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Modeling climatic effects of carbon dioxide emissions from Deccan Traps Volcanic Eruptions around the Cretaceous–Paleogene boundary

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ABSTRACT

Warming events observed in paleotemperature proxy records within 500 ka of the Cretaceous–Paleogene (K–Pg) boundary have often been attributed to atmospheric CO_2 increases due to Deccan Traps Flood Volcanism. Currently, there is uncertainty in the size, nature, and timing of the Deccan eruptions, all of which lead to uncertainty in the likely climatic effects. Modeling the impact of Deccan Traps eruption on climate is complicated by the discrepancy between the lifetimes of emitted gasses and the length of the total eruptive sequence. Though SO_2 emissions can have important climatic effects, the short atmospheric lifetime of SO_2 and resulting aerosols means these effects are unlikely to be recognized in the proxy record. Here we focus on the CO_2 emissions, and attempt to match paleotemperature proxy records with plausible emissions scenarios. We also test the relevance for climate of the number, length, and arrangement (e.g., increasing or decreasing size) of individual eruptions as well as the total duration and size of the overall eruptive sequence. We find that the number and length of individual eruptions are largely unimportant to CO_2 based climate effects, but that the pattern and duration of eruption have measureable effects. Unsurprisingly, the total emitted CO_2 from the Deccan Traps exerts a strong control on climatic effects, and better constraints on the volume of emitted gas are necessary. At the high end of the uncertainty range, the Deccan Traps eruptions are capable of generating warming events recorded in the proxy record, but rates of silicate weathering above modern rates are necessary to draw down CO_2 in accordance with those records.

1. Introduction

The end-Cretaceous mass extinction is generally thought to be the consequence of a large bolide impact (Schulte et al., 2010) that effectively defines the Cretaceous–Paleogene (K–Pg) boundary (Molina et al., 2006). However, climatic impacts from Deccan Traps flood volcanism have also been implicated as a primary or aggravating contributor to the mass extinction (Tobin et al., 2012; Keller, 2014; Tobin et al., 2014; Wilson, 2014). The possible temporal correspondence between the Deccan Traps and extinction has been the primary driver of this hypothesis, and similar correlations between large igneous provinces and mass extinctions have been noted throughout the Phanerozoic (Courtillot and Renne, 2003; Bond and Wignall, 2014). The largest mass extinctions are global events, and to have global biotic effects, flood volcanism must alter atmospheric chemistry and/or climate in ways that spread globally as well. The primary means through which volcanism alters atmospheric chemistry is the release of carbon dioxide (CO_2) and sulfur dioxide (SO_2), though the release of halogens may also generate acid rain, potentially globally (Font et al., 2014).

Carbon dioxide and SO_2 are generally thought to have competing climatic effects — CO_2 warms the planet through increased absorption of Earth's radiated heat (increased greenhouse effect), while SO_2 forms aerosols that block incoming solar radiation, cooling the planet (Bond and Wignall, 2014). Because the atmospheric lifetimes of these constituents are very different: the cooling effects from volcanism essentially end a few years after the eruption, and may be reduced in flood basalt eruptions when compared with more explosive eruptions (Schmidt et al., 2016), while the warming effects of CO_2 can persist well beyond (thousands of years) the initial release of the gas. In many studies of the potential atmospheric impact of flood volcanic volatile release, it is assumed that cooling from SO_2-derived volcanic aerosols is the more likely candidate to have biological consequences, as even an individual flow is capable of generating substantial global cooling (Self et al., 2014; Self et al., 2015). While these cooling events could be the primary means through which flood basalts affect global biota, the duration of these cooling events makes it highly unlikely that they would ever have been detectable and confirmed in the stratigraphic record. It is also possible that SO_2 leads to substantial acidification and related biotic effects, but Schmidt et al. (2016) suggest this is unlikely.

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The longer duration of CO_2 related warming is likely detectable in the fossil record. Paleotemperature data from periods of flood basalt eruption are mixed, but it appears that most large continental flood basalts are associated with global warming (Bond and Wignall, 2014). For the end Cretaceous mass extinction, a warming event during the last ~350 ka (though see discussion of timeframe below) of the Cretaceous has often been linked with the Deccan Traps volcanism (Li and Keller, 1998; MacLeod et al., 2005; Tobin et al., 2012). The CO_2 release from an individual eruption is almost certainly too small to have a significant impact on atmospheric CO_2 levels, and this observation, combined with the spacing between eruptions, has been used to argue that volcanic CO_2 from flood basalts cannot generate substantial warming (Self et al., 2006). Modeling of modern emission scenarios suggest that 20–25% of a suddenly emitted CO_2 perturbation will persist for over 10 ka (Archer et al., 2009), a long enough period that CO_2 could potentially accumulate in the atmosphere between eruptions in a flood basalt eruptive period where average spacing is likely on the order of 1 ka (Self et al., 2014).

2. Deccan Traps and warming

Below we investigate whether the size and episodic nature of Deccan CO_2 emissions is sufficient to generate warming that has been observed using paleotemperature proxies. Many authors have attributed warming near the K–Pg boundary to Deccan Traps CO_2 emissions based on plausible contemporaneity (e.g. Li and Keller, 1998; Barrera and Savin, 1999; Wilf et al., 2003; Tobin et al., 2012), but there are few ways to prove a causal connection. Most of the Deccan Traps emissions are emitted during magnetochron C29R, an interval lasting roughly 700 ka spanning the K–Pg boundary (Ogg, 2012 and references therein). Recent and ongoing research into the timing of Deccan emissions could potentially rule out a causal connection (Renne et al., 2015; Richards et al., 2015), but temporal correspondence will always be insufficient in proving causality. At present, it is unlikely that definitive proof of causality can be obtained from the geologic record, but climate modeling based on constraints of eruptive size and duration can provide an additional test of a Deccan — warming link.

Previous attempts at modeling warming from Deccan Traps flood volcanism have produced mixed results. Caldeira and Rampino (1990a) found little to no measurable impact from possible Deccan volcanism, though they also found potential warming below 2 °C for what they considered unreasonably high levels of CO_2 emissions (Caldeira and Rampino, 1990b). Dessert et al. (2001) modeled a more substantial warming, up to 4 °C, but they used CO_2 emissions that are likely too high (see discussion below). Recent attempts to model the combined contributions of SO_2 and CO_2 emissions suggest that reduced warming from individual eruptions would have suppressed weathering and CO_2 drawdown, increasing the accumulation of CO_2 in the atmosphere and consequent warming (Mussard et al., 2014). Unlike the previous models, their model simulated individual eruptions, rather than modeling a single increased rate of emissions for the entire period of Deccan eruptions. However, due to the complexity of their hybrid model, they did not test how varying eruptive duration, length and pattern affected their results. We employ a simpler model that allows a more complete testing of these parameters, but focused exclusively on CO_2 emissions.

3. Model details

We use a modified version of the GEOCYC model (Archer et al., 2009), which originally was based on previous GEOCARB models developed by Berner (Berner, 1994; Berner and Kothavala, 2001). This model iterates over a user-defined time step and tracks carbon through globally-averaged atmospheric and oceanic reservoirs, with the oceanic reservoir partitioned into dissolved inorganic carbon species ($CO_{2\ (aq)}$, HCO_3^-, and CO_3^{2-}). Carbon is removed from the atmosphere through silicate and carbonate weathering and added through volcanic emissions. Carbon is removed from the ocean through carbonate burial and added through weathering, with gas exchange moving carbon between the ocean and atmospheric reservoirs. Atmospheric CO_2 concentration (or level) is converted to atmospheric temperature using a climate sensitivity set to 3 °C per doubling of CO_2, likely on the low end of Cretaceous climate sensitivity estimates (Breecker et al., 2010; Royer, 2010). The atmosphere temperature equilibrates instantly with CO_2 level, while the ocean temperature has a 1 ka relaxation rate with respect to the atmosphere. The ocean temperature primarily affects gas solubility and exchange. As this model is functionally similar to its predecessors, we refrain from a detailed description here, but provide a commented MATLAB script in the Supplemental material for others to use. Archer et al. (2009) demonstrated that this model compares favorably in terms of CO_2 drawdown with other more complex models in modern simulations, particularly over geologically relevant time scales. GEOCYC was designed to test modern day climate scenarios, and used pre-industrial conditions as a baseline, as did the model of Mussard et al. (2014).

3.1. Model modifications

Several modifications to GEOCYC were made to match more closely with Cretaceous climatic conditions prior to the eruption of the Deccan Traps and are detailed in the MATLAB climate code (see Supplemental material). We altered the percentage of exposed land area, mean continental latitude, and a parameter relating global river runoff to changes in global mean temperature. The sensitivity of the model to these parameters is outlined below (Section 4.1). The solar constant was reduced by a small fraction (~0.4% — Feulner, 2012) to replicate the slightly weaker sun at 66 Ma, but the effect was negligible. In each model run, we prescribe a CO_2 emission scenario representative of the Deccan trap eruptions, added to a background CO_2 level. Because CO_2 drawdown and temperature scale non-linearly with CO_2 level the climate response depends on both the background CO_2 level and the Decan trap CO_2 emissions scenario. It is important to initiate our Deccan emission tests at background CO_2 levels (and hence temperatures) similar to those present at the end of the Cretaceous. We tuned background CO_2 levels to 450 ppm (Beerling et al., 2002) by altering background CO_2 emission rates to a higher value, a plausible change given the faster seafloor spreading rates in the Cretaceous (Seton et al., 2009). The model was allowed to stabilize at these new conditions during a “spin-up” period, resulting in a global air temperature of 17 °C prior to the simulated eruption of Deccan Traps. The time step in the original model was 50 years, and here we reduced it to 10 years, a necessary change to test shorter duration eruptions. Nonetheless, using MATLAB, the model completes a run of over one million simulation years in under a minute on a modern desktop computer. Tests were completed for shorter time steps, 1 year or less, with no discernible difference in results.

3.2. Eruption scenarios

Previous studies, with the exception of Mussard et al. (2014), have generally assumed continuous eruption of Deccan basalts over the entire eruptive period. In our case we simulate eruptions by increasing the rates of CO_2 emission above background for discrete time periods that can vary in their size, pattern, duration, and spacing (see Section 4.2 below), allowing us to test whether the episodic nature of these eruptions is important to their climatic effects. We can alter these eruptive parameters independently of each other and the total CO_2 emissions. The major areas of uncertainty in determining the total CO_2 emitted are the volatile content percentage of the lavas and the original total volume of eruptive material (see Section 4.2 below). We input total CO_2 emission into the model that are calculated from lava quantity and volatile percentage, or use previously calculated estimates of emitted CO_2 (see below).

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