Effects of Volcanism on Climate – Paul Withers

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Intro:

The effects of subaerial volcanism extend far from their source. Long-distance effects include brilliant optical phenomena, which I will not discuss here, and climatic effects.

An eruption on Etna in 44 BC, coincident with the assassination of Julius Caesar, caused poor harvests around the Mediterranean. Plutarch wrote that the haze from the eruption had prevented fruit from ripening.

The foundations for scientific study of the effects of volcanism on climate were laid by Benjamin Franklin, then US ambassador to France, in 1784. He noted a constant *dry* fog over much of Europe and North America in the summer of 1783 and suggested that it caused the following harsh winter by blocking the sun's heat. A suggested possible source of the unusual fog was volcanic eruptions in Iceland – the Laki flows.

The miserable weather of 1815 – 1816, culminating in the famous "Year without Summer" over parts of Europe and North America, which confined Shelley to a chateau on the shores of Lake Geneva and inspired *Frankenstein*, was caused by the Tambora eruption in Indonesia, though a connection was not suggested at the time. The effects of this eruption can also be seen in Turner's glorious sunsets.

The cataclysmic eruption of Krakatoa, Indonesia, in 1883, had many optical effects but no major climatic perturbations were noted at the time. However it spurred a number of scientists to study the possible effects of volcanism on climate.

By 1950, the existence of a connection had been well established. Quantitative measurements had revealed decreases in the intensity of solar radiation correlated, to a certain extent, with major volcanic eruptions. However, outstanding questions remained. The lack of correlation between volume of magma erupted and climatic effects hinted at problems with the paradigm of climatic effects being predominantly due to suspended ash and dust and no good quantitative models existed for predicting climatic effects.

In the past fifty years, improvements in measurement technology, theories of volcanism, studies of historical eruptions, and the Gunung Agung (Indonesia, 1963), Mt. St. Helens (USA, 1980), El Chichon (Mexico, 1982), Mt. Hudson (Chile, 1991), and Mt. Pinatubo (Philippines, 1991) eruptions have improved our ideas as to the true connections between volcanism and climate.

Volcanic plumes:

Volcanic plumes carry three major components: ash, volcanic gases, and entrained tropospheric air. The quenching of magma to glass and its subsequent fragmentation forms the ash. Volcanic gases are produced by degassing of the erupted magma, partial degassing of unerupted magma, and the eruption of a separate vapour phase. This vapour phase is only found for a gas-saturated magma.

A typical size for an ash particle is 100 microns. The ash will fall out of the atmosphere in about a week, depending on the height of the eruption column, having been transported less than 1000 km for any eruptions in the Holocene, or past 8000 years. It has local climatic effects but usually not regional, and definitely not global, effects. Volcanic ash is not the major contributor to the climatic effects of volcanism. The 1991 Kuwaiti oil fires clearly demonstrated the localization of climatic effects from smoke and ash, albeit with injection at ground level.

Mafic volcanic gases can be roughly described as 80% H_2O, 10% CO_2, 5% SO_2, and traces of halogens such as HF, HCl, and HBr. Most authors seem comfortable with the idea that the water and carbon dioxide have little climatic effect, though they don't tell you why. I assume that the water and carbon dioxide injections are small in comparison to their steady state values. The halogens can probably destroy ozone. However there hasn't been a large volcanic halogen injection since detailed measurements of the ozone layer began.

The importance of Sulphur:

The sulphur dioxide has significant climatic effects. SO_2 gas reacts with water in the atmosphere to form submicron-sized liquid sulphuric acid aerosols, mostly as 75% H_2SO_4 – 25% H_2O solution. Any sulphuric acid in the troposphere rains out quickly as acid rain. Residence times in the stratosphere are much longer, on the order of months, before aggregation to large sizes or tropopause folding returns them to the troposphere. This aerosol layer has climatic effects due to its interaction with radiation and the possibility for chemical reactions on aerosol particle surfaces. The stratospheric aerosol layer is predominantly sulphuric acid of volcanic origin.

The background emission rates of sulphur (S) into the atmosphere is about 100 Mtonnes yr^{-1}, of which ~80% is anthropogenic. This is almost entirely tropospheric. For comparison, Mt. Pinatubo injected ~17 Mtonnes of SO_2, or 9 Mtonnes of S, into the stratosphere. These stratospheric aerosols will absorb and scatter downward propagating visible solar flux and upward propagating infrared terrestrial flux to differing degrees, reradiating in the infrared in all directions. The net effect is stratospheric heating and tropospheric and surface cooling. Note that these temperature changes can have knock-on effects to global wind circulation patterns, with additional climatic effects.

Eruption volume, magma sulphur content, eruption style, and volcano location all influence the climatic effects. The first two are obvious, more sulphur, more climatic effects (up to a point...). Magmatic sulphur content seems to correlate well with FeO content, with more mafic magmas having up to 1 wt% S and less mafic magmas as low as 100 ppm. Eruption style, controlling the height of the eruption column, affects how much sulphur gets into the stratosphere. Volcano location is also important. Terrestrial wind patterns are primarily zonal, that is around lines of latitude, spreading volcanic sulphur around a latitude band in a few weeks. Hemispheric transport is much slower, and aerosols from an eruption poleward of 20^{o} latitude are unlikely to cross the equator.

A rough and ready expression for hemispherical temperature decrease is:

$$\text{Temperature decrease/K} = 6\text{x}10^{-5}\ (\text{S/grams})^{1/3}$$

where S is the mass of volcanic sulphur injected into the atmosphere. Note that this completely neglects eruption style and self-limiting behaviour in large S injections. A sulphur-rich eruption will increase the particle size (to micron size), rather than the number of aerosol particles through coagulation. These large particles will have a shorter residence time in the stratosphere and hence a reduced climatic effect than that predicted by this simple expression. Volcanically induced hemispheric temperature decreases of 0.5 – 1.0 K occur about every 50 years, though decoupling them from other climatic fluctuations is difficult. [There now follows a series of guesses.] In the modern world, temperature decreases of a few K are probably needed to cause a subsistence crisis. These probably come along every few hundred years. [Speculation has now ceased.]

The increased total surface area of stratospheric aerosols, especially when sedimenting out of the atmosphere, provides nucleation sites for cloud condensation and potential changes in terrestrial cloud cover and subsequent scattering of solar radiation. It also provides many places for other chemical reactions to occur, including the conversion of benign halogen-containing species to ozone-destroying ones. The effects of volcanism on the ozone layer is not well understood, with only the 1991 eruptions really constraining models at present. However, the effects may be large – tropical ozone column abundances decreased by almost 10% shortly after the Mt. Pinatubo eruption. OH from volcanic water may also destroy ozone. Nitrogen oxides are also affected by volcanic aerosols.

<u>Historical eruptions:</u>

Temperature changes can be studied using ^{18}O records in ice cores and forams, frost damage in tree rings, and no doubt other ways as well. Sulphur loading in the atmosphere can be studied using petrological studies of lava (assuming gas-saturated magmas) and acidity in ice cores. In recorded history, reports of overcast skies, crop failure, and so on can be interpreted to constrain the sulphur loading and temperature changes resulting from volcanic eruptions.

Flood Basalts:

These voluminous mafic eruptions would have introduced huge quantities of sulphur into the atmosphere. Uncertainties on the duration of the eruption, sulphur injection altitude, and self-limiting processes for large sulphur eruptions make it difficult to assess their climatic impact. It has been suggested that the effects would be similar to an overcast sky for a decade, with surface cooling of 5-10 K, and perhaps triggering glaciation. This is speculative.

Final thoughts:

Impact-generated sulphur and other climatic effects. Extraterrestrial volcanism and climate.

References:

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vol_fig1	overview of plume and effects
vol_fig2a/b	Pinatubo SO_2 locally
vol_fig3	Pinatubo SO_2 several weeks after eruption – no scale given
fsheet_fig1	overview of plume and effects
pina	Pinatubo blowing up
gas2	T effects of Laki
slide13	as vol_fig3 pretty much

Rampino et al "Volc winters"

1 T decrease after major eruptions, composite
2 optical depth after Tambora

Sigurdsson GSA247

1 column height vs eruption rate
2 ash transport distances
3 forams
4 S solubility
5 S yield as fn of SiO_2
6 T decrease as fn of S yield

Self Pinatubo
4.Pinatubo S loading vs time
6.global optical depth vs time shows dispersal very well
9.Mauna Loa tau after El Chichon, pinatubo
10.lower strat heating after El Chichon, Pinatubo
15.optical depth of atm from 1850-2000 (guesstimated)
Pinto
-
Thordarson and Self
-
Stothers Tambora
-
McCormick Pinatubo
1.just like vol_fig1
2.cloud dispersal
4.Ozone losses
Sig Laki
-
Kring, Jay, Don
-
Sparks
1.T drop as fn of S
2.Surface T drop as fn of aerosol size
3.as 2 for strat T
6.fallout times
11.as self.4
19.strat heating for Agung, Chichon, Pina
Francis Volcanoes

nothing that isn’t elsewhere

Overheads plan
gas2, Rampino2
volc_fig1, McC1
Sig2, self10, rampino1, sparks2,3
self4, self6, sig6
self9, self15
sparks6
McC4