VOLATILE TRANSPORT BY VOLCANIC PLUMES ON EARTH, VENUS AND MARS.

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Introduction: Explosive volcanic eruptions can produce sustained, buoyant columns of ash and gas in the atmosphere (Fig. 1). Large flood basalt eruptions may also include significant explosive phases that generate eruption columns. Such eruptions can transport volcanic volatiles to great heights in the atmosphere. Volcanic eruption columns can also redistribute chemical species within the atmosphere by entraining ambient atmosphere at low altitudes and releasing those species at much higher altitudes.

Fig 1. *Eruption of Mt. Pinatubo 3 days prior to the cataclysmic eruption on 15 June 1991, that reached 35 km altitude.*

Volcanoes and Climate: The relationship between volcanoes and climate is complex and operates over a range of time scales, from days to possibly centuries. On Earth, volcanoes have long been associated with short-term local weather, and may influence longer-term climate (see [1] and references therein). Sulfur species (SO_2 and H_2S) are the primary volcanic volatiles that impact climate. Sulfur dioxide is particularly important when injected into the stratosphere because the sulfuric acid (H_2SO_4) aerosols derived from SO_2 can have long residence times (1 – 2 years). By far the most important impact of increased stratospheric H_2SO_4 is increased backscatter at optical wavelengths, resulting in stratospheric warming and a net cooling at the surface, particularly in the summers following an eruption [1]. In addition, the 1991 Pinatubo eruption was linked directly to increased depletion of ozone through heterogeneous chemical reactions between volcanic aerosols and anthropogenic chlorine [2]. In some instances, complex atmospheric circulation can result in 'winter warming' in some continental regions following tropical eruptions [3]. Separating climatic variations due to volcanic eruptions and other periodic phenomena, such as El Niño or solar variability, can be a complicated process. The lack of oceans on Venus and Mars should simplify the interactions between volcanoes and climate, but there are still many unknowns in these environments, including magmatic volatile composition and levels of volcanic activity now and in the past. On Venus and Mars, where water is not as abundant as Earth, H_2O may also be a key greenhouse gas supplied by volcanoes that has influenced climate.

Buoyant plume dynamics play an important role in the ability of explosive volcanic eruptions to supply climatically sensitive gases (e.g., H_2O, SO_2, CO_2) to planetary atmospheres. The altitude at which these gases are injected into the atmosphere is controlled in large part by the composition and density of the ambient atmosphere. Thus, the dynamics of plume rise and ultimately the final rise height of a plume are strongly influenced by the ambient atmospheric properties. Models of volcanic plume dynamics are largely based on the original buoyant plume work of Morton et al. [4], and include models for axi-symmetric plume rise from circular vents [e.g., 5-7] as well as planar plumes from linear fissure vents [8,9].

Earth. Recent examples of large, historic eruptions that have impacted climate on the 1–2 year timescale through the injection of large amounts of SO_2 into the atmosphere include Krakatoa (1883), Agung (1963), El Chichon (1982), and Pinatubo (1991; Fig. 2). Despite widespread notoriety in the US, the eruption of Mt. St. Helens (1980) was relatively small by both explosive standards and contribution of SO_2. The eruption of Laki (1783) [10] is an example of a sustained fissure eruption that fed SO_2 into the upper troposphere (and likely the lower stratosphere) through repeated eruptions over a period of eight months, affecting weather in western Europe during the summer of 1783 and possibly through 1784 [11]. Volumes of SO_2 injected by historic volcanic eruptions range from 7 Mt (= 7 teragram) by El Chichon [12], to 20 Mt by Pinatubo [12], and up to an estimated 122 Mt by Laki [10]. In addition to SO_2, volcanic eruptions on Earth are capable of redistributing large volumes of water from the lower atmosphere into the stratosphere. Models indicate that a 25 km plume erupting into a wet, tropical atmosphere, can transport up to 4 Mt of H_2O

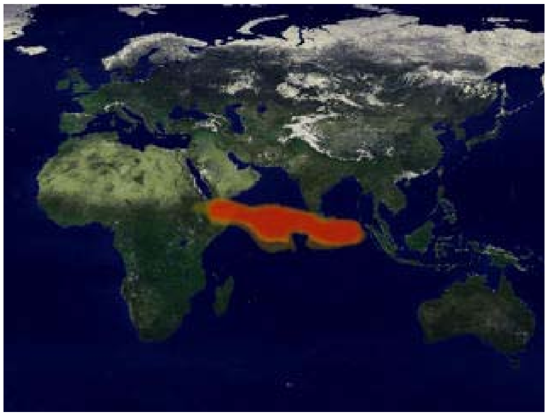

Fig 2. *SO_2 emission seven days after Mt. Pinatubo erupted in 1991. Image curtsey NASA/Goddard Space Flight Center Scientific Visualization Studio.*

per hour to the plume top, ~30% of which is entrained in the lower atmosphere [6].

Based on the impact observed following the Laki eruption, some have speculated that the large flood basalt eruptions (e.g., Columbia River Basalts, Deccan Traps) may have supplied large volumes of SO_2 and other gases to the upper troposphere, or possibly even the stratosphere. The flood basalt lava fields are made up of multiple flow units that are estimated to have erupted with volumetric flow rates similar to the maximum estimated for Laki, each emplaced on decadal time scales [13]. Long duration effusive basaltic eruptions, such as the current 30 year eruption of Puu Oo, Hawaii, are consistent with flood basalt events that may have had more or less constant volume eruption rates over hundreds of years, injecting up to 1000 Mt of SO_2 into the atmosphere for decades at a time. [14]

Venus. Compared to Earth, it is extremely difficult to generate buoyant plumes under current atmospheric conditions on Venus [9, 15, 16]. This is due, in part to the relative densities of volcanic volatiles and the 95% CO_2 atmosphere, at Venus surface temperatures (450°C) and pressures (92 bar). In general, explosive eruptions on Venus would tend to generate collapsed columns and pyroclastic flows. However, when magmatic temperatures exceed 1100 °C, and when water is assumed to be the driving magmatic volatile, models predict that buoyant plumes can be sustained [16]. It is possible that Venus is still volcanically active [17], and observations of spikes in SO_2 at the top of the troposphere may indicate current volcanism on Venus [18]. For boundary conditions producing a buoyant plume that can be sustained, models suggest that plumes may be able to rise to the top of the troposphere (70 km above the surface). Injections of volcanic SO_2 of the order 250 MT/hr and H_2O up to 2500 MT/hr could be injected into the cloud layer (Table 1). Venus is thought to have possibly been resurfaced through a global volcanism 500 -750 Ma. Such an event would have contributed huge amounts of H_2O, SO_2 and other volatiles into the atmosphere.

Table 1. *Estimated rates of injection of H_2O and SO_2 at maximum plume heights on Venus, for magmas with 7 wt% volatiles (70% H_2O, 15% CO_2, 8% N_2, 7% SO_2).*

Plume Height (km)	H_2O flux (Mt/hr)	SO_2 flux (Mt/hr)
20 – 30	275 – 877	28 – 88
30 – 40	620 – 1750	62 – 175
40 – 50	1100 – 2630	110 – 263

Mars. The key driver of plume buoyancy is the warming of entrained ambient atmosphere through convection. Thus, the term ‘buoyancy’ loses its meaning in the tenuous atmosphere on Mars where there simply is not enough atmosphere to entrain. The current low density atmosphere can sustain buoyant plumes up to heights of ~10 km, above which, ballistic transport likely dominates [19]. However, Mars may have had a somewhat warmer climate in the past with an atmospheric density similar to Earth (~1 bar). If so, then explosive plumes on Mars would have been capable of injecting volatiles at altitudes of 30 – 40 km, similar to large pyroclastic eruptions on Earth. For example, the Medussa Fossae deposit has been postulated as being formed by large pyroclastic eruption(s) in the Hesperian (3000 – 3700 Ma) [20]

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