and therefore conductive to weathering) for even radically different pCO2 levels. Accordingly, we derived our inference that the sustained insertion of fresh basalts along the equator should control much of the long-term climate game. Although beyond the time frame (120 Ma to Recent) of our primary consideration in this paper, the 201 Ma CAMP is an interesting case in point. Its status as one of the largest known LIP stems in good part from an extrapolation from very widely dispersed basement dikes that were assumed to have fed ∼200 m of surface lavas over a broad geographic area (McHone 2003, cited in text). The vast majority of the hypothesized basalt flows have been eroded away. Indirect evidence that supports both the large size of CAMP volcanism and its rapid removal through weathering and erosion is the pCO2 record from interbedded paleosols, which shows a ∼2000 ppm spike associated with each of the major igneous (i.e., outgassing) events followed by longer-term (yet still quite rapid over only ∼200 kyr) subsequent decreases in pCO2 that are likely due to CAMP weathering (Schaller et al., 2011, 2012, cited in text).



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7) Indeed, not every cooling event needs to be associated with a basalt province transiting the equator, especially a transient cooling such as following the C-T that could be due to enhanced organic carbon burial associated with OAE (ocean anoxic event) 2, itself a likely manifestation of an oceanic (Caribbean) LIP. And Milankovitch forcing, especially at low pCO2 background levels such as in the late Neogene, could of course also produce rapid climate changes.

8) We acknowledge that there may be an appreciable weathering flux on the Ganges floodplain that is ultimately driven by intense physical erosion in the Himalayas, as reported by West et al. (2002), but whether this CO2 weathering sink was sufficient to have steered late Cenozoic climate is more questionable. In a revised section, we now point out the underlying similarities in the Himalayan uplift-erosion and our drift-weathering hypotheses, but stress the important difference of venue, i.e., we argue that weatherable rocks need to be in the equatorial humid belt, either by drift or uplift, to exert a big drawdown in CO2.

9 & 10) We agree that reconsideration of the Mg/Ca record further back in the geologic record in terms of weathering of basalt provinces (rather than presumed changes in ocean crust production and seafloor hydrothermal activity) could be instructive but agree with another reviewer that this requires more quantitative modeling, which is beyond the scope of this paper; hence we have taken this section out of this paper.

Specific Comments:

All changed per referee suggestions.

We thank David Kidder for his careful consideration of our manuscript and hope our responses addequately address his comments, or at least help advance the debate on some issues.

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Interactive comment on Clim. Past Discuss., 8, 4513, 2012.