THE TAMBORA PROJECT: AN ATMOSPHERIC SIMULATION AND HISTORICAL EVALUATION OF THE MOUNT TAMBORA ERUPTION AND ITS IMPACTS ON GLOBAL CLIMATE AND SOCIETY (1815-18)

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THESIS

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ABSTRACT

The Tambora Project reconstructs on a global scale the most destructive episode of abrupt climate change in the modern historical record. The volcanic sulfate veil produced by the Tambora eruption in the period 1815-18 depressed temperatures and disrupted storm tracks in monsoonal India, thereby likely initiating the first global cholera pandemic, while famine, refugeeism and civil unrest threatened hard-hit nations from China to Western Europe to New England. Tambora is thus an invaluable modern case-study in the impacts of abrupt, short-term climate change. Because of its impacts on the vulnerabilities of human communities to rapid changes in the climate system, a multidisciplinary collaboration between atmospheric science, computer modeling and humanistic analysis was developed in order to fully reconstruct this epochal global event. This project reviews the existing scientific and journalistic literature on Tambora and proposes a series of computer simulations that will better represent the climatic effects from the 1815 eruption and the contributions of the unfamiliar eruption of 1809 utilizing the Community Earth System Model (CESM), the most sophisticated modeling yet attempted for the Tambora eruption. The results will help fill in the extensive gaps in scientific knowledge regarding the global impact of the eruption. Marriage of these results with qualitative description from the historical record will enable the first comprehensive analysis of the global climate crisis of 1815-18. This thesis focuses on the scientific literature and modeling aspect of the project, specifically the climatic and atmospheric local and global impacts of the eruption.

DEDICATION

I dedicate this thesis to my family. To my parents and grandparents for all the loving care-packages containing all the needed essentials. To my siblings for looking up to me, encouraging me to be better every day. Finally, to my family away from home (Vaiden-Moller) for "adopting" me into the family and making me feel closer to home.

Esto es para ustedes. Gracias.

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1. INTRODUCTION

Climate change is one of the most challenging and controversial topics facing the world today. Climate models used to study this issue require full consideration of the complexity affecting the various components of the Earth's climatic system. In order to develop and improve these models, a better understanding of Earth's components and their interactions is crucial. One of the most important naturally occurring influences on our climate system is volcanic eruptions. Studying the responses of climate to volcanic eruptions can help us better understand important radiative and dynamical processes that occur in our atmosphere and that respond to both natural and anthropogenic forcing. In addition, by quantifying the natural fluctuations of gases and other volcanic materials, we can separate these forcings from anthropogenic fluctuations in the climate record, helping us to detect and properly attribute anthropogenic influences on climate.

Large explosive volcanoes, such as that of Mt. Tambora, inject massive amounts of mineral material and various gases, including sulfur, into the upper atmosphere. Resulting sulfate aerosols in the stratosphere can have an approximate lifetime of about 1-3 years. (Budyko, 1977; Stenchikov et al., 1998). The aerosol cloud produced from the eruption undergoes further chemical (ozone depletion) and radiative (increased planetary albedo) interactions with the background atmosphere that can cause noticeable changes in the climate system (Devine et al., 1984; Rampino, 1988; Sigurdsson, 1990). The scattering of solar radiation to space causes a temporal cooling at the surface, increasing the planetary albedo. Meanwhile, the absorption of both solar and Earth's radiation at the stratosphere, heats the layer (Robock, 2000; Kinnison et al., 1994). Several studies have summarized the known effects of many large-scale volcanic eruptions on our atmosphere (e.g., Sear et al., 1987; Mass and Portman, 1989) .However, the most explosive known eruption in the historical record, that of Mt. Tambora, still remains one of the least explored. There is a substantial but unscientific popular and journalistic archive devoted to "The Year Without a Summer" in the North-Eastern United States, but studies on the impact of the Tambora eruption in Asia, both scientific and historical, are very limited. The existing scientific studies of the Tambora eruption, to be discussed later, have limitations in the modeling tools used and in the extent they consider relevant physical and chemical processes. The one academic history of Tambora's impact is more than thirty years old—John Post's *The Last Subsistence Crisis in the Western World* (Post, 1977)—and is confined to Western Europe. Post's study also predates the emergence of climate change as a central scientific and cultural issue for the global community. It is the intention of this thesis to investigate the current state of scientific knowledge of the 1815 eruption and to develop a project in which scientific computer simulations aid journalistic research in order to explain history.

The *Tambora Project* is a collaboration between disciplinary fields to produce the most complete and comprehensive study yet undertaken of this major historical event and communicates to the academic and general community, the full significance of similar disasters in modern climate and human history. *The Tambora Project* itself is divided into two main sections: (1) the historical analysis of the time period pre- and post eruption; and (2) the scientific analysis of the Tambora eruption and its climatic impacts. It then culminates with the evaluation of these two components in tandem. The scope of this thesis is limited to the second (2) section of the project; the scientific analysis of the eruption and its climatic impacts. An evaluation of all previous historic, climatic and modeling studies is performed, resulting in an elaborate methodology of computer simulations aimed specifically to answer the remaining questions of the eruption and its aftermath.

2. BACKGROUND

2.1 Mt. Tambora

Mt. Tambora is an active composite volcano (stratovolcano) located on the island of Sumbawa, Indonesia. The volcano inhabits most of the Sanggar Peninsula in central Sumbawa and it reaches an altitude of 2,850m; almost 1,500 meters less than previously recorded (4300m). **(**See **Figure 1)** The caldera is 1000m deep with a rim diameter of approximately 6000m.

Composite volcanoes are made out of numerous layers of rock and lava that have accumulated after multiple eruptions. The magma usually found in this type of volcano is very viscous and when it rises through the chamber, it clogs the volcanic pipe, leading to an accumulation of gases that in turn results in very explosive eruptions. Sigurdsson & Carey, 1992b establish four major volcanic formations before the eruption of 1815 from the stratigraphy on the walls inside the caldera. Two pyroclastic units that overlay these lava formations are the Black Sands and the Brown Tuff. The Brown Tuff formation represents the latest volcanic activity (ash fall deposits and pyroclastic surges) dating earlier than 1815. Using radiocarbon dating, the isotope samples from the lower and upper layers of the formation suggest sporadic volcanic activity between 5900 to 1210 ^{14}C BP, which in calibrated (real) years, indicates a period of inactivity of at least 1000 years before the catastrophic eruption in 1815. After 200 years of the historical eruption, and increase in seismic activity in 2011 alerted the population of Indonesia that Tambora was awake again and has been restless ever since.

2.2 Tambora's Eruption Chronology (1815)

On April 5, 1815, in the volcanic island of Sumbawa, Indonesia, the first signs of an awakening Mt. Tambora took place. Loud explosions were heard by the lieutenant-governor

Thomas Stamford Raffles more than eight-hundred miles away at his residence in Java. Alarmed, the British officials (thinking the explosions where cannons firing in the distance) dispatched the troops and launched rescue boats. Northeast of Tambora, approximately 240 miles away, the *Benares*, a British East Indian Company cruiser reported "a firing of cannon" coming from the south. In the island of Ternate, another five-hundred miles to the east, the cruiser *Teignmouth* was sent to explore the same noise. In the morning of April 6, a veil of ash reached Java, this ash fall continued for several days as it gradually stopped.

On the night of April 10, 1815, Tambora violently erupted and has been since the biggest and most explosive volcanic eruption recorded in human history. (e.g., Yokoyama, 1957; Self et al. 1984). Eruptions are measured using the Volcanic Explosivity Index (VEI), which uses a scale of whole numbers from 0 to 8 to rate the approximate amount of ash, sulfur and dust ejected into the atmosphere. Similar to the Richer Scale used for earthquakes, the VEI scale increases in factors of ten. The Tambora eruption recorded a VEI of 7 (Newhall and Self, 1982), making it one of the largest and deadliest eruptions in recorded history (see **Table 1** for a list of known eruptions since 1480). Past eruptions can be measured by using layers of volcanic debris found in ice cores and lake sediments. The chemical composition of each volcano is different, allowing using the chemical signature of the layers to distinguish each different eruption from the cores. The explosion and the caldera collapse were strong enough to thrust plumes up to 43km in altitude and to distribute ash fallout as far as 1300 km away. According to Stothers (1984) the explosion caused the mountain to reduce an estimate of 4,200 feet in height while ejecting some 25 cubic miles of debris and creating a 6 km wide, 1 km deep caldera. A re-evaluation of the Tambora ejecta by Self et al. (2004) estimated a total of 33 km^3 of magma. In addition, the eruption injected an estimated ≈60Tg of sulfur into the stratosphere in the first 24 hours and a total of ≈118 Tg of stratospheric aerosol, equivalent to six times that of Pinatubo (1991). Other gases emitted by the eruption are discussed by Sigurdsson and Carey (1992). They estimate a release of 70 Tg of fluorine (as HF). Fluorine was readily absorbed by ash particles and by the soil, and fluorine poisoning was likely widespread in livestock and humans.

Pumice rocks fell for the remainder of the night of the 10^{th} while loud explosions were heard until the evening of the 15th. Ash covered the summit and smoke emissions were still reported as late as August. Within a week or two of the eruption, the coarser ash particles fell out as a result of rapid tropospheric mixing and washout. Gas molecules, fine ash particles and aerosols then reached the stratosphere, where some resided for months or years, carried by winds and meridian currents around the globe and into all latitudes. As a result of photochemical reactions (ozone-water vapor-sulfur), secondary aerosols were formed in the atmosphere. The last volcanic aftershock was reported four years after the explosive eruption.

Tambora caused the highest immediate mortality of any historical eruption with >80,000 deaths. The village of Tambora was consumed under the vast amount of pumice. Sanggar, a village further away, was completely destroyed by falling pumice. Lieutenant Raffles conducted a survey to evaluate the extent of the damage. Around 10,000 people are believed to have died within the first 24 hours from pyroclastic flows, ash falls and hot gas, all buried under lava. Crops, cattle and inhabitants were wiped. During the following months, thousands died due to respiratory infections and disease from poisoned water, crops and cattle.

The volcano is better known, however, for its catastrophic impacts on regional and global climate than for the ground zero impacts from its eruption. Proxy and observational records show a pre-existing cooling trend in the global Northern Hemisphere and tropics at the time the

Tambora event occurred, which the eruption then amplified significantly, causing worldwide damage to crops and massive civil disruption through famine, disease and refugeeism. This resulted in the death of seventy to eighty thousand people. (Briffa et al., 1998; Cole-Dai et al., 2009; D'Arrigo et al., 2009; Jones et al., 1995).

2.3 Tambora's Current Volcanic Activity

On September 8 of 2011, the villagers of the island of Sumbawa in Indonesia reacted to a volcano alert level of 3 (on a scale of 1 to 4). Hundreds of farmers and other villagers (on the danger zone) were told to evacuate to other areas of Sumbawa. Some living on the slopes of the volcano, aware of the volcano's explosive and deadly past, took no chances and fled once the seismic activity noticeably increased since April of that same year. Intermittent swarms of small earthquakes were reported and large amounts of ashes and gas were released on numerous occasions, observed to reach heights of more than 1000 meters. The people of Sumbawa were reminded of the explosive eruption that changed history. Indonesia's Center of Volcanology and Geological Hazard Mitigation (CVGHM) has actively monitored Mt. Tambora as it continues to degas and rumble. Although the current alert level has lowered to 2, the continuous increase in activity presents possibilities of yet another significant eruption.

2.4 Volcanic Aerosols' Impact on Climate

Volcanoes have always been considered an important natural driver of climate Their emissions represent a significant source of aerosol contribution to the global troposphere. The main component of the volcanic ejecta, is the solid matter known as tephra. Tephra however, falls out of the atmosphere in a matter of hours and days and has no atmospheric impact. Following tephra, the most abundant components of the ejecta are the greenhouse gases water vapor (greater than 80%) and carbon dioxide (around 10%). These, although being very effective climate modifiers, fail in comparison to the already high background concentrations in the atmosphere and thus have little to no effect. The main driver of volcanic climate impact is sulfur gas, sulfur dioxide (SO2) and sulfuric acid (H2SO4) being the most common species. Chlorine, bromine and fluorine species are also found in the volcanic ejecta but in very low concentration and their effects are mainly felt in the stratosphere (Tabazadeh & Turco 1993). **(See Figure 2)**

Volcanic SO_2 released into the atmosphere is rapidly oxidized to form sulfuric acid (sulfate) aerosol particles and the layers of sulfate can spread globally within a few weeks to months. Depending on where the volcano is located, the effects will be felt globally or at least on one of the hemispheres. Sulfate removal is mainly through gravitational sedimentation but the rate is mainly dependent on the season and the size of the particles. The e-folding time of these aerosols can extend for more than a year (depending on explosiveness and location of eruption) and affect atmospheric circulation by effectively backscattering and absorbing incoming solar radiation, which results in decreasing surface temperatures. Other effects include regional reductions in light intensity and severe unseasonable weather (cool summers and uncommonly colder winters).

Large explosive eruptions are more likely to inject a considerable amount of gases and aerosols into the stable stratosphere, where they are rapidly spread globally by stratospheric winds and their lifetimes are significantly increased, extending the impact to more than just a couple of years. The thick aerosol sulfur cloud, having an effective radius of about 0.5 µm, (wavelength of visible light), strongly impacts shortwave solar radiation compared to the longwave impact. The aerosols backscatter and absorb the incoming solar radiation causing a localized warming in the stratosphere and a noticeable cooling at the surface.

Several volcanic eruptions have caused winter warming in the first (tropical eruptions) or second (mid-latitude eruptions) winters following the eruption. (Robock and Mao., 1992) Tropical eruptions have a localized warming in the tropics, resulting in a strong temperature gradient from high to low latitudes more noticeable in the winter. The strong temperature gradient strengthens the polar vortex, leading to stagnant tropospheric circulations in the northern hemisphere and thus winter warming that resembles the positive phase of the North Atlantic Oscillation (NAO). Furthermore, Stenchikov et al., 2002 discusses a positive feedback loop initiated by the chemical reactions that result in stratospheric ozone depletion, which cool and strengthen the vortex, leading to reduced temperatures and thus more ozone depletion. A positive Arctic Oscillation corresponds to anomalous low pressure over the pole, and the opposite at mid-latitudes. After large volcanic eruptions, observations confirm a positive phase of the AO in the first and second winters following the eruptions. (Robock and Mao, 1992)

Driscoll et al., 2012 further explored observed winter warming using CMIP5 simulations and concluded that although all the models reproduce well the increase in geopotential height in the tropical lower stratosphere, none of the used models manage to simulate an adequately strong volcanic dynamical response.

Volcanic aerosols have the potential to change radiative fluxes in the stratosphere but most importantly, its chemistry. Chemical changes in the stratosphere by volcanic eruptions affect the temperature, UV flux and surfaces(heterogeneus reactions) present in the stratosphere that lead to the production and destruction of ozone (O3) . Sulfate aerosols produced by volcanic eruptions can also provide these surfaces, but it's important to keep in mind that these effect are only important now because of anthropogenic chlorine in the stratosphere readily available to interact. The Montreal Protocol allowed the banning of these emissions and hence, only volcanic eruptions occurring during the emissions and lifetime (decades) of these are likely to display such evident impacts (Robock, 2000). Anthropogenic chlorofluorocarbons (CFCs), are not the only ones capable to react and destroy ozone. Volcanic emitted chlorine has possible direct effects on ozone, but little is known about the amount of chlorine species after an eruption and its interaction also depends on many different conditions(availability of water vapor) Only a few studies have focused on the topic (Tabazadeh & Turco 1993; Textor *et al*. 2003).

With respect to El Nino events, there is still no convincing evidence that volcanic eruptions produce El Nino events or vice versa, but El Nino and volcanic signals must be separated and studied in-depth in order to understand the climatic response to each. Observations show the simultaneous appearance of a large El Nino signal with El Chichon's eruption and a smaller El Nino signal with the Pinatubo eruption, suggesting a relationship. Nonetheless, further research in oceanography has resulted in only theories. The examination of the entire record of past El Ninos and volcanic eruptions for the past two centuries shows no significant correlation.

In the case of Tambora, there was an observed decadal cooling. Volcanic aerosols usually remain in the stratosphere for less than 2 or 3 years. The radiative effect of volcanoes has been determined as interannual in scale in contrast to the observed interdecadal effect on the record. However, a series of volcanic eruptions could significantly raise the mean optical depth over a longer period of time and could result theoretically to a decadal scale cooling, supporting our suspicions on the 1809 volcano influence on the observed cooling.

2.5 Climate Impacts and Observations after the Eruption.

Data records suggest that the period of 1810–1819 may have been the coldest decade globally over the past 500 years. (Briffa et al., 1998; D’Arrigo et al., 2009; Jones et al., 1995).The records show significantly below average temperatures before and after Tambora's eruption. Proxy tree rings and ice core data have been used to substantiate the effects of major volcanic eruptions on our climate. The unusual cooling trend that took place over the 1809-1819 decade appears to be largely explained by two major volcanic eruptions recorded on ice cores (e.g., Cole-Dai et al., 1997, 2000; Dai et al., 1991; Mosley-Thompson et al., 2003; Palmer et al., 2001).

The sulfate records from Greenland and Antarctic ice cores confirm that the timing of this event is 1809, in a tropical location with a major perturbation on both hemispheres for roughly 2 years. In addition, the 1809 eruption's sulfur contribution to the atmosphere is roughly half that of Tambora but larger than that of Krakatoa (**See Figure 3)**; Cole-Dai et al., 2009). This event is not found in historic documentation (such as Lamb, 1970) but, it is evident in ice core data. Even though the climate system should have largely recovered by 1815, the question remains as to whether there may have lingering effects from the earlier eruption by the time of the Tambora eruption. Though not rich in historical observation, Tambora is much better documented than the unrecorded eruption of 1809 (Cole-Dai et al., 2009), was significantly larger, and was principally responsible for the global thermal deficit of 1815-18. Ships' logs corroborate the anomalous conditions in the 1815-1818 period. Chenoweth (1996) extracted weather data from 227 logbooks that collectively support evidence of the impact the eruption.

The unusual extreme weather at mid-latitudes in the 1815-18 period had major socioeconomic and public health impacts, particularly in terms of poor yield of agricultural production and epidemic outbreaks of cholera and typhus in South Asia, North America, Europe and the Mediterranean countries. **(See Figure 4)** shows known significant ecological and social impacts following the eruption). Europe endured widespread food riots and mass refugeeism, to which governments responded with regressive authoritarian and protectionist policies (e.g., Lamb, 1970, 1995; Post, 1970; Harington, 1992; Xoplaki *et al*., 2001; Webb, 2002; Bronnimann, 2003; Le Roy Ladurie, 2004; Pisek and Brázdil, 2006). In East Asia, Tibet witnessed snowfalls in July, and the Southwest provinces suffered their shortest growing season on record, destroying rice and buckwheat crops. Even the Qing dynasty's much vaunted granary reserve and famine relief programs were unable to meet the demand for grains. Peasants were reduced to eating clay, selling their children in return for food, and growing the cash crop opium (Yang, 2005).

The Tambora eruption altered the political balance of power in South-East Asia, strengthening the indigenous systems of piracy and slavery against the "liberal" westernizing influences of the colonial powers. Beyond ground zero, emissions of dust and sulfur from Tambora disrupted the South Asian monsoons for three consecutive years, a sustained weather crisis that altered the disease ecology of the estuarine delta of Bengal, creating conditions for the birth of modern epidemic cholera in 1817, which spread across the globe in the nineteenth century, killing millions. The winter Asian monsoon was reported to be uncommonly severe with extreme cold and snow in Japan (Mikami and Tsukamura, 1992), China (Zhang et al. 1992) and some of northeast India (Jameson, 1820). Furthermore, the onset of the summer Indian monsoon was seriously delayed, while subsequent unseasonal flooding was unprecedented for the region, and accompanied by locally severe drought in some regions (Jameson, 1820). Across the Himalayas in southwest China, imperial control weakened during the famines of the Tambora period, spawning ethnic rebellion against the Qing Dynasty, and allowing the opium trade to flourish in the narco-state of Yunnan. Meanwhile, across the hemispheric divide in Western Europe, great waves of environmental refugees, driven from their homes by Tamboran impacts on weather systems, headed east to Russia and west to America—the first major wave of nineteenth-century transatlantic migration—while post-Napoleonic governments lurched to the right, embracing authoritarian rule. Mortality from famine and disease in Europe was also high. In Ireland, for example, up to 100,000 mostly rural inhabitants died of starvation following the crop failures of 1816-17, while another 65,000 at least died of famine-friendly typhus. Tambora's social influence extended beyond raw statistics of death and disease. In the polar north, volcanic winter warming in 1815-18 melted the Arctic icepack, prompting the first race of nations to the North Pole. The exploits of Kotzebue, Parry, and Franklin subsequently launched arctic exploration as a defining para-colonial enterprise and cultural fantasy of the nineteenth century. Finally, the so-called Year Without a Summer in the United States produced the only recorded instance of zero tree growth, deducible from the missing 1816 ring in the oak trees of the North-East. Farmers there suffered their shortest ever growing season, interrupted by brutal summer frosts, and left New England in droves for Ohio and Pennsylvania, while the infant frontier Midwest seized the moment to secure a position as a major agricultural producer for the nation and the Atlantic world. Subsequently, when the transatlantic harvest resumed its normal output in 1819, the midwestern economy crashed—in the so-called "Panic of 1819"—plunging the United States into its first major economic depression, which persisted through the early 1820s. This and other documented evidence suggest a strong relationship between the Tambora eruption and the climatic effects that unfolded in its aftermath

2.6 Historical and Cultural Impacts

Tambora caused more than just a climatic ruckus, the volcanic eruption is likely involved in a serious of cultural events mainly triggered by the climatic response of the eruption. Although Tambora cannot be completely singled out for the sole cause of all the following events, ("cooling trend" observed in the record) the extreme weather provoked in the Northern Hemisphere by the eruption was significant enough to contribute. For example, in North America, the year 1816 was characterized by very dim days and an unusually cold summer with snowfalls and reoccurring frosts. These conditions lasted all summer, decreasing the growing season and resulting in total crop failure. The unsuccessful crop yield continued for another year after, which led to a wave of emigration from the Northeast of the United States to establish in Central New York and the Midwest. Indiana and Illinois, due to the mass of migration became states in 1816 and 1818 respectively. One of the farmers that decided to give up and migrate was Joseph Smith. Him, his wife and their nine children were renting a farm in Norwich, Vermont where their stay was short of miserable. Their crops failed for 3 years in a row (1814-1816) that led Joseph to emigrate to Palmyra, New York. In the spring of 1820, in a grove of trees near Palmyra, Joseph Smith claimed an appearance that told him the location where to retrieve The Book of Mormon (near Manchester), which marked the beginning of the Mormon religion.

In Europe, the similar cold and wet summer conditions inspired several known writers and led to the creation of significant literary work. The torrential rain and the gloomy weather in Switzerland forced Lord Byron, John Polidori, Percy Shelley, and his future wife Mary Godwin to stay indoors in Villa Diodati in Lake Geneva and challenge each other to write the best "ghost story." Mary wrote her famous classic horror novel *Frankenstein* and John Polidori wrote *The Vampyre*. Lord Byron on the other hand, wrote several pieces during that summer, including *Darkness*, a poetry piece that describes the anomalous weather experienced that year. Not too far from Switzerland, Germany was also struggling with failing crops and the dramatic increase of food prices. As a result, people could not afford to feed their horses, the main mode of transportation back in the day, thus making traveling too expensive. Coincidentally, a German

man named Karl Drais invented a way to get around without a horse: the early stages of what is today the bicycle.

2.7 Previous Atmospheric Modeling of Tambora Effects on Climate.

The importance of the Tambora eruption is discussed in books and journal articles (e.g., Harington, 1992; Rampino and Self, 1982 ; Stommel and Stommel, 1983; Stothers, 1984), with more recent summaries and narrative articles by Oppenheimer (2003) and Robock (2002). The above provide chronological narratives of the eruption followed by weather records, historical events, scientific estimates and some of the available modeling studies at the time. In their conclusions, these authors all encourage further scientific investigation of the aerosol effects on climate using state-of-the-art modeling capabilities.

Modeling studies have previously explored current and pre-historic volcanic eruptions and the different feedbacks tropical volcanic eruptions and high latitude volcanoes have on climate. There are several modeling studies (discussed below) that include Tambora among their other investigated eruptions. However, less than a handful devote the simulations to Tambora. More complete modeling studies are available, but have only examined more recent volcanic eruptions such as Pinatubo (1991) and Krakatoa (1883). These studies are still evaluated since they provide useful insights to this project. This section discusses prior empirical and modeling studies, their methods and their relevant findings.

Fischer et al. (2007) explored the winter and summer climatic signal in Europe following major tropical volcanic eruptions over the last half millennium using high resolution multi-proxy reconstructions of surface temperature and precipitation (0.5º x 0.5º) and 500 hPa geopotential height fields (2.5º x 2.5º). The multi-proxy predictor information for temperature covers from

1500–2000 while precipitation and 500 hPa geopotential height fields cover 1769–2000. The authors use superimposed epoch analysis to filter out non-volcanic features. These regional analyses will be useful in evaluation of our model results.

Early modeling studies used proxy data, comparative estimates and then available chemistry and physical representations of the atmosphere to perform numerical simulations of its impact on temperature. Recent studies have analyzed more recent and generally well monitored volcanic eruptions such as Pinatubo (1991) to establish comparative estimates. Although Pinatubo and Krakatoa have many similar characteristics to the Tambora's eruption, neither can compare in intensity and climatic consequences. Therefore, assumptions made in earlier computer simulations need to be carefully assessed and justified.

The earliest atmospheric simulation of Tambora's eruption was Vupputuri (1992), which used a coupled one-dimensional radiative-convective-photochemical-diffusion model to simulate the volcanic forcing of the eruption. The simulation involved a volcanic cloud of estimated height with estimated optical thickness to calculate temperature changes through time. This study determined that global average surface temperature decreased steadily with a maximum cooling of 1°K during the spring of 1816. The model results also show significant warming of the stratosphere, with a 15° K maximum temperature increase at 25 km within six months after the date of eruption. It also explored the impact on stratospheric ozone. However, this model was greatly simplified relative to current capabilities for studying atmospheric physics and chemistry. Shindell et al. (2003) explored volcanic and solar forcings during the pre-industrial era using a general circulation model. All simulations were performed using a coarsely gridded (8° x 10°) version of the NASA Goddard Institute for Space Studies (GISS) global climate model containing a mixed layer ocean with fixed heat transports and a simplified representation of the stratosphere with parameterized ozone photochemistry. Their results are largely in agreement with available historical and proxy data. In order to simulate Tambora, the authors approximated emissions from the June 1991 Pinatubo eruption but shifted the forcing 2 months in advance and increased the aerosol amount in separate calculations either using the Pintatubo level of emissions or by increasing them by a factor of 2 or 3. Results are compared with a control run without the volcanic forcing with all runs beginning from stable initial conditions. Their results show a mean annual average cooling of 0.35°C for the lowest (Pinatubo-size eruption), -0.77°C for the factor of 2 eruption case and -1.09C for the factor of 3 assumed eruption case.

Another study that provides partial insight into Tambora's climate impact is Stendel et al. (2005). This study simulated the climate of the last five centuries with the Hamburg coupled atmosphere–ocean general circulation model (ECHAM4) run at T42 (approximately 2.8°) resolution. Prescribed changes in tropospheric ozone are approximated but no stratospheric chemistry was included. Only surface emissions of sulfur are included suggesting that the altitude distribution of emissions was not considered (only optical depth at the tropopause was included). Their results generally match proxy data for "The Year Without a Summer" but fail to reproduce the detailed effects expected following a large volcanic forcing.

Eliseev and Mokhov (2008) simulate the influence of volcanic activity on climate change in the last few centuries using a model of intermediate complexity with a horizontal resolution of 4.5° latitude and 6° longitude, but with only eight vertical levels from the ground to 80 km altitude. The authors supplemented the model with a stratospheric volcanic aerosol scheme in which instantaneous radiative forcing at the top of the atmosphere depends linearly on the optical depth and other modules for radiative properties, convection, precipitation formation, tropospheric sulfate aerosols and water vapor. The model successfully reproduces the annual mean response of surface air temperature and precipitation to major eruptions both at a global and regional scale. However, the model shows poor agreement with tropical and subtropical volcanoes in comparison with how well it matches seasonal distributions during high-latitude eruptions.

Max-Planck Institute has published analyses of several supervolcanoes using their Earth System Model (Timmreck et al., 2011; Toohey et al.,, 2011; Thomas et al.,, 2009; Niemeier et al., 2009). Their publications include some well known volcanic eruptions like Pinatubo, Toba and the Unknown super eruption of 1258 AD. Additional publications on climate response to tropical volcanic eruptions, ENSO dynamics and aerosol characteristics are available. Although Max-Plank Institute supervolcano project has encompassed a number of volcanic eruptions and has targeted some of the scientific uncertainties, there is no published modeling study yet on the Tambora eruption and its global climate consequences.

The bottom line: Notwithstanding the various data arising from these studies, none of the existing studies uses a state-of-the-art model of the Earth's climate system with full interactive chemistry to simulate and assess the climatic impacts of Tambora's eruption in sufficient detail to provide a working foundation for in-depth historical analysis at a global scale.

3. METHODOLOGY

3.1 Proposed Modeling Methodology

The following section describes the proposed methodology resulting from the extensive and comprehensive journalistic and scientific literature review discussed in the previous section. Note that although the following proposed methodology is theoretical for this thesis, the computer simulations proposed here will be executed and analyzed in future works.

3.2 Modeling tools: Community Earth System Model version 1.0.4

The primary modeling tool for this study is the state-of-the-art Community Earth System Model version 1.0.4 (CESM 1.0.4) developed at the National Center for Atmospheric Research (NCAR). CESM is a fully-coupled global climate-chemistry model that provides cutting-edge computer simulations of the Earth's past, present, and future climate states. CESM as used here will have fully coupled chemistry to calculate the distributions of gases and aerosols in the troposphere and the lower to mid-stratosphere. CESM is made up of separate models (atmosphere, ocean, land-surface, land-ice, and sea-ice) connected by a coupler that exchanges fluxes and state information among these components. Its structure enables a large range of physical configurations among the components and a variety of resolutions and individual component input and parameterization configurations.

Each of the component models in CESM 1 is greatly improved over its predecessors in the Community Climate System Model version 4 (CCSM4). The ocean component model is the Parallel Ocean Program version 2 (POP2) developed primarily at Los Alamos National Laboratory. POP 2solves the three-dimensional primitive equations for fluid motions on the sphere. It uses a displaced-pole grid with the logical North Pole displaced into the Greenland

land mass and has 60 levels. Among the improvements it includes new near-surface eddy flux parameterization and abyssal tidally driven mixing parameterizations.

For the atmospheric component, CESM allows a choice between two versions of the Community Atmosphere Model, CAM4 or CAM5. Both CAM4 and CAM5 will be used for the Tambora Project. The simulations will run using CAM 4 first, followed by the same set of runs using CAM 5. Both models use a finite volume dynamical core and the horizontal discretization is based on a conservative flux-form semi-Lagrangian scheme (Lin and Rood, 1996, 1997). CAM5 however, contains many enhancements to the physical parameterizations over those in CAM4 particularly in the area of aerosol and cloud microphysics. CAM5 includes a two-moment cloud microphysics parameterization (Morrison and Gettelman, 2008; Gettelman et al., 2008, 2010) and a modal representation for aerosols allowing for interactions between clouds and aerosols and simulations of the aerosol direct, semi-direct and indirect effects (a capability not present in CAM4). The radiation scheme was also updated to the Rapid Radiative Transfer Model (RRTM) (Iacono et al., 2008) to improve radiative flux and heating rate calculations. These new features enhance the research capability of CAM5 by allowing accurate assessments of natural and anthropogenic aerosol impact on Earth’s radiative budget. In relation to the Tambora project, because of the enhanced treatment of aerosol (including volcanic aerosol) microphysical processes, CAM 5 is notably improved for simulating large volcanic eruptions compared to CAM4 (based on a preliminary analysis at NCAR). A comparative study of the new CAM5 model with the previous CAM4 model shows that CAM5 more accurately represented the 1991 Pinatubo eruption radiative and dynamical effects relative to satellite data using prescribed volcanic aerosol mixing ratios. Like CAM4, the CAM5 model used in this study will have complete representation of tropospheric and stratospheric chemical processes. For this study CAM vertical domain will extend from the surface to ~ 40km with 30 vertical levels. Both the CAM and POP component models will be run at a 1 x 1 degree horizontal resolution.

The chemical mechanism chosen for this is formulated to provide an accurate representation of both tropospheric and stratospheric chemistry (e.g,, Lamarque et al., 2008, 2010, Lamarque and Solomon, 2010; stratospheric chemistry is updated relative to Kinnison et al., 2007). The chemistry mechanism has a simplified representation of non-methane hydrocarbon chemistry in addition to standard methane chemistry, extended from Houweling et al. (1998) with the inclusion of isoprene and terpene oxidation and updated to JPL-2006 (Sander et al., 2006). The model represents aerosol processes, including relevant chemistry, e.g., sulfate aerosol is formed by the oxidation of SO_2 in the gas phase (by reaction with the hydroxyl radical) and in the aqueous phase (by reaction with ozone and hydrogen peroxide). CAM4 has a bulk mass approach following Tie et al. (2001, 2005), while CAM5 has a new much more comprehensive treatment of aerosol microphysics.

3.3 Derivation of the Background Atmosphere

As part of the simulations being done for the next IPCC climate assessment, NCAR scientists ran CESM1 (CCSM4) for a millennium-plus analysis of the climate changes from 850 A.D. to 2011 and beyond. While this run does not have interactive chemistry, it provides an excellent starting condition (restart point) for the study. The restart file for the year 1800 used for the first pair of runs is (b40.lm850-1850.1deg.001), the other configurations and input data will remain as those used by NCAR.

3.4 Initial conditions data

Initial conditions for trace gases and aerosols in this study represent the conditions from that time period as accurately as possible. The concentrations of long-lived gases like carbon dioxide, methane, and nitrous oxide are well characterized from ice core analyses. Other emissions were assumed based on available estimates for this time period corresponding to that expected for the pre-industrial atmosphere. For example, Robertson et al. (2001) have compiled annually resolved time series of atmospheric trace gas concentrations, solar irradiance, tropospheric aerosol optical depth, and stratospheric (volcanic) aerosol optical depth for use in climate modeling studies of the period 1500 to 1999 A.D.

3.5 Volcanic Loading data

Volcanic forcing data used for this study is acquired from (Gao., et al 2008). The data files of atmospheric volcanic loading available extend from 501 to 2000 AD and were derived from bipolar ice cores while accounting for the spatial distribution of volcanic deposition. They provide two separate data files; one containing both global and hemispheric annual stratospheric volcanic sulfate aerosol injections in Tg of sulfate aerosol. The second file contains the monthly, latitudinally, and height dependent aerosol loading for the same period in kg of sulfate aerosol/km2 .

The chemical emissions of the Tambora eruption for ash and other materials will be based on estimates from Self et al., (2004) and ice-core indices. Self et al., (2004) estimated 93–118 Tg of sulfate aerosols, much smaller than some previous estimates of the mass of Tambora's aerosols, that ranged from 150 Tg from (Hammer et al., 1980) to 200 Tg (Stothers, 1984;

Sigurdsson and Carey, 1989), but in good agreement with Zielinski's (1995) estimate of 107 Tg from acidity in the GISP2 ice core and in good agreement with (Gao, et al 2008).

3.6 Modeling Runs

The first two proposed runs are the recreation of a portion of the Last Millennium Run by NCAR, beginning instead at 1800 and ending in 1820. One of the runs will include the volcanic aerosol loading and other will run without the volcanic aerosol loading. These runs have a case ID of (SpinUpLM and SpinUpLMNV) and are important since they will verify the configurations of the model and the validity of the restart and input files. A comparison of the results could be done for academic purposes. Once these two runs successfully finished, the rest of the runs can take place. (See **Table 2** for a summary of all the runs)

The second proposed set of runs are similar to the SpinUpLM runs except that these will include interactive chemistry in the fully coupled climate model. These will be known as (SpinUpCAM and SpinUpVCAM). Similar to the SpinUpLM, they will run also 20 years of model time to get the tropospheric and stratospheric composition settled down. Depending on the results, a set of three to five ensemble runs with fully interactive chemistry and climate for the time period from 1800-1820 (without any volcanic emissions) should be performed in order to get the most accurate representation of the state of the atmosphere at the time. The set of ensembles will run separately using the CAM4 and CAM5 atmospheric models until the derived atmosphere is settled and then compared with analyses of the conditions known for the early 19th century before the time of the eruptions (e.g., such as the analyses by Fischer et al., 2007, mentioned earlier). Using the restart pointers as initial conditions, the final pair of runs will be performed by branching from 1808 with volcanic perturbations occurring on 1815 using CAM4 first and then CAM5.

3.7 Derived effects including earlier eruption (1809)

In order to evaluate the climatic impact the unknown eruption of 1809 had in the years preceding Tambora, this study proposes a couple of runs branching from 1808 to be performed. One run is only with the assumed emissions for the unknown 1809 eruption (UNK1809) and the other run with just the perturbation in 1815 (TMB1805). Finally a run with both the perturbations in 1809 and 1815 (TMB) will take place for comparison. All of these runs will be performed using both CAM4 and CAM5. Several different cases may be necessary, but we will start by assuming the eruption occurred in the tropics -- Central or South America is the most likely location given that ship logs show no clear record of the eruption. Cole-Dai et al. (2009) suggests that the eruption occurred in February. The magnitude of the emission is based on ice core data (Gao et al., 2008 The resulting climate changes will be compared with data records for the time period to provide further evidence for the effects of the eruption.

3.8 Tambora Eruption in Today's Climate

Finally, this particular run is not needed for the full understanding of the event however it could be a possibility, given the resources and time. Instead of simulating what already happened, this simulation would recreate what could happen if an atmospheric volcanic perturbation of that magnitude would occur in today's atmospheric background (TMB2000). The configurations for this run are still being evaluated and prepared and thus, I only present an idea that we would like to investigate in the future..

4. CURRENT/FUTURE WORK

This thesis provides a theoretical framework that serves as the stepping stone for The Tambora Project. Currently, the computer simulations proposed in this thesis are being prepared and executed. To be exact, we are currently running the first pair of runs (SpinUpLM). We expect to do all or most of the runs during the first half of next year. Following that, extensive analyses will be performed in order to fully comprehend the cause and effects of this event and the potential indirect influences that took place during that cold decade. We expect to write at least two or more journal articles on our findings.

In addition to peer-reviewed journal papers, the resulting general interest trade book on the Tambora eruption, to be published by Princteon University Press under their science imprint in 2013, will utilize the simulation data of this thesis and simulations as the scientific basis for its historical narrative chronicling Tambora's human impacts across six distinct regions of the globe. The study promises to significantly challenge conventional wisdom regarding the world-historical events of the nineteenth century by foregrounding the socio-ecological relation between the climate systems and its dependent human communities around the globe, a subject traditionally neglected by historians. The publication of the book will be accompanied by the development of an online "Tambora Map" that will digitally dramatize the information generated by the computer simulation and historical research in a user-friendly, interactive format. The global image representing the Tambora period of 1815-18 will layer Google Earth with historical maps, feature a virtual recreation of the course of the volcanic cloud, and contain embedded, geo-referenced text and video links for researchers, students, journalists, policymakers, and the general public interested in the Tambora event.

5. CONCLUSIONS

Tambora provides a challenging framework since the ability to gather scientific data at the time was scarce and the amount of available data is limited to historical documentation and proxy-data analyzed presently. For this reason, several articles and books on proxy data and historic documentation about Tambora have been published but only a few of these include modeling results, none of which offer a complete assessment of Tambora's eruption effect on climate. In order to make the The Tambora Project a reality, we had to dig deep in historical records, journalistic accounts and scientific articles to look for evidence of climatic impact after the eruption. From the extensive literature review performed in this study, we were able to discover overwhelming evidence from all over the world of the endured weather anomalies in 1816, supporting reconstructed proxies. Furthermore, the gaps in scientific literature became more apparent and the realization that no scientific project had devoted state-of-the-art computer simulations in order to recreate such event, only prevented The Tambora Project from immediately taking off. As a result, this thesis focused on providing the modeling framework needed in order to pave the way for the modeling and execution of the project.

We were successfully able to develop a series of proposed runs that aim to clarify and shed some light to the epochal event that impacted thousands of people globally. These runs are now currently being configured and built in order to then be executed and analyzed as results become available. The Tambora Project in itself is of great magnitude, the multidisciplinary collaboration between the physical sciences and the humanities however, eases the load and f

acilitates the dissemination of information not only to academic audiences, but to the general audiences as well. It is our main goal to understand this historical event in order to provide important lessons not only for historians, but scientists and policymakers tasked with responding to the current climate change and its impact on the global human community.

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7. TABLES

Explosive Eruptions with VEI of 5 and Higher : 1500 - 2011

VOLCANO	LOCATION	DATE	VEI
Tambora	Indonesia	1815	7
Pinatubo	Philippines	1991	6
Azul	Chile	1932	6
Novarupta	United States	1912	6
Santa Maria	Guatemala	1902	6
Krakatau	Indonesia	1883	6
Unknown	Unknown	1809	6
Laki	Iceland	1783	6
Long Is	New Guinea	1700	6
Cerro Hudson	Chile	1991	5
El Chichon	Mexico	1982	5
St. Helens	United States	1980	5
Bezymianny	Russia	1956	5
Kharimkotan	Kuril Islands	1933	5
Cerro Azul	Chile	1932	5
Colima	Mexico	1913	5
Ksudach	Russia	1907	5
Tarawera	New Zealand	1886	5
Askja	Iceland	1875	5
Sheveluch	Russia	1854	5
Cosiguina	Nicaragua	1835	5
Galunggung	Indonesia	1822	5
Katla	Iceland	1755	5
Tarumai	Japan	1739	5
Tarumai	Japan	1667	5
Usu	Japan	1663	5
St.Helens	United States	1480	5

Table 1. Volcanic eruptions with volcanic explosive index (VEI) of 5 and higher since 1480. Sources: Global Volcanism Program, (Robock, 2000) and (Bradley and Jones, 1992).

Case ID(Runs)	Volcanic Loading	Interactive Chemistry	CAM4	CAM 5
SpinUpLM	**YES**	**NO**	**--**	**--**
SpinUpLMNV	**NO**	**NO**	**--**	**--**
SpinUpCAM	**NO**	**YES**	**YES**	**YES**
SpinUpVCAM	**YES**	**YES**	**YES**	**YES**
TMB1815	**YES (1815)**	**YES**	**YES**	**YES**
UNK1809	**YES (1809)**	**YES**	**YES**	**YES**
TMB	**YES (ALL)**	**YES**	**YES**	**YES**
***TMB2000**	**YES**	**YES**	**YES**	**YES**

Table 2: A summary of the proposed runs for The Tambora Project using CESM version 1.0.4.

***Not yet fully developed.**

8. FIGURES AND CAPTIONS

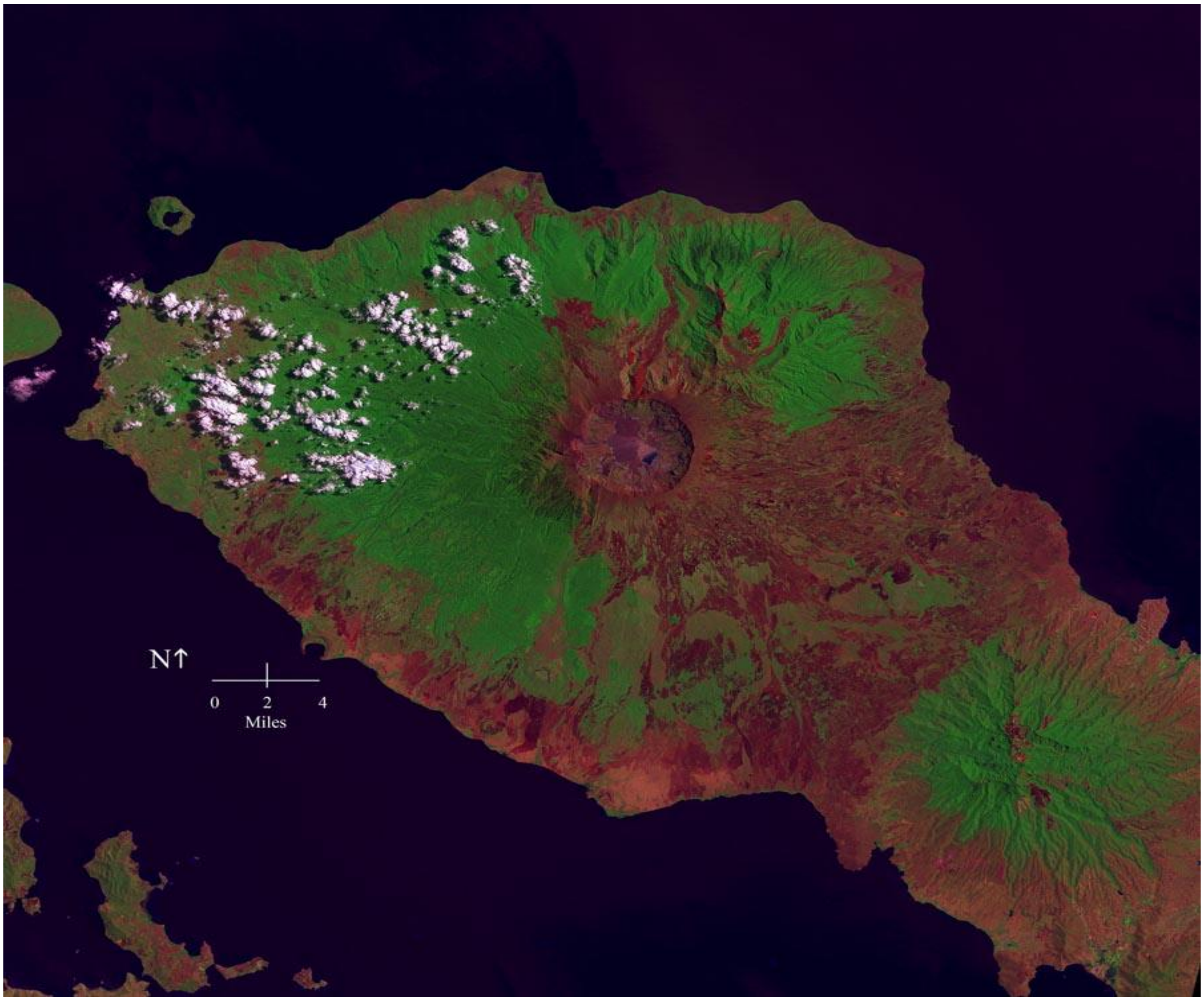
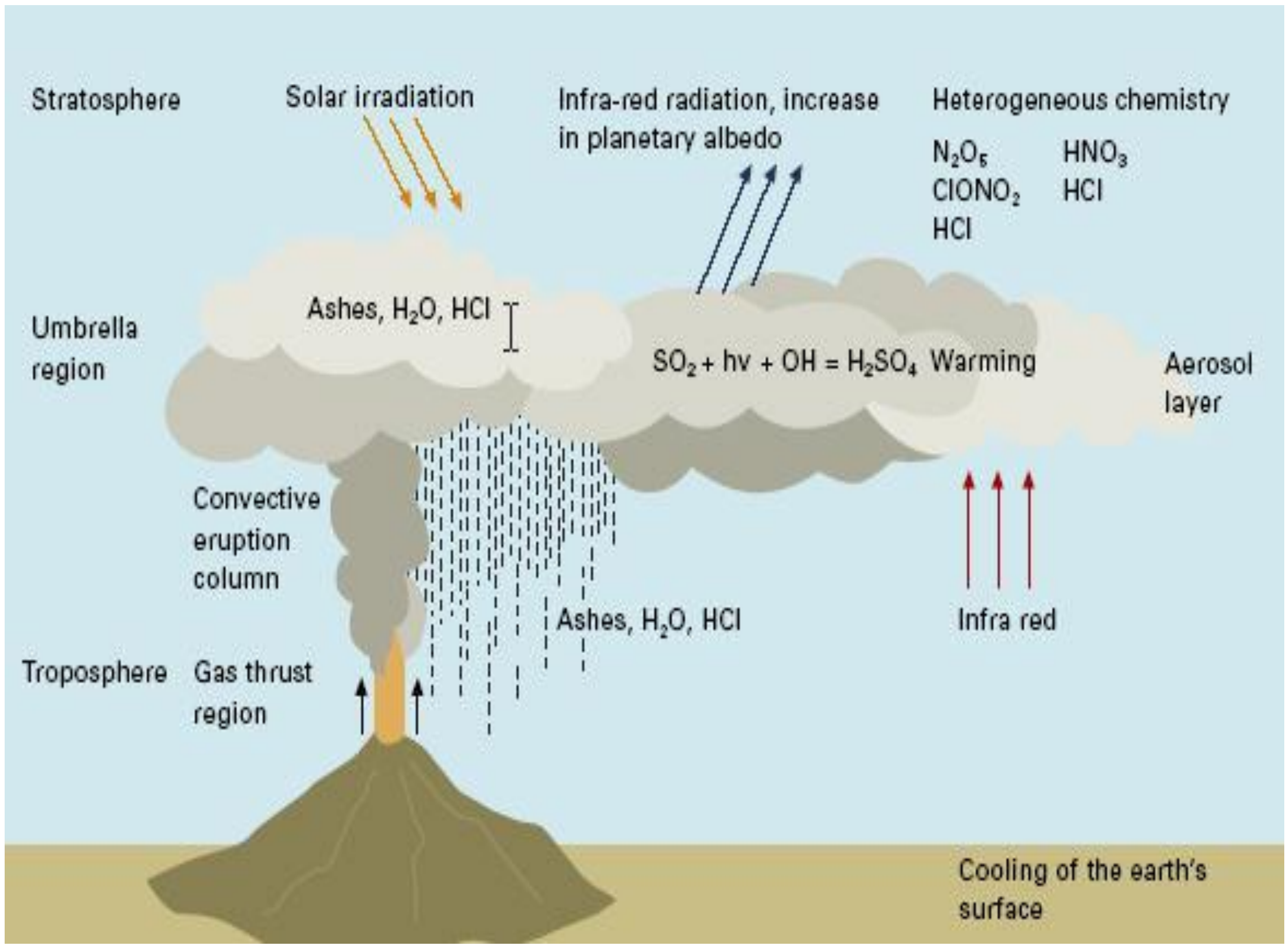


Figure 1. Image shows the Sanggar Peninsula as taken by the Landsat 7SLC-on on September 13, 2000. Tambora and its caldera can be observed, located in the center of the image. Source: USGS, http://landsat.usgs.gov/about_LU_Vol_1_Issue_4.php

Figure 2: Emission of gases after a violent volcanic eruption and formation of aerosols in the stratosphere.

Source: After H.-U. Schmincke, 2000. Website: http://www.munichre.com.



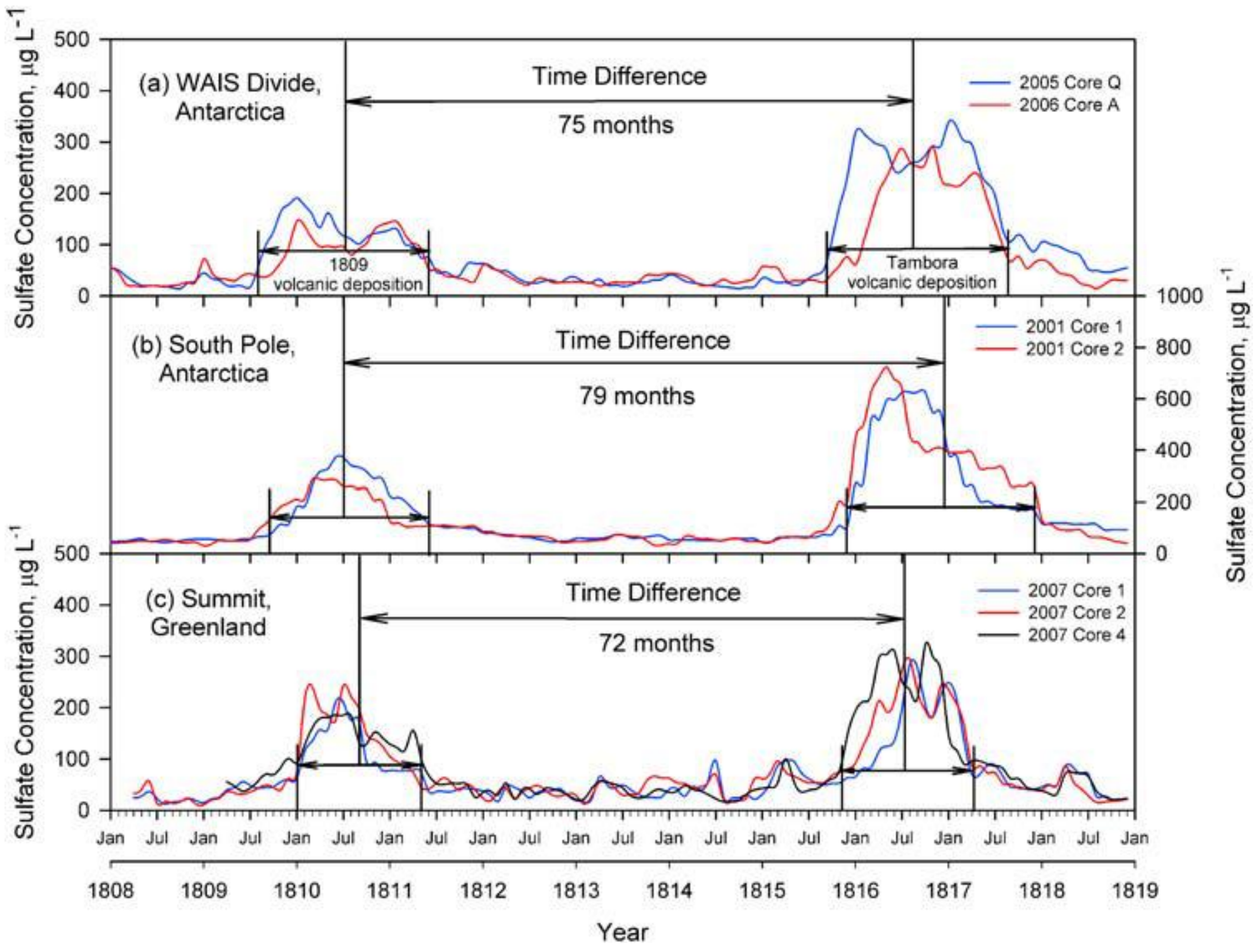


Figure 3. Sulfate deposition from the Tambora and the unknown 1809 volcanic eruptions in Antarctica and Greenland ice cores as evaluated by Cole-Dai et al. (2009).

Figure 4. Map shows select areas of known significant ecological and social deterioration following the Tambora eruption.

World Map Source: NASA earth-huge.png: 8192x4096, 3.7M