INFLUENCE OF VOLCANIC ERUPTIONS ON TROPICAL HYDROCLIMATE DURING THE LAST MILLENNIUM

by

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Abstract

Volcanic eruptions exert the most important radiative forcing on Earth's climate during the pre-industrial interval of the last millennium. In this thesis, I investigate the role of volcanic eruptions in altering tropical climate, including temperature and rainfall. I primarily use forced transient simulations of the last millennium as a tool to explore how explosive volcanic events project onto the hydrologic cycle, as well as the imprint of water isotopologues ($H_2{}^{16}O$, $H_2{}^{18}O$) associated with rainfall. Attention is given to the South American continent specifically (in chapter 2), and to the entire tropics (in chapter 3).

In Chapter 2, I show that volcanic eruptions cool the South American continent and alter rainfall, decreasing the intensity of the austral summer monsoon, and decreasing rainfall in the northern part of the continent during austral winter. These factors also conspire to influence the isotopic signal left behind, informing the detectability of volcanic excursions in the paleoclimate record and the anticipated hydroclimate response at the continental scale for future eruptions.

The results of chapter 2 emerge from a simple composite response to many of the largest volcanic eruptions during the last millennium and instrumental period. In chapter 3, I advocate for a more targeted approach in how volcanic eruptions are stratified when interpreting physical responses or comparing to past records; in particular, I highlight the role of the spatial structure in volcanic forcing in altering the mean intertropical convergence zone (ITCZ) position, and the associated response of different monsoon systems. The main finding in chapter 3 is that the ITCZ moves away from the preferentially forced hemisphere, which leads to unique ENSO behavior, river discharge anomalies, or patterns in isotopic anomalies, depending on the location of the eruption. In this chapter, I also make contact with recent advances in understanding ITCZ

migrations through the lens of the atmospheric energy budget. I discuss the significance of these findings for interpreting the paleoclimate record.

In chapter 4, I expand upon chapter 3 by quantifying individual feedbacks (including water vapor and clouds) that arise in response to different spatial structures of volcanic forcing. I demonstrate that cloud and water vapor distributions differ dramatically for aerosol loadings that are northern hemisphere focused, southern hemisphere focused, or fairly symmetric about the equator. Such feedback differences may amplify or dampen ITCZ movements or complicate inferences of how feedbacks are expected to behave in a warming world.

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Statement of Publication/Contribution of Authors

I, Christopher Colose, was the lead researcher for all material presented in this manuscript. Dr. Mathias Vuille at the University at Albany, and Dr. Allegra LeGrande at NASA's Goddard Institute for Space Studies, contributed to Chapters 2 and 3 through discussions of methodology and results. Both acted in a supervisory capacity through the duration of my PhD track, and provided comments on all chapters. Dr. LeGrande also provided data used in Chapters 2 and 3.

Chapters 2 and 3 of this dissertation include the following published material, with only minor changes to ensure continuity in figure/section numbering throughout the thesis. Inclusion of these chapters is necessary to provide a coherent and appropriately sequenced investigation of the subject-matter.

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Chapter 1

Introduction

1.1. Opening

“During several of the Summer Months of the Year 1783, when the Effect of the Suns Rays to heat the Earth in these northern Regions should have been greatest, there existed a constant Fog over all Europe. This Fog was of a permanent Nature; it was dry, and the Rays of the Sun seem’d to have little Effect towards dissipating it, as they easily do a moist Fog arising from Water. They were indeed rendered so faint in passing thro’ it, that when collected in the Focus of a Burning Glass they would scarce kindle brown Paper; Of course their Summer Effect in heating the Earth was exceedingly diminished. Hence the Surface was early frozen…

Hence the first Snows remained on it unmelted, and received continual Additions.

The Cause of this Universal Fog is not yet ascertained. Whether it was adventitious to this Earth, and merely a Smoke proceeding from the Consumption by Fire of some of those great burning Balls or Globe which we happen to meet with in our rapid Course round the Sun, and which are sometimes seen to kindle and be destroy’d in passing our Atmosphere, and whose Smoke might be attracted and retain’d by our Earth: Or whether it was the vast Quantity of Smoke, long continuing to issue during the Summer from Hecla in Iceland, and that other Volcano which arose out of the Sea near that Island; which Smoke might be spread by various Winds over the northern Part of the World; is yet uncertain.”

-Benjamin Franklin

The above quote, written over 200 years ago by Benjamin Franklin (Franklin, 1784) was perhaps the first attempt to link volcanism and atmospheric phenomena, in particular when a strange ‘‘dry fog’’ (a sulfate haze resulting from tropospheric oxidation of volcanogenic sulfur gases) and unseasonably cold weather struck Europe. Franklin also suggests in the quote that a meteorite may have been responsible. However, there was indeed a major eruption in Iceland (albeit Laki, not Hekla, which is ~75 km away) in 1783-1784, one of the largest volcanic eruptions in recorded historical times. The Laki eruption produced ~14.7 km^3 of basaltic lava

(Thordarson and Self, 1992), a volume sufficient to cover New York City (~789 km^2 in area) with over 18 meters in basalt. In Iceland, the haze lead to the loss of most of the island's livestock (from eating fluorine contaminated grasses), crop and vegetation failure (due to acid rain), and because of famine and disease, the death of ~20% of the country's human residents (Thordarson and Self, 2003).

Volcanic eruptions are very important for society, and have strongly impacted past cities and civilizations (e.g., an eruption at Santorini in Greece at ~1620 B.C. produced a thick layer of pumice and ash that buried Bronze Age settlements and permanently altered the local topography, see Friedrich et al., 2006; or the 79 A.D. Vesuvius eruption that deposited large quantities of ash onto the buildings of the Roman city, Pompeii). In 1883, the eruption of Krakatoa in Indonesia destroyed hundreds of villages and killed ~33,000 people. In 1902, the Pelée eruption in the Caribbean killed ~29,000 people (e.g., Luong et al., 2003).

Historical paintings reflect changes in the color of the sky following large eruptions due to the optical effects of the volcanic cloud, and in fact the ambitious task of using red-to-green ratios in historical artwork to reconstruct paleo- aerosol optical depths has been undertaken (Zerefos et al., 2014). The optical effects caused by Tambora for several years following 1815 have been widely reported, including sunspots seen from the naked eye, dimming of the moon and stars in a clear-sky atmosphere, and prolonged sunsets and twilights observed near London, features that have been used to calculate visible optical depths (Stothers, 1984).

Volcanic eruptions also impact air travel, as with the Icelandic Eyjafjallajökull eruption in 2010. Since the residence time of ash can be as long as weeks, the ash does not have a strong climate impact but is able to paralyze air traffic far away from the source. Eyjafjallajökull caused the cancellation of 108,000 flights, particularly in Europe, disrupted the travel plans of 10.5 million passengers, and cost the airline industry in excess of $1.7 billion (Budd et al., 2011).

Many eruptions of the sort described above are therefore of interest as a geologic hazard and to historians and archeologists. However, in many cases, the aerosol cloud is primarily restricted to the troposphere and the volcanic material (see next section) falls out on timescales of days to weeks, leaving minimal long-term impact extending beyond the recovery timescale of that which was affected by the eruption.

Explosive stratovolcanic events provide an extra dimension to the impact of volcanic eruption. The 1815 Tambora eruption (on the Indonesian island of Sumbawa), for instance, immediately killed tens of thousands of people people, but the impacts of the volcano were felt worldwide due to significant global cooling (Oppenheimer, 2003; Raible et al., 2016), resulting in major changes to European and North American weather, as well as crop failures. The eruption allegedly inspired Mary Shelley's "Frankenstein" while North America experienced the so-called "Year without a Summer" (anecdotally, summer frosts were pervasive in the northeast United States and snowfall was recorded in June in Albany, NY; Baron, 1992). Limited instrumental measurements suggest Northern Hemisphere (NH) temperatures dropped by ~1°C in 1816 (Stothers, 1984).

1.2. Volcanoes and Climate— A primer

This remainder of this thesis focuses on the climate impact of volcanic eruptions, especially on tropical hydroclimate and during the last millennium (LM)[1]. I also stress the relatively short-to-intermediate impact (~seasons to years) following volcanic eruptions, which approximately corresponds to the residence time of sulfate aerosols that form in the stratosphere. Indeed, it is now recognized that the metric most closely related to the volcanic projection onto climate is the sulfur dioxide (SO_2) emissions from volcanoes, not necessary the explosivity, volume of erupted magma, or ash injection (Pollack et al., 1976; Rampino and Self, 1984). Volcanoes also emit Hydrogen Sulfide (H_2S) that is rapidly converted to SO_2, along with Halogens, CO_2, and water vapor. The oxidation of SO_2 by OH and subsequent reactions yield sulfuric acid vapor (H_2SO_4) that condenses onto particles to form sulfate aerosols, typically at sizes similar to a visible wavelength and where scattering of solar radiation is strongest.

It would be possible for eruptions to warm the surface if the sulfate aerosols were very small or large ($<0.05\mu m$ or $>2.2\mu m$; see e.g., Coakley and Grams, 1976; Lacis et al., 1992). In the former case, scattering is very small; for the large particle limit, the thermal component begins to increase with particle size while scattering asymptotes to a constant value as particle size becomes larger than the contributing solar wavelengths (Lacis, 2015). Thus, for large particles, the shortwave and longwave contributions will be of comparable magnitude. The longwave component also depends on the height of the aerosol, since the greenhouse effect depends upon the temperature difference between the surface and emission layer. However, particles are only very small in their formative stages, and if very large, tend to fallout quickly, leaving intermediate size particles (where solar scattering dominates) as the expected players to

[1] This will refer to either the 850-1850 or 850-2005 C.E. interval, corresponding to the pre-industrial LM and historical simulation period for the experiments in CMIP5/PMIP3. The study in chapter 2 includes the historical extension period, but chapter 3 does not.

the perturbation in the stratospheric aerosol layer. Thus, large sulfur-rich volcanic excursions will almost always be expected to cool the terrestrial climate.

Sulfate aerosols typically heat the stratosphere via absorption of longwave radiation, but in principle could cool the stratosphere if injected in the upper stratosphere, because of the higher local temperatures and increased efficiency for cooling to space (Lacis, 2015) relative to the capacity for absorbing upwelling radiation from lower layers. Stratospheric temperatures are observed to increase in the lower and mid stratosphere following the El Chichón (April 1982) and Mt. Pinatubo (June 1991) eruptions (Randel et al., 2016). For large tropical eruptions, the stratosphere warming results in anomalous temperature gradients aloft between the equator and poles, and an enhancement of the polar vortex. This has been implicated in leading to warming over sectors of the northern mid-latitudes during boreal winter (e.g., Robock and Mao, 1992; Kirchner et al., 1999; Shindell et al., 2004; Stenchikov et al., 2004, 2006) via dynamical responses in the jet stream that overcome the direct radiative effects of shortwave scattering in the winter high-latitudes. This highlights a difference between tropical and high latitude eruptions. However, fewer studies have targeted the implications of hemispheric asymmetry in the aerosol loading until very recently, which I visit in chapter 3.

The fragmented magmatic material forming the ash of the eruption is comprised of larger (typically >10μm to mm) and settles out quickly, leaving behind the aforementioned sulfur gases that form the enduring aerosol layer of concentrated sulfuric acid. It is worth noting that explosive eruptions may have a relatively small sulfur injection. For example, Mt. St. Helens in 1980 was very explosive but did not put much sulfur into the stratosphere, thus resulting in minimal climate impact (Robock, 1981). Similarly, sulfur-rich eruptions that are not sufficiently explosive to protrude into the stratosphere will have little climate impact. In fact, annual anthropogenic SO_2 emissions are larger than background eruption fluxes or even the input from a Pinatubo-sized eruption. However, the actual sulfur burden from volcanoes and human activity is comparable (Graf et al., 1997), due to the fact that the sulfur is often injected at higher elevations with volcanoes, even for background tropospheric eruptions. However, volcanoes dominate the variability in stratospheric loading where the residence time is much longer. Thus, the residence time for volcanic SO_2 is higher than for anthropogenic SO_2. Water vapor released in the eruption also affects atmospheric chemistry and the rate of sulfate formation (LeGrande et al., 2015), although a proper treatment of chemistry in models is in its infancy and not the way volcanic forcing is implemented in the Coupled Model Intercomparison Project Phase 5(CMIP5)/Paleoclimate Model Intercomparison Project Phase 3 (PMIP3) generation of GCM's.

CMIP5/PMIP3 is the most recent iteration of coordinated model experiments with multiple contributing groups (Braconnot et al., 2012; Taylor et al., 2012); the simulations covering the period 850-1850 C.E. as part of the past1000 initiative (with some groups contributing historical extensions to these runs) are a subset of the contributing target paleo time intervals (along with the Last Glacial Maximum and mid-Holocene). Notably, the past1000 runs are transient simulations using the same model versions as for future projections, and include sporadic volcanic activity in the input forcing, allowing for a greater sample of events to be probed than is possible using just the instrumental period.

The most recent climatically meaningful volcanic excursion was that of Mt. Pinatubo in 1991, which briefly interrupted the ongoing long-term global warming trend (Figure 1.1) and helped produce global cooling by up to ~0.5 °C despite the concurrent El Niño at the time (the effects of ENSO are linearly removed in Figure 1.1, which amplifies the Pinatubo influence). Such cooling also emerges in a composite sense when considering the largest eruptions during