VOLCANIC CLIMATE WARMING THROUGH RADIATIVE AND DYNAMICAL FEEDBACKS ON SO2 EMISSIONS

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Introduction: Flood basalt, or large igneous province, volcanic eruptions are the largest volcanic events in Earth's history. At times, they have covered thousands of square kilometers with kilometers thick layers of basalt [1]. Flood basalt eruptions are known to occur on each terrestrial world (Mercury, Venus, Earth, the Moon, and Mars) in our Solar System [2,3,4,5] and are thus plausible on terrestrial composition exoplanets. Massive quantities of climate-modifying gas species are released during such eruptions, which can span millennia or more [6]. This volcanic climate modification is strongly implicated in coincident mass extinction events in Earth's history such as the Cretaceous-Tertiary (coincident with the Deccan Traps eruption) and end Permian (coincident with the Siberian Traps) [7,8,9]. Flood basalt eruptions in Mars' history may have pushed the climate toward habitable conditions [e.g., 10].

The precise mechanisms by which flood basalt eruptions influence a planet's climate is still unknown. Eruption durations, rates, and cadences [6], altitude to which volcanic plumes extend [e.g., 1], and the volume of climate-modifying species such as SO_2 and CO_2 that are degassed [11,6] all likely weigh on a planet's climate response. Following an eruption, the complex climate responses such as greenhouse warming, circulation changes, aerosol and cloud radiative impacts, and photochemistry (e.g., aerosolization of SO_2 into H_2SO_4) must be simulated by a sophisticated and comprehensive global climate model (GCM).

In the existing literature on Earth's climate response to large eruptions, there is broad consensus on general cooling (i.e., the "volcanic winter" response) due to shading by upper tropospheric and stratospheric H_2SO_4 aerosols [e.g., 12]. Smaller volcanic events can produce varied regional impacts [e.g., 13]. But importantly, much of the literature has studied short-duration explosive eruptions (e.g., Pinatubo) that release ash and climate-relevant gas species into the lower stratosphere. Limited studies of flood basalt sized eruptions have looked at CO_2 release and how much warming could have occurred [e.g., 14], but without full treatment of aerosol, cloud, and chemistry physics in a GCM.

Methods: The geologically youngest and smallest flood basalt eruption on Earth is the Columbia River Flood Basalt (CRB) [15,16]. It occurred 15-16 Mya in eastern Washington and Oregon. The mid-Miocene climactic optimum was proximal to the CRB eruption and there has been suggestions in the literature that its CO_2 released helped warm the climate during that period. The largest phase of the CRB eruption is termed the "Grande Ronde" basalt formation.

We have simulated one specific (notional) eruption within the Wapshilla Ridge member of the Grande Ronde formation. Using the Goddard Chemistry Climate Model (GEOSCCM) [17] , we simulated an eruption scenario that lasts 4 years and emits 1/10th of the SO_2 that may have been emitted during the largest Wapshilla Ridge eruption [6] with 20% emitted in the near-surface and 80% in the upper troposphere and lower stratosphere [1]. In total, this corresponds to 30 Gt of SO_2. We use fixed pre-industrial CO_2 levels of 280 ppm, modern continent and ocean topography, fully interactive chemistry to convert SO_2 into radiatively-active H_2SO_4 aerosols, and a fully dynamic and interactive ocean. SO_2 is not radiatively active. Additionally, we conducted a baseline simulation without the eruption for comparison.

Results: Despite the massive release of SO_2 being rapidly converted to H_2SO_4 aerosols, the climate *warms* dramatically after a very brief initial cooling. The planet is completely shrouded in sulfate aerosol, with global area-weighted opacities exceeding 220 after the 4-year long eruption, comparable to thick cumulonimbus clouds. Surface downward shortwave radiation is attenuated by 85% with a 70% reduction in outgoing longwave radiation at the top of the atmosphere.

The climate warming response is maximized 3-4 years following the end of the eruption with a global mean +6 K temperature anomaly compared to the baseline simulation (Figure 1). On a regional level, summertime monthly mean temperatures *exceed 40°C*, which likely would create major habitability challenges for mammals [18].

The warming climate response is radiatively- and dynamically-driven. While sulfate aerosols cool the surface through shading, they warm the atmosphere *in situ* at their altitude, which results in the elimination of the tropical tropopause. The tropical tropopause is the water cold trap in Earth's atmosphere, and its absence allows water vapor to flood into the stratosphere and results in a 3 orders of magnitude increase in stratospheric humidity (Figure 2). This water vapor produces downward infrared flux that cools the stratosphere, while warming the surface and troposphere. Briefly, the Earth crosses the moist greenhouse limit, which may have implications for water loss during such eruptions on ancient Mars and Venus.

In addition, the stratospheric ozone layer is largely destroyed with global reduction greater than the modern Antarctic ozone hole. Precipitation patterns are altered and the global ocean circulation is generally slowed.

However, even such a huge perturbation to the climate system returns to near-normal conditions approximately 15 years after the end of the eruption. Sulfate aerosol is removed from the atmosphere, stratospheric humidity levels return to pre-eruption levels, and global temperatures largely match the baseline simulation. This suggests that the cadence of individual eruptions within the longer duration flood basalt eruption activity is important for understanding the climate response and that the canonical expectation of "volcanic winter" during flood basalt eruption periods should be reevaluated.

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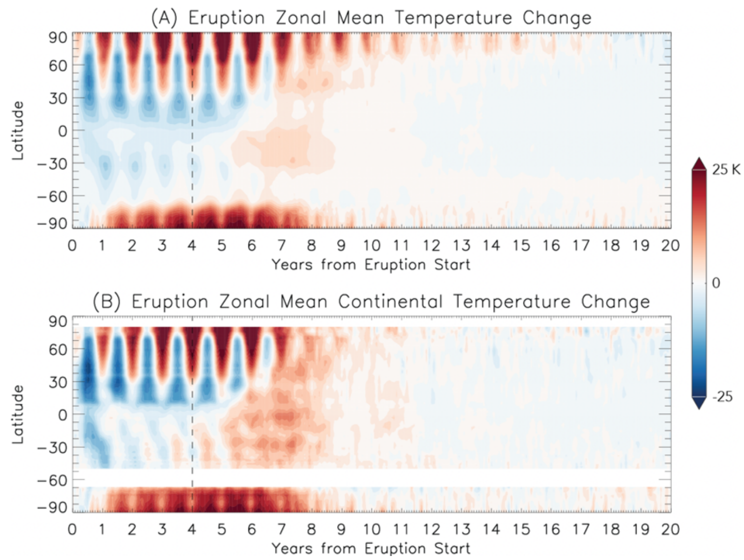

Figure 1. (A) Zonal mean temperature change (K) of the eruption simulation relative to a 20-year average of a baseline simulation as a function of time and (B) the zonal mean temperature change over continental areas only. The vertical dashed line represents the end of the eruption.

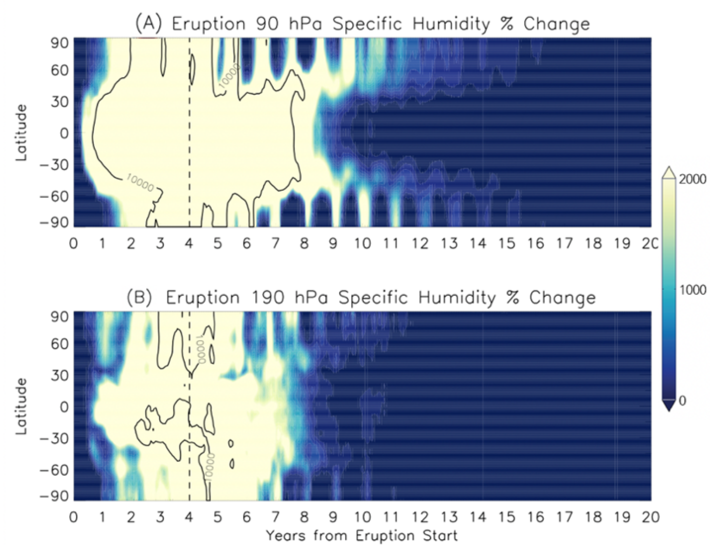

Figure 2. (A) Percent change in specific humidity of the eruption simulation over the baseline simulation as a function of time at 90 hPa and (B) at 190 hPa. The thick black contour is the 10,000% contour. The vertical dashed line represents the end of the eruption.