Climactic Effects of the 1815 Eruption of Tambora

by Jacob Smith

'Civilization exists by geologic consent, subject to change without notice" - Will Durant

INTRODUCTION:

In 1815, Tambora catastrophically erupted after three years of increased rumbling. This was one of the largest known ash-producing eruptions in the last 10,000 years, reducing the volcano to half its former size. Tambora is still a large stratovolcano (2860 m tall and >1000 km^3 in volume) located on the Indonesian island of Sumbawa (part of the Lesser Sunda Islands) This is a segment of the Sunda Arc, a string of volcanic islands forming the southern chain of the Indonesian archipelago. Tambora lies 340 km (211 mi) north of the Java Trench system and 180 - 190 km 112—118 mi) above the upper surface of the active north-dipping subduction zone. The 1815 eruption has had a significant impact at the global scale.

Vast amounts of aerosols were injected into the atmosphere, clouding out the Sun in the region for several days after the initial eruption. The year after the eruption became known as the "Year Without a Summer" for people throughout Indonesia, the English Isles, and even America. This year has also been linked to massive crop failure that led to widespread famine, disease and social stress.

An understanding of the composition and dynamics of Earth's atmosphere will provide a base knowledge to what role volcanism play in the system. It is then possible to recognize to what extent its effects, both regionally and globally, will have on weather and the Earth's inhabitants.

EARTH'S ATMOSPHERE

Earth's radiation budget dictates that incoming radiation from the Sun must be balanced by outgoing radiation. As the Sun heats the Earth, the temperature increases, causing it to radiate in the infrared spectrum. Infrared radiation tries to escape into space, but greenhouse gases absorb a portion of it. These particles can therefore increase overall atmospheric temperatures substantially (Sigurdsson *et al*. 2000). In order to understand atmospheric dynamics and the role that volcanism plays, it helps to have knowledge of the key components of the Earth's atmosphere:

The Earth's atmosphere is divided into several regions based on its thermal structure (Figure 1). There are two primary divisions in the atmosphere: the homosphere and the heterosphere. The homosphere contains the troposphere, tropopause, stratosphere, ozone, stratopause, mesosphere, the mesopause and 5% of the ionosphere. The homosphere is a region in which the composition and molecular weight of air varies little throughout Sigurdsson *et al*. 2000). While the mixing ratios of trace elements may vary greatly it is primarily composed of 80% N_2 and 20% O_2. The heterosphere contains the thermosphere, exosphere and the remaining 95% of the ionosphere. This paper will focus on the region from the troposphere to the stratopause and the effects that volcanic aerosols have within this region.

Troposphere and Tropopause

The troposphere is the region of the atmosphere occupying the lowest layer on Earth. It is where weather is created by instability, due to the absorption of solar radiation at the surface that heats air, which may then rise through the colder, more dense air above. The troposphere contains naturally occurring N_2, O_2, H_2O, Ar, CO_2 and a variety of other pollutants such as O_3 (ozone), NO_2, OCS (carbonyl sulfide) and SO_2. Particles of various composition and type, many arising from surface sources such as soil and organic gases, pollute this region heavily (Sigurdsson *et al*. 2000). Tropospheric particles are typically removed from the atmosphere after several weeks by precipitation. For example, rainout provides the dominant sink for volcanic sulfur injected into the troposphere, which will be discussed in more detail later.

The transition boundary between the troposphere and the layer above is called the tropopause. The temperature and altitude of the tropopause vary from about -83°C (- 118°F) and 18 km (11 mi.) at the equator to -53°C (-64°F) and 8 km (5 mi.) in the polar regions. Both the tropopause and the troposphere are known as the lower atmosphere.

Stratosphere

The stratosphere is the region above the tropopause containing the ozone layer, which heats the atmosphere by absorption of high-energy ultraviolet rays from the Sun. The increasing temperature profile of the stratosphere insures it is a much more stable region of the atmosphere than the troposphere. Air from the troposphere enters the stratosphere in the tropics, where convective storm systems create strong updrafts that can break through the cold tropical tropopause. Much of the water vapor freezes out of the rising air, leaving the stratosphere much drier than the troposphere. Therefore, particles in the stratosphere are not rained out, and may remain in the stratosphere until transferred with ambient air particles (Sigurdsson *et al.* 2000).

At midlatitudes, tongues of stratosphere are folded into the troposphere. These tongues are responsible for transferring about 75% of the air into the stratosphere (Sigurdsson *et al.* 2000). The air mixture that is transferred in this zone remains in the stratosphere for 2 years. The remaining 25% of the air mixture is again transferred by air moving downward at the poles by the strong winter jet stream. The transport of air out of the tropics to higher latitudes depends on the direction of zonal winds over the equator. By the time this air reaches high latitudes, chemical tracers indicate that the air is 3-5 years old.

Stratospheric Chemistry

The stratosphere contains elements such as N_2, O_2 (atomic oxygen), O_3 (ozone), OCS, Cl, and Br. Stratospheric chlorine is derived from anthropogenic chlorofluorocarbons (CFC's) and methyl chloroform which has natural sources), rather than volcanic eruptions (Fig. 1). Stratospheric bromine comes from anthropogenic halocarbons and methyl bromide, not volcanoes. Halocarbons are one or more atoms of C covalently bonded with one or more halogens such as Cl, Fl. Br, or I, and are typically produced as solvents for industrial cleaning. Volcanic aerosols alter stratospheric chemistry in such a way that it activates chlorine and bromine for ozone depletion by means of reactions on molecular surfaces.

Ozone Chemistry

Ozone (O_3 and atomic oxygen (O) make up the "odd oxygen" family of atmospheric species. The two species can interchange rapidly with one another by means of numerous chemical reactions. The reactions that produce or destroy total odd oxygen are much slower. Stratospheric chemistry typically occurs homogeneously while aerosols are in their gaseous phase. However, heterogeneous chemistry of an aerosol can occur between any combinations of phases (gas, liquid or solid). The rates of heterogeneous reactions increase strongly as these aerosols become more dilute, thus, the reactions often go faster at colder temperatures. Odd oxygen and the ozone are believed to be controlled dynamically in the lower stratosphere, and chemically controlled in the upper stratosphere where temperatures are colder and promote heterogeneous chemistry (Sigurdsson *et al.* 2000). Transport of aerosols in the stratosphere generally takes weeks to months to circulate air globally. While odd oxygen is produced and destroyed within several hours at 60 km, it survives for weeks at 35 km, and for several years at 20 km.

The Antarctic Ozone Hole

As winter approaches and temperatures decrease in the polar stratosphere, sulfate aerosol becomes very dilute, taking up not only water but also significant quantities of nitric acid (HNO_3 from tropospheric pollutants. Ice core chemistry provides further information on the atmospheric impacts of the eruption. Oppenheimer (2003) found that Greenland ice core ratio of winter-to-summer deposition of NO_3 increased following the eruptions of both Tambora and Katmai (1912). He attributes this to condensation and removal of stratospheric HNO_3 for the Antarctic stratosphere during the winter, and slower formation of HNO_3 during the summer because of removal of OH through oxidation of SO_2. Looking at Antarctic ice core chemical stratigraphy, evidence is lacking for changes in atmospheric chlorine thought to have been released by the eruption (100 Tg). It is thought that most of the halogens were rapidly and efficiently scavenged by the troposphere as the eruption clouds ascended (Sadler and Grattan 1999).

Though stratospheric chlorine and bromine are expected to decline over the 21st century due to international treaties regulating CFC's and halocarbons, their ozone- depleting effects may still be greatly magnified over time by volcanic eruptions. Recent examples include the 1991 eruption of Pinatubo and El Chichón in 1982 (Table. 1). Following their eruptions, springtime Antarctic ozone declined relative to pre-eruption levels by about 15 to 20%, respectively, before recovering somewhat as aerosols declined over several years (Sigurdsson *et al.* 2000).

AEROSOLS

Stratospheric Aerosols

Aerosols play a very important role in the climate because they can potentially be an external forcing mechanism on the global climate. Proof for the existence of a layer of particles in the stratosphere was discovered in 1961 by a team led by Christian Junge with the use of high-altitude balloons. They determined that a non-volcanic source is responsible for maintaining stratospheric sulfate aerosol. In 1976, Paul Crutzen suggested carbonyl sulfide (OCS) as the major source of "background" layer (Sigurdsson *et al.* 2000). OCS originates from biological, volcanic, and some anthropogenic sources, such as the burning of fossil fuels. The troposphere is relatively inert and has a chemical lifetime of about 30 years. The long-lived existence of OCS allows it to be distributed relatively uniformly throughout the troposphere (figure 2). The mixing ratio is about 500 parts per trillion by volume pptv), making OCS the most abundant sulfur bearing compound in the atmosphere.

In the stratosphere, ultraviolet light reacts with atomic oxygen to destroy OCS, this produces SO_2, which then oxidizes to sulfuric acid. While OCS clearly provides an important source of stratospheric sulfate, it breaks apart at a rate too high to account for the aerosol observed in volcanically quiet periods. SO_2 of tropospheric origin, via anthropogenic pollution and reduced biologically produced sulfur compounds, strongly influences aerosol(s) in the lower stratosphere.

Generally, for a given mass of aerosol, a large number of small particles provides a greater optical depth than a small number of large particles. The albedo of an aerosol layer is dependent on its optical depth. Increases in the planetary albedo decrease the amount of radiation absorbed, which results in decreasing the Earth's temperature (Sigurdsson *et al.* 2000).

Volcanic Aerosols

Whether the net effect of aerosol absorption and reflection is to cool or to heat the Earth depends on particle size. For the warming effect to overcome the cooling effect, particles must be larger than about two µm in radius (Sadler and Grattan 1999). Volcanic eruptions introduce large quantities of ash and magmatic gases into the atmosphere. The major gases released are water vapor (>80% by volume) and carbon dioxide (~10% by volume), with smaller, more variable contributions of SO_2, H_2S, CO, H_2, N_2, HCl and HBr (Sigurdsson *et al.* 2000). The global distribution of aerosols from volcanic eruptions depends primarily on its latitude and intensity. Aerosols from tropical eruptions have the potential to spread globally in the stratosphere, as was the case with Tambora in 1815 and Mount Pinatubo in 1992. However, aerosols from many tropical eruptions such as El Chichón in 1982) have remained largely in their hemisphere of origin. Plumes which do not break through the troposphere, or which occur at high latitudes, have fewer global consequences. Volcanic aerosol clouds produced during such eruptions may result in a significant drop in surface pressure across midlatitudes of the North Atlantic sector (Rampino *et al.* 1988).

Tambora-size (100 km^3 of magma) explosive volcanic eruptions emit large quantities of sulfur dioxide gas into the stratosphere, where it is converted into a sulfuric acid aerosol dust veil that encircles the Earth (Sigurdsson *et al.* 2000). The sulfur mass injected into the stratosphere by the Tambora eruption has been estimated by several independent methods including modeling of polar ice core sulfate concentrations, petrological measurements of 1815 tephra, and analysis of atmospheric optical phenomena. The results vary by an order of magnitude but excluding the outlying estimates, the figures average around 60 Tg of estimated stratospheric aerosol loading of SO_4 Oppenheimer 2003). In contrast, Sigurdsson *et al.* (2000) suggests that the 1815 Tambora eruption to be >100 Tg of SO_4. They also further estimated the amount for the 1991 Pinatubo eruption to be 30 Tg of SO_4 and the 1982 El Chichón, 12 Tg of SO_4 .

Oppenheimer (2003) states that it is difficult to separate this total from the different phases of the eruption and, in particular, to determine the different parts that derived from plinian versus co-ignimbrite 'phoenix') clouds.

THE 1815 ERUPTION OF TAMBORA

Understanding Volcanic Impact on the Atmosphere

Humans have unknowingly experienced the global atmospheric affects of volcanic eruptions for thousands of years. While people close to an active volcano might have been able to account for strange local phenomena, correlation between the effects on the atmosphere on a global scale would not begin to be linked to volcanism until the 18th century. Sigurdsson *et al.* (2000) stated that Benjamin Franklin might have been the first to report the link between volcanism and unusual atmospheric phenomena in 1784, when strange "dry fog" and unseasonably cold weather struck Europe. Franklin speculated that the fog was the cause of the cold summer, and that it originated as smoke from either meteorites or volcanic eruptions he knew to have occurred in Iceland over the course of the previous year (1783 eruption of Laki). This would be confirmed only recently and has now been linked to the famine that reduced the population of the Nile valley by one-sixth. It was not until the 1883 eruption of Krakatoa, that strange atmospheric effects would be linked to volcanoes worldwide.

The Eruption

Tambora became active at least 1 year prior to the 1815 eruption (Self et al. 1989). On the evening of April 5 1815, Tambora had a short-lived two-hour plinian eruption. The first eruption had an intensity that exceeded 108 kg s^{-1}, propelling the plume 33 km above sea level, and the total mass of erupted material was 1.11 X 10^{12} kg (Oppenheimer 2003).

On April 10 1815, around 19:00 local time, the second major, more powerful, phase of the eruption began and only lasted <3 hours. It is estimated that the phase of the eruption had a discharge rate of 3 X 10^8 kg s^{-1} and the plume reached over 43 km above sea-level (Oppenheimer 2003), making it the second highest estimated eruptive cloud in the last 2000 years. The last major phase of the eruption was ignimbrite dominated. It has been estimated that during the duration of this ignimbrite phase of the eruption, the mean intensity must have been around 5 X 10^8 kg s^{-1} Oppenheimer 2003). This would have propelled the phoenix clouds to around 23 km above sea level, a modest height considering the eruption intensity (Oppenheimer 2003). His estimate is probably sufficiently close enough because he compared phoenix plumes to plinian columns in terms of their thermal efficiencies.

Self *et al.* 1989) estimated that 175 km^3 of nepheline-normative trachyandesitic pyroclastic material (the equivalent to about 50 km^3 of dense rock) was erupted over the duration of the eruption. Of particular interest, the largest known increase in the estimated stratospheric aerosol loading, >100 Tg of SO_4, (more than 6 times the amount of the 1991 Pinatubo eruption) resulted from the eruption Sigurdsson *et al.* 2000). Ash fallout was noted over an area in excess of 4 X 10^5 km^2 (and probably fell over an area of more than 10^6 km^2 (Rampino *et al.* 1988). In addition to vast amounts of material erupting from several pyroclastic flows, tsunamis and pumice rafts were reported over the next couple of days. Meteorological conditions spawned by the explosion started with a hot, followed by an "extremely cold," pocket of air directly under the tropospheric ash clouds, as reported at Banjuwangi, 400 km from the volcano. Freezing temperatures were recorded in Madras, India, two weeks later (Rampino *et al.* 1988).

The Summer of 1816: "The Year Without a Summer"

For two to three days after the eruption, there was complete darkness within a 600 km radius of Tambora accompanied by a reported dramatic lowering of air temperature, although it is not clear to what extent Oppenheimer 2003). Light eventually returned to regions furthest away after one or two days and gradually by the second or third day, faint light was visible near the volcano. Sunsets were orange or red near the horizon, purple to pink above, and were sometimes streaked by diverging dark bands for almost a year after the eruption (Oppenheimer 2003). This phenomena was observed nearly everywhere from Indonesia to Western Europe and all the way to New England. This provides strong evidence for atmospheric disturbance into the stratosphere. This is further supported by accounts that claim, "neither surface winds, nor rain would disperse" the lingering haze.

History has shown us that volcanic eruptions are associated with colder-than-normal temperatures at the Earth's surface, and Tambora was no exception. Average temperatures fell 1°C to 2.5°C below normal throughout New England and the British Isles, and the global average is estimated to have fallen by 0.4 to 0.7°C. (Sigurdsson *et al.* 2000).

This had significant human impact on many regions across the world throughout the next 2 years. Abundant evidence exists for extreme weather in 1816, especially during the spring and summer in Indonesia, the British Isles, North America, and parts of Canada.

GLOBAL HUMAN IMPACT

Indonesia

The area within up to a 200 km radius from Tambora was hardest hit by the 1815 eruption. Of the island of Sumbawa's 12,000 inhabitants, only 26 survived. In addition to the death toll from the eruption and the subsequent earthquakes, pyroclastic flows and tsunamis associated with the event are conservatively estimated to have a death toll of 90,000 just within the first couple of days. For those who survived the initial devastation, there was little refuge. The vast amounts of ash quickly tainted the water supply and made the air chokingly thick with fine dust and ash. Famine and disease quickly spread throughout the region and the exact number of dead may never be known.

British Isles

The volcanic cloud traveled around the world, and within 3 months, its optical affects were observed at distant locations in Europe (Rampino *et al.* 1988).

As stated in the section on "aerosols", the effect of the volcanic aerosol clouds may produce a significant drop in surface pressure across midlatitudes of the North Atlantic sector, leading to a southward shift in the track taken by middle-latitude cyclones. Rampino *et al*. 1988 then predicts that a major anomaly would thus be centered over England and would extend over much of Western Europe, giving rise to a cold and wet summer.

The summer of 1816 was cool and exceedingly wet. Massive crop Failures led to famine, disease, and social unrest (Rampino *et al.* 1988). In central England, the temperature was about 1.5°C cooler than during the summer of 1815 (Oppenheimer 2003). Typhus was reported in almost every town and village in England, and was reported in many cities throughout Scotland. An interesting side note, this period coincides with publication of Mary Shelley s *Frankenstein* and Lord Byron's poem *Darkness*.

In Ireland, around 800,000 people were infected during the typhus epidemic, and of that, 4,300 perished from the joint ravages of famine, dysentery and fever (Oppenheimer 2003). Elsewhere in Europe, the summer of 1816 was also reported to one of the most miserable winters in recent history.

North America

1816 was marked by a persistent dry fog, or dim sun, as reported in the northeastern United States. According to a report from New York, the atmospheric pollution reddened and dimmed the sun so much that sunspots were visible to the naked eye Oppenheimer 2003). The total lunar eclipse on June 9th-10th was also reported to be extremely darker than normal. The summer of 1816 was the coldest in New Haven, Connecticut, for the entire period from 1780 to 1968 (Rampino *el at*. 1988). On June 4th, frosts were reported in Connecticut and, by the following day, a cold front gripped most of New England. On June 6th, snow fell in Albany New York, and Dennysville Maine, and there were killing frosts at Fairfield Connecticut. Severe frosts had spread as far as south as Trenton New Jersey the next day (Oppenheimer 2003). Such conditions persisted over the next 3 months, which shortened the growing season and resulted in almost total failure of main crops.

Canada also experienced severe weather and the same cold wave that hit New England. In Montreal, snow fell June 6th to the 8th 1816, and 30 cm of snow accumulated near Quebec City (Oppenheimer 2003). Unlike Indonesia, America and the British isles, the Canadian population avoided serious social distress from the severe weather, primarily thanks to an embargo on grain exports between July and September 1816 and to the favorable ratio of population to resources.

CONCLUSION

Plumes which do not break through the troposphere, or which occur at high latitudes, have fewer global consequences (Oppenheimer 2003). Volcanic eruptions can introduce large quantities of ash and magmatic gases into the atmosphere, which may affect atmospheric dynamics, and thereby determine its own distribution throughout the atmosphere and may have had strong impacts on regional and global climate (Sigurdsson *et al.* 2000). Large eruptions do not necessarily produce greater or more protracted temperature anomalies, rather only those volcanoes with very explosive eruptions are of concern to the climate and stratospheric chemistry. Aerosols from tropical eruptions like Mount Pinatubo in 1991 (15ºN) did spread globally in the stratosphere. However, aerosols from many tropical eruptions, such as El Chichón (l7ºN) in 1982, have remained largely in their hemisphere of origin (Oppenheimer 2003). Natural dynamical perturbation lasted less than a year in the case of Pinatubo, making it less worrisome than long-term ozone depletion observed at midlatitudes (Sigurdsson *et al.* 2000).

Particles of radius greater than two µm fall at rates of more than 30 km per year in the lower stratosphere, ensuring their removal within months. Thus, sedimentation limits the size of stratospheric aerosol, making it unlikely that volcanic aerosol could be large enough to warm the Earth for significant periods of time (Sigurdsson *et al.* 2000). The volcanic cloud from the Tambora eruption traveled around the world, and within three months, its optical effects were observed at distant locations throughout Europe (Rampino *et al*. 1988). History has shown us, however, that volcanic eruptions associated with colder-than-normal temperatures at the Earths surface because of increases in the planetary albedo decrease the amount of radiation absorbed, and also the Earth's temperature (Sigurdsson *et al.* 2000). The following year (1816) was marked by a persistent dry fog, or dim Sun, as reported in the northeastern United Slates Rampino *et al*. 1988).

Weather recorded in Indonesia, the British Isles and North America fits in closely with the summer cooling and winter warming expected for the northern hemispheres response to major sulfate aerosol veils. Estimates from northern hemisphere temperature data suggest that Tambora cooled the atmosphere by 0.4 to 0.7°C (Sigurdsson *et al.* 2000). The atmospheric and climatic effects of the eruption affected the Northern Hemisphere until 1817 (Self *et al.* 1989).

It seems plausible that Tambora's eruption, and its global climatic reach really played a role in the outbreaks of disease from 1816-19. Far beyond Indonesia, the pattern of climatic anomalies has been blamed for the severity of a typhus epidemic and the great epidemic of cholera that broke out in Bengal in 1816-17 (Oppenheimer 2003). However, the epidemic of cholera is thought to have arisen because of troop movements in India displacing people out of the endemic source of the disease, and the epidemic did not reach Europe until 1831-32. The New England region was probably particularly vulnerable to disaster because farming was already taking place on climatologically marginal lands, and there was increased competition from the mid-western USA and central Canada (Oppenheimer 2003).

A Tambora-size eruption in the 21st century will have much more profound affects on humans living on an overcrowded Earth, where natural resources are already strained to the limit. It has been calculated that there is perhaps as high as a 10% chance of a Tambora-sized eruption occurring somewhere in the next 50 years, and that it is more likely to be in Indonesia than any other country (Rampino *et al.* 1988). Will Durant offered us this simple, yet profound statement: "Civilization exists by geologic consent, subject to change without notice!"

FIGURES

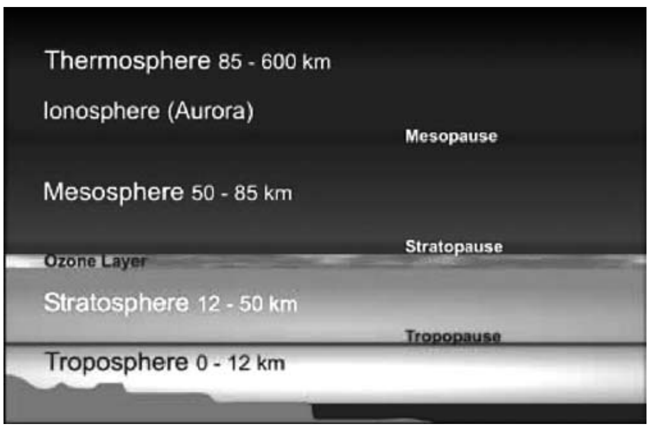

Figure 1: Divisions of Earth's atmosphere

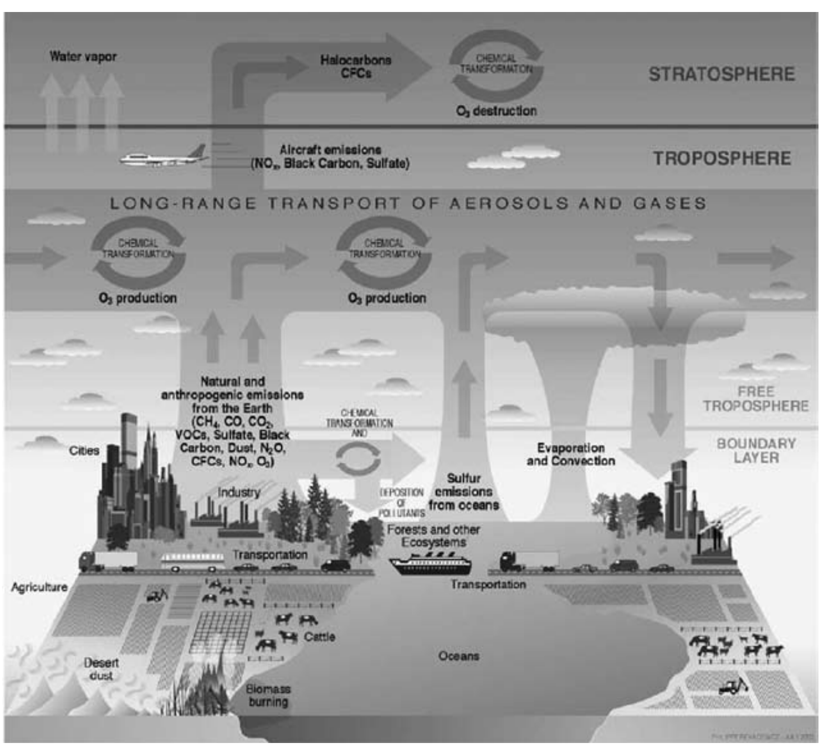

Figure 2: Aerosol sources and cycles into the atmosphere (from US Climate Change Science Program) http://www.climatescience.gov/Library/stratplan2003/final/graphics/images/SciStratFig3-1.jpg

Volcano	Eruption year	Column height (km)	Magnitude (kg)	Sulfur yield (Tg S)	Northern hemisphere summer temperature anomaly (K)	Fatalities
Taupo	≈ 181	51	7.7×10^{13}	?6.5	?	Unlikely
Baitoushan	≈ 969	25	5.8 ´ 10^{13}	>2	?	?
Unknown	≈ 1258	?	?	>100	?	?
Kuwae	≈ 1452	?	$>8 \times 10^{13}$	?40	–0.5	?
Huaynaputina	1600	46	2.1×10^{13}	23	–0.8	≈ 1400
Tambora	1815	43	1.4×10^{14}	28	–0.5	>71,000
Krakatau	1883	25	3.0×10^{13}	15	–0.3	36 600
Santa Maria	1902	34	2.2×10^{13}	11	No anomaly	7,000–13,000
Katmai	1912	32	2.5×10^{13}	10	–0.4	2
Mt St Helens	1980	19	7.1×10^{11}	0.5	No anomaly	57
El Chichón	1982	32	3.0×10^{12}	3.5	In the noise	>2000
Nevado del Ruíz	1985	27	4.5×10^{10}	0.35	No anomaly	23,000
Pinatubo	1991	34	$1.3–1.8 \times 10^{13}$	10	–0.5	1202

Table 1: Comparison of selected volcanic eruptions (after Oppenheimer 2003).

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