MODELING FLOOD BASALT VOLCANIC CLIMATE DISRUPTIONS: IMPLICATIONS FOR TERRESTRIAL PLANET HABITABILITY

S. D. Guzewich[1], L.D. Oman[1], J. Richardson[2,1], P. Whelley[2,1], S. Bastelberger[2,1], K. Young[1], J. Bleacher[3], R. Kopparapu[1], and T. Fauchez[4,1], [1]NASA Goddard Space Flight Center, Greenbelt, MD, 20771 scott.d.guzewich@nasa.gov, [2]University of Maryland, College Park, MD, [3]NASA Headquarters, Washington, DC, [4]Universities Space Research Association, Columbia, MD, 21046.

Introduction: Volcanic flood basalt eruptions in Earth's history have covered thousands of square kilometers with basalt deposits up to kilometers thick [1]. The massive size and extended duration (up to centuries or millennia) result in enormous releases of climactically-relevant gas species such as SO_2 and CO_2 [2]. Flood basalt eruptions on Earth such as the Siberian and Deccan Traps are coincident with mass extinction events, although the casual linkages are still being studied [3, 4, 5]. Additionally, flood basalt eruptions seem to be a common feature of terrestrial planets in our Solar System [6, 7, 8, 9] and are hence plausible on terrestrial exoplanets. Indeed, flood basalt eruptions may have made the ancient martian climate *more* habitable [e.g., 10].

However, what is still unknown is precisely how flood basalt eruptions influence planetary climate via their eruption rates and cadence [2], height of the volcanic plumes [e.g., 1], and relative degassing abundance of climactically-relevant species like SO_2 [11, 2]. Once eruptions occur, the complex interplay of photochemistry (e.g., turning SO_2 into H_2SO_4 aerosols), greenhouse gas warming, changes to the atmospheric circulation, and aerosol-cloud interactions can only be properly simulated with a comprehensive global climate model (GCM).

Previous work on the terrestrial climate response to large volcanic eruptions has settled on the initiation of "volcanic winter", a cooling response to the reduced surface insolation caused by a widespread blanket of H_2SO_4 aerosols in the upper troposphere and stratosphere [e.g., 12]. Smaller-scale eruptions produce more varied regional effects, but again, largely with cooler temperature anomalies at the surface [e.g., 13]. However, these previous works have generally focused on single–short-duration explosive eruptions that inject material into the stratosphere. This is in contrast to flood basalt eruptions, which have much longer durations and likely injected material at the surface, into the troposphere, and lower stratosphere.

Methods: Our ongoing work has simulated a short-duration Columbia River Flood Basalt (CRB)-like eruption, a medium-scale flood basalt eruption that occurred ~15-16 Mya in eastern Washington state and Oregon. While the CRB is not believed to have initiated an extinction event, it occurred in the midst of the Mid-Miocene climactic optimum [14] and there is some evidence of a coincident glaciation [e.g., 15]. The CRB eruption occurred in a variety of phases, the largest produced the Grande Ronde Basalt Group. Following [1], we created an eruption scenario for the Goddard Chemistry Climate Model (GEOSCCM) [16] that emits SO_2 in the atmospheric boundary layer constantly and periodically (four times per year) an explosive eruption that emits much more SO_2 in the upper troposphere/lower stratosphere. The eruption lasts for 4 years, following minimum emplacement time of the Grande Ronde's largest flow unit, the Wapshilla Ridge Member [2], and emits 30 Gt of SO_2 in total. This corresponds to approximately 1/10th of what was likely emitted during the Wapshilla Ridge eruption phase of the CRB [2]. Note that we have used a post-industrial atmosphere with 400 ppm of CO_2 and an ocean with a modern continental configuration as our baseline, and simulations with a pre-industrial atmosphere are ongoing. Our simulations do not include SO_2 as a radiatively active species, however H_2SO_4 aerosols are radiatively active.

We additionally use a 1D radiative-convective model, Clima, to compare with the GCM results.

Results: The massive flux of SO_2 into the atmosphere is quickly converted to H_2SO_4 aerosols. Global area-weighted mean visible band sulfate aerosol optical depth reaches 230 near the end of the eruption, comparable to cumulonimbus clouds. This reduces the surface shortwave radiative flux by 85% and top-of-atmosphere outgoing longwave flux by 70%. Contrary to our expectations, we find that the climate *warms* during and immediately following the eruption after a very brief initial cooling. Global mean surface temperature peaks 3-4 years after the eruption ends with a +7 K anomaly relative to a baseline simulation without the eruption (Figure 1). Post-eruption regional temperatures, particularly near-equatorial continental areas, see drastic rises of summertime temperatures with monthly mean temperatures equaling or exceeding 40°C, which are uninhabitable temperatures for mammals [17].

These temperature responses are radiative- and circulation-driven. The eruption warms and raises the tropical tropopause, allowing a massive flux of water vapor into the stratosphere. Stratospheric water vapor, usually ~3 parts per million reaches 1-2 parts per thousand (Figure 2). This increase results in increased thermal infrared flux from the stratosphere, which cools that portion of the atmosphere while also warming the surface and troposphere. Such a water flux into the stratosphere may have implications for historic water loss on planets such as Mars and Venus.

Additionally, much of the stratospheric ozone layer is removed, with global column-integrated ozone abundances dropping to 50-100 Dobson units, lower than the modern Antarctic ozone hole.

Despite the massive perturbation to the climate during the four-year eruption, the climate quickly approaches pre-eruption normal. We find that after seven years post-eruption: (1) H_2SO_4 aerosols are nearly absent, (2) surface radiative fluxes are near normal, and (3) global temperatures are cooling toward normal levels. However, the stratospheric water vapor more slowly returns to pre-eruption levels and remains more than one order of magnitude higher than pre-eruption levels after seven years post-eruption.

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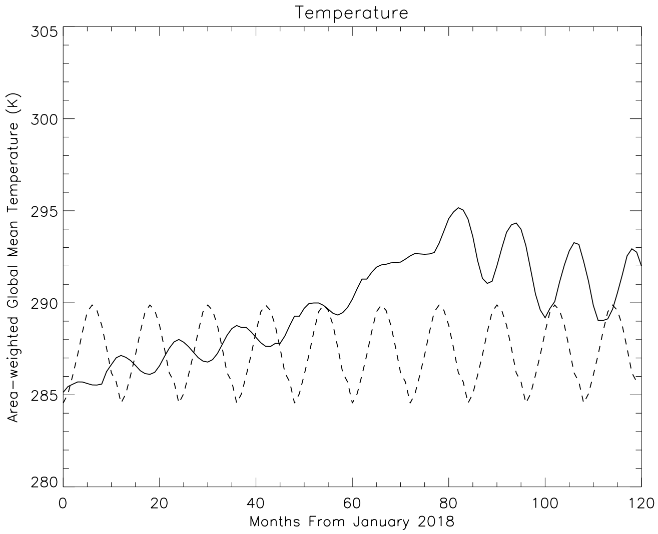

Figure 1. Post-eruption global area-weighted surface air temperature over the simulation (solid line) compared to a baseline simulation (dashed line).

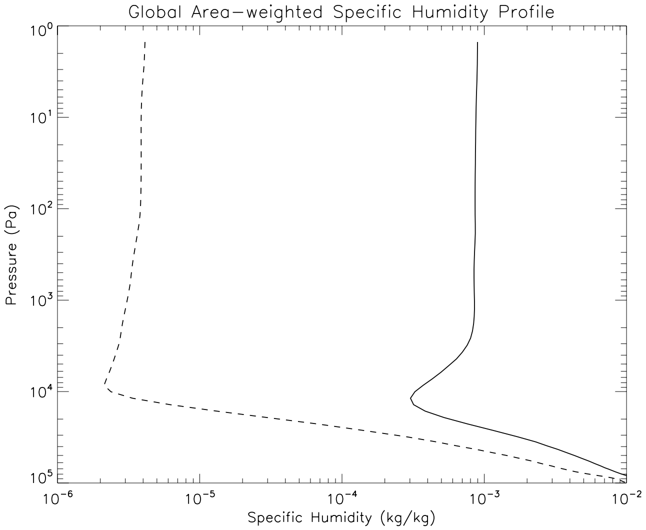

Figure 2. Post-eruption global area-weighted specific humidity vertical profile (solid line) compared to a baseline simulation (dashed line).