PART IX

VOLCANICALLY INDUCED CLIMATE CHANGE

The bright sun was extinguished and the stars
Did wander darkling in the eternal space,
Rayless, and pathless; and the icy earth
Swung blind and blackening in the moonless air;
Morn came and went - and came, and brought
no day,.......
Happy were those who dwelt within the eye
Of the volcanoes, and their mountain torch.....
To look once more into each other's face.

Lord Byron. Geneva, July 1816

Introduction

It is generally believed that the source of inspiration for Byron's poem 'Darkness' was the highly unusual climatic conditions of 1816 - "the year without a summer" (Rudolf, 1984). During that year, temperatures across the globe fell to abnormally low levels from late spring until autumn. In N. America and W. Europe snow and heavy rain accompanied the cold, and in Madras the temperatures fell well below freezing in the middle of summer. As a consequence there was widespread crop failure with disease and famine to follow (Stothers, 1984).

In April of the previous year, Mount Tambora in Indonesia erupted, sending roughly 200Tg ($2x10^{14}$g) of volcanic aerosols into the stratosphere in only three hours following one of the most cataclysmic volcanic explosions in 75000 years (Rampino *et al.*, 1979). Tambora was considerably more powerful than the better-known eruption of Krakatoa (1883) and vented more than 3 times the amount of aerosol into the stratosphere. It is now widely accepted that the terrible weather of 1816 was directly related to climatic perturbations which resulted from Tambora's eruption. However despite reports of world wide disruption, it has been estimated (Stothers, 1984) that averaged northern hemispheric temperatures fell by only 0.4 - 0.7C° (2-sigma significance) which puts the relationship between global mean temperature change and local climate change in some perspective. Although the climatic modifications which apparently occur following major volcanic eruptions arise from different effects, there are instructive analogies with global warming which may give some insight into the magnitude of regional impacts following a significant rapid change in the earth's radiation budget. This is especially so in relation to the potential impact on man, since volcanic eruptions can produce a contempory, major and rapid perturbation of the global climate. In contrast, modulations in solar insolation due to changes in the Earth's orbital parameters occur over timescales of tens of thousands of years. Smaller changes ~~also~~ occur over the 11yr solar cycle. ~~Indeed world cooling due to a major volcanic eruption could have a greater impact on mankind than global warming, albeit over a far shorter timescale.~~

Indeed a major volcanic eruption could act as a significant depressant of global temperatures, superimposed on any upward trend caused by the greenhouse effect.

IX.1 Volcanically Induced Climate Perturbations.

It has long been known that significant volcanic eruptions induce local meteorological disturbances or "volcanic storms", as described in the discussion by Humbolt in his *Cosmos* over 140 years ago (Humboldt, 1848). However, only recently has the possibility of a global effect on climate been seriously considered (Rampino & Stothers, 1985; Stothers, 1984; LaMarche & Hirschboeck, 1984; Sear *et al.*, 1987). A major eruption can eject very large amounts of volcanic dust and gas into the atmosphere. A large proportion of this is either rained out or settles by virtue of gravity, in the vicinity of the volcano within the order of a few days (ash from the Tambora eruption fell on Jakarta nearly 1000 miles westward). However if the explosion is sufficiently severe, significant amounts of fine ash and gas can be ejected into the stratosphere above the cloud-forming layer, where it can remain for several years. Stratospheric winds then operate to distribute the veil around the globe while chemical processes continue to modify its optical properties. It is not only the amount of material which is ejected that is important, but also its composition. In particular, sulphur dioxide gas from sulphur-rich eruptions reacts with stratospheric water to form sulphuric acid, and it is these tiny droplets or aerosols of sulphuric acid which have the most important implications for the Earth's radiation budget. In contrast to the greenhouse effect where water and CO_2 trap long wavelength radiation on its way out of the atmosphere, acid droplets scatter and absorb the short wavelength radiation before it reaches the lower atmosphere and the ground. The result: stratosphere warming and tropospheric cooling (LaMarche & Hirschboeck, 1984; Hansen *et al.* 1978). As with the greenhouse effect, the consequences may be more severe than the temperature deficits suggest. Modifications of atmospheric heating disturb atmospheric circulation patterns: in particular an expected effect following a volcanic eruption in the northern hemisphere is a southerly displacement of the jet stream which guides depressions across the North Atlantic (LaMarche & Hirschboeck, 1984). As a result, temperatures across north-west Europe should fall and rainfall increase.

Equally important is the potential effect of volcanic aerosols on the depletion of ozone. Ozone is currently being depleted by a series of complex chemical reactions with anthropogenic chlorofluorocarbons (CFCs) which take place on the surface of stratospheric cloud droplets. Stratospheric clouds occur almost exclusively at the poles and so at present, ozone depletion is restricted to the polar latitudes. However, major volcanic eruptions produce large amounts of stratospheric cloud. El Chichon in 1982 was sulphur-rich and produced as much mid-latitude stratospheric cloud as was present over the poles. Significant ozone depletion occured (Lynch, 1989). As levels of CFCs continue to increase, another eruption of similar or greater magnitude could cause major losses of stratospheric ozone, with the associated consequence of increased ground surface U.V. flux - a further stimulus to halt atmospheric pollution by CFCs.

It is clear therefore, that a large volcanic eruption could have an impact on the global climate broadly similar in magnitude and significance to the greenhouse effect. For understanding the mechanisms and consequences of change in global temperatures, volcanoes have the additional advantage of being recent historical events. Therefore empirical analysis of local weather data together with a study of the historical socio-economic impact can give a unique insight into the societal significance of a global-scale perturbation of the climate. Such insight is presently denied us by the uniqueness of the greenhouse effect, and the coarse resolution offered in the predictions made by present-day general circulation models (GCMs).

IX.2 Post Glacial Climate Records - Evidence for an Effect and a Test for Theory.

(i) Ice-core Acidity and Tree Rings.

The large amount of acidic aerosol which reaches the stratosphere following a major volcanic eruption gradually rains out, until after about three years the veil is almost completely depleted. Interestingly, a rough calculation indicates that the acid deposition rate from the Tambora eruption (_ 1 m moles m^{-2} yr^{-1}) would have been about 1 order of magnitude less than current deposition rates in Scotland due to acid rain (Linehan, personal communication). A portion of the aerosol-loaded precipitation falls in the polar regions where it forms a frozen layer in the ice caps providing a permanent record of atmospheric acidity. At the same time, water which contains a concentration of the heavy oxygen isotope ^{18}O is frozen in. Because of effects related to the relative mobility of the oxygen isotopes through the photosythetic system, there is an imbalance in the ratio of the concentrations of ^{16}O and ^{18}O during periods of high photosynthetic productivity, i.e. the summer months. Therefore locked into the polar ice are successive layers providing a "tree-ring" chronology of isotopic abundances, modulated by the annual summer flush of hemispheric vegetation cover. Any layers of enhanced acidity can thus be dated, and an accurate history of the Earth's volcanic activity can be drawn up. This method has been used to date acidity levels back to the previous glacial period when the modulations in oxygen isotopic abundance become indistinct in response to reduced vegetation cover. Ice cores from Greenland have been collected which contain acidity records dating back to 7900BC (Hammer *et al.*, 1980). The correlation of acidity peaks with known historic volcanoes dating back to 1600AD is striking. [Fig of ice core acidity peaks] Earlier than 1600 most volcanism went unrecorded and as a result of poor communication, went unnoticed in all but the areas most directly affected by the eruptions. For these cases, ice cores are one of the few pieces of evidence that they ever took place. Using information relating to the global deposition pattern of ^{90}Sr released during bomb tests as a reference, it is also possible to gain a crude measure of the strength of a particular eruption if its location is known.

The corresponding data required to test for the effect of particular volcanic eruptions on climate is provided by measurements of tree ring growth in different parts of the globe. Frost damage to growing trees is a rare event brought about as a result of temperatures during the growing season falling below -5°C for a few successive nights with an intervening daytime temperature of around freezing (La Marche & Hirschboeck, 1984). These severe conditions result in abnormally narrow growth rings in the secondary xylem. Narrow growth rings can also occur as a consequence of stress brought about in response to other locally adverse growth conditions, e.g. drought or waterlogging. However, when narrow rings occur simultaneously in trees over widely separated areas, it can be assumed that weather conditions world-wide were unusually detrimental to growth at the time. Using such an approach, La Marche & Hirschboeck (1984) studied the growth rings of trees in seven different localities in the western U.S. By cross-dating trees in overlapping generations, it was possible to recover data representing two or more sites for a period extending from AD595 to the present. By comparing the tree ring data with the ice core chronology, they found that extensive frost events occured across western U.S. within a year following each known major eruption, at better than the 99% confidence level. A similar study of Irish bog oaks relating to the period from 5289-116BC also produced a persuasive coincidence of notably narrow ring events and volcanic eruptions (Baillie & Munro, 1988). At one site (White Mountains) in the La Marche et al. study, it was possible to obtain tree ring data back to 3435 BC, providing an overlap with the data of Baillie and Munro. Although the identification was difficult (La Marche &

Hirschboeck, 1984) there were three discernable frost events in the White Mountain sample which occurred in this overlap period. As further evidence for the global nature of the effect, two of these events also occur in the Irish data, in particular frost damage was associated with the eruption on the Aegean island of Thera (Santorini) at around 1626BC (Hughes, 1988), and with the eruption of Mount Etna in 44BC. An additional interesting effect observed by Baille & Munro is the duration of the period of restricted growth. For their oak trees growing in marginal bog-land areas, the period of restricted growth lasted for around 10 years. Since volcanic veils clear from the stratosphere in 1-3 years, there must have been some longer lasting indirect effect which caused problems for tree growth in these areas (e.g. flooding). This is evidence that on a local scale, climatic anomalies other than temperature persist following a large eruption, and these anomalies can have as severe consequences for vegetation.

(ii) Contemporary Data.

The most direct way to look for a climatic effect of volcanic aerosols is to study meteorological data collected at the time of the eruption. Sear *et al.* (1987) collated land and marine surface air temperature data covering the period from the mid-19th century to present. They selected nine of the most explosive volcanic events (including Krakatoa, 1883) which occurred in that period. Because the expected temperature anomalies are near the level of natural variability, in order to reduce the random noise effects the data pertaining to each volcano was superimposed using the date of each eruption as "day-zero". The magnitude of the effects of an eruption depend on its location as well as the composition of the ejecta, the season of the year and the prevailing circulation patterns. For example, Mount St. Helens which erupted explosively on May 18th 1980 had the potential to make a significant impact on climate. However the eruption was sulphur poor and as a consequence when the aerosols got into the stratosphere, they had little or no effect on global temperatures or circulation patterns. In their study of the effect of location, Sear *et al.* (1987) found that eruptions which occur in the northern hemisphere have little or no effect on southern hemispheric averaged temperatures. In contrast, southern eruptions reduce temperatures both north and south of the equator. The likely reason for the lack of any influence of northern eruptions on southern temperatures is the proportionately larger surface area of ocean in the southern hemisphere, with its associated thermal inertia. The forcing provided by the aerosols which cross the equator is simply insufficient to generate a significant response in the southern oceans (Sear *et al.*, 1987). The dominance of the oceans for heat storage in the southern hemisphere is also responsible for the greater lag time for cooling effects measured against the northern hemisphere response. According to Sear and co-workers, northern hemispheric temperatures start to drop immediately, reaching a minimum within 2 months following a major northern hemisphere eruption. The response to southern eruptions has a lag of over 6 months, with the global deficit persisting for around 2 years. The response of the southern hemisphere climate to southern eruptions follows a different pattern. A slight drop in temperature develops almost immediately, but it is not until well into the second year following the eruption that the maximum deficit occurs - again a consequence of the oceans' high thermal inertia. The implications of the effect for calibrating climate models is discussed in the next section. The typical temperature deficit which occurred as a result of the eruptions in the Sear *et al.* sample was around three tenths of a celsius degree, for both northern and southern volcanoes.

(iii) A Test for Climate Models.

Accurate monitoring of tropospheric and stratospheric temperatures has only recently been possible, but allows a more precise assessment of the impact of the radiative forcing of volcanic aerosols on the atmosphere. When Mount Agung on the island of Bali erupted in 1963, not only could the effects on atmospheric temperature be determined but measurements of aerosol optical depth and chemical composition made it possible to incorporate the induced radiative perturbation as a test of global climate models. Hansen *et al.* (1978) used a simple one-dimensional radiative convective model to simulate the temperature profile through the atmosphere. In order to simulate the transient response of the atmosphere accurately, they included dissipation of heat to the mixed layer of the ocean (see Part I). However, the model ignores potential cloud cover feedbacks and does not allow for an interaction between heating and large scale atmospheric dynamics. Nevertheless a simple model atmosphere coupled to an ocean with a mixed layer depth of 70m provides an atmospheric temperature response curve which is of the correct magnitude and decays with time in a manner closely following the observed behaviour. The maximum tropospheric deficit (averaged over the latitude range +30° to -30°) was around 0.4C° which was reached approximately one year after the eruption. Temperatures returned to near normal after about 3 years. Therefore in spite of its simplicity, the 1-D model can reproduce the gross transient behaviour of the perturbed climate. This lends remarkable support for the more sophisticated climate models, although the 1-dimensional nature of the model prevents any comparison with the spatial predictions of more modern GCMs. However, present-day general circulation models are not sensitive enough to accurately simulate the regional effects of volcanic veils on climate (Kelly, personal communication). The sulphur-rich eruption of El Chichon in 1982 offered the possibility of a second study of the effects of volcanic veils on climate. Unfortunately, in this year there was a particularly strong El Nino event which almost entirely offset the cooling effects of the eruption and confused the data (Robock, 1989).

The evidence for a direct effect on climate of major volcanic eruptions is compelling. The induced effects on a global scale confirm the gross accuracy of current climate models in simulating the climatic response to a significant radiative perturbation. It is also suggested by empirical evidence that local effects which occur in response to the induced temperature anomalies, and which are below the spatial resolution of current climate models, may be more severe than the globally averaged deficits suggest. In order to gain some perspective on the effects at a local level, we look to the historical accounts of the world-wide consequences of one of the most energetic volcanic explosions in 75000 years (Rampino *et al.*, 1979) - Mount Tambora in Indonesia, 1816.

IX.3 A Perspective on Some Socio-Economic Implications.

By sifting through historic accounts (Stommel & Stommel, 1979) from different locations across the globe, it is possible to piece together a coherent picture of the consequences of a world-wide climatic anomaly. It is important to remember two important points at the outset. Firstly, that the global mean temperature deficit following the Tambora eruption was less than 1C° (Stothers, 1984). Secondly, when comparing the potential of volcanic eruptions for causing climate change, the impact of a particular eruption depends both on its sulphur content as well as its explosive power.

One interesting observation regarding the weather on a local scale as reported in 1816 was its extreme variability. This is one aspect of the transient climate which is difficult to predict using current climate models (see Part I), although Hansen *et al.* (1988) suggest that temperature variability should remain unchanged. During an otherwise normal summer, New England experienced three cold waves, when temperatures fell below freezing for several days in succession. Weather patterns changed dramatically in timescales of hours: the *North Star* of Danville, Vermont reported warm and sultry weather on one day to be followed by hail and snow the following morning. The consequences of this rapid variability for crop production were predictable. Accompanying drought cut yields in pasturage crops by about 50% in Connecticut. However, the cooler conditions meant that what there was had a high nutritional value. Indeed, because of the longer filling and ripening times resulting from slowed development in the cool conditions, those crops of wheat and rye which survived the cold were of very high quality and yield. This is one advantage which will be absent in a future "greenhouse climate". In central Europe, unusually cold and dry weather led to wide-scale reductions in yield, while in Switzerland, food was so short that mosses and cat flesh were eaten and information regarding the edibility of wild plants was issued. The situation in France was worse because grain stores were already depleted following the Napoleonic wars. Reports of effects on pests and diseases are scant; however, there were accounts of fewer than normal numbers of fleas and mosquitos in New York during 1816.

In general, the climatic effects of the Tambora eruption had more severe consequences for Europe than America, and the economic consequences of this imbalance are informative. For example, France imposed a tax on wheat to cut consumption and by August had suspended import duties on grain. Despite this, continuing shortages pushed the price of wheat to twice its usual value by the early part of 1817. The high cost of food in Europe became so prohibitive that military intervention was necessary to protect farmers from being robbed on their way to market. The scarcity of food also gave rise to large scale movements of population from areas of chronic shortage. Because the foreign situation made the European market very attractive, exports of wheat from America increased and this pushed up the domestic price to nearly double the recent average. The situation was further aggravated by farmers making wrong decisions due to their lack of experience regarding such decisions. For example farmers worried about crops failing to ripen harvested too early. Concern for the prospects of hay and winter fodder led to a panic selling of live-stock and a consequential fall in prices. In New York markets, pork and beef were being sold in late summer and autumn at two-thirds the usual price - a reversal of the usual trend of low spring and high autumn prices.

Similar consequences followed the 1150BC Hekla-3 eruption in Iceland (Lynch, 1989). A mass evacuation of some 600,000 inhabitants of the Scottish highlands over a period of some 40 years marked the end of the late Scottish bronze age. Narrow tree rings again point to a significant climatic anomoly and resulting stunted agriculture as the cause.

These accounts give some insight into the possible scale of the problems which may result from a global-wide change in climate occurring over a short timescale. The possible problems are made worse to-day by the five-fold increase in the world's population which has occurred since the early 1800s - mostly in the Third World. Present food reserves are sufficient to feed the world's population for no more than sixty days, far less than the expected duration of a 'volcanic winter'. Furthermore, since the climatic consequences of a dense volcanic dust veil are analogous to, although less severe than, the effects of the anticipated smoke cloud from a significant nuclear exchange (Schneider & Thompson, 1988; Rowan-Robinson, 1985) a modern and potentially more immediate threat exists.

It is still not known what impact the Greenhouse effect will have on world food production. It is clear, however, that some areas are very likely to become less productive, especially the tropical regions where the portion of the world's population least able to cope with the changes reside. For these areas, many of the difficulties outlined above may be relevant, and it is all the more important to approach these problems now since lives rather than economies are at stake. It is likely that these countries will have to rely heavily on the agricultural productivity and technology associated with the more temperate latitudes to sustain their already malnourished populations. This will require substantial backing from the Developed World since it is clear that the Third World countries simply do not have the resources either to increase imports or to make any substantial modifications to domestic farming practices. ~~As far as the U.K. is concerned, its immediate responsibility will be to the poorer Commonwealth member states~~. It is therefore important not to remain complacent in a country where agriculture is, in the present climate, relatively highly efficient and well managed. The future climate presents challenges concerning decision-making and investment for farmers in a period of rapid change. The problem is not limited to a particular country or to a particular government, it is a global problem requiring international cooperation.

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