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FOREWORD

The European Union is committed to monitoring the environment to ensure the quality of life and security of European citizens. The Earth's atmosphere presents one area in which strategic monitoring is essential; scientists, politicians, the media and the public have vested interests in addressing issues such as stratospheric ozone depletion, increasing surface ultraviolet (UV) radiation, global climate change and air quality. GMES is a joint initiative between the European Commission and the European Space Agency to establish, by 2008, a truly European capacity for Global Monitoring for Environment and Security (GMES).

GMES-GATO is an extension of the European research cluster, Global Atmospheric Observations (GATO), which is central to the coordination of stratospheric ozone research and was established in support of the Montreal and Kyoto Protocols. GMES-GATO is one of four GMES thematic projects concerned with the monitoring of the Earth's atmosphere. In this report, the GMES-GATO consortium has defined a strategy for GMES to help develop an integrated global atmospheric observing system by 2008. The preparation of this report has involved a wide range of people from different backgrounds and areas of expertise.

This strategy report assesses what the current European capabilities are and describes how a more rational European monitoring system could be developed. It examines facets such as the observational capability itself, quality assurance and control, data storage and accessibility, and the provision of useful information (often in the form of derived products) to all concerned parties. The recommendations contained herein would help achieve best overall use of data from ground-based and satellite observation systems. This report complements the European Commission's publication, 'A Global Strategy for Atmospheric Interdisciplinary Research in the European Research Area, AIRES in ERA', which describes a balanced research programme to improve our understanding of atmospheric issues.

On behalf of the European Commission, I would like to express my sincere thanks to the authors, reviewers and editors whose commitment and keen interest are reflected in this report. Furthermore I would like to acknowledge the expertise of the European atmospheric community, on which the preparation of this report relied.

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Chapter 5

VOLCANO MONITORING AND PUBLIC SAFETY

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5.1 THE ISSUES

5.1.1 Introduction

Around 380 volcanoes were active during the last century, with around 50 volcanoes active per year (Andres and Kasgnoc, 1998). Volcanic activity is not randomly distributed over the Earth, but is linked to the active zones of plate tectonics. Figure 5.1 shows the location of 1509 volcanoes thought to have been active in the last 10,000 years (Holocene). Two thirds of the volcanoes are in the northern hemisphere and only one fifth are located between 10ºS and the South Pole. There is no significant variation in the concentration of volcanoes with longitude, but over 1000 volcanoes (two thirds of those displayed) lie on the Pacific Ocean margin and form the `Ring of Fire'.

Global climatic impacts of volcanic eruptions are caused by the injection of millions of tonnes of sulphur dioxide (SO_2) into the stratosphere: the SO_2 is converted into submicron aerosols that remain in the stratosphere for years and change both the Earth's radiation budget and the circulation of the atmosphere. On average, there is one eruption every ten years that has a global impact, e.g. El Chichón (1982) and Mt. Pinatubo (1991). The Mt. Pinatubo eruption (possibly augmented by El Nino effects) was followed by a severe drought in East Africa which led to the mass emigration of millions of refugees. Very large eruptions take place every hundred years. Previous eruptions of this size (e.g. Tambora, 1816) have led to a dramatic reduction of harvests in Europe and consequent widespread hunger and disease.

In Europe, large cities are at risk where they have developed on the slopes of active volcanoes (e.g. Naples). However the danger to people is not restricted to local hazards; island volcanoes (e.g. Santorini, La Palma) can produce huge tsunamis which have the potential to severely impact on coastal regions. There are world-wide risks to aviation as modern jets are extremely vulnerable to inadvertent encounters with volcanic ash clouds: several severe accidents have been reported in the last two decades.

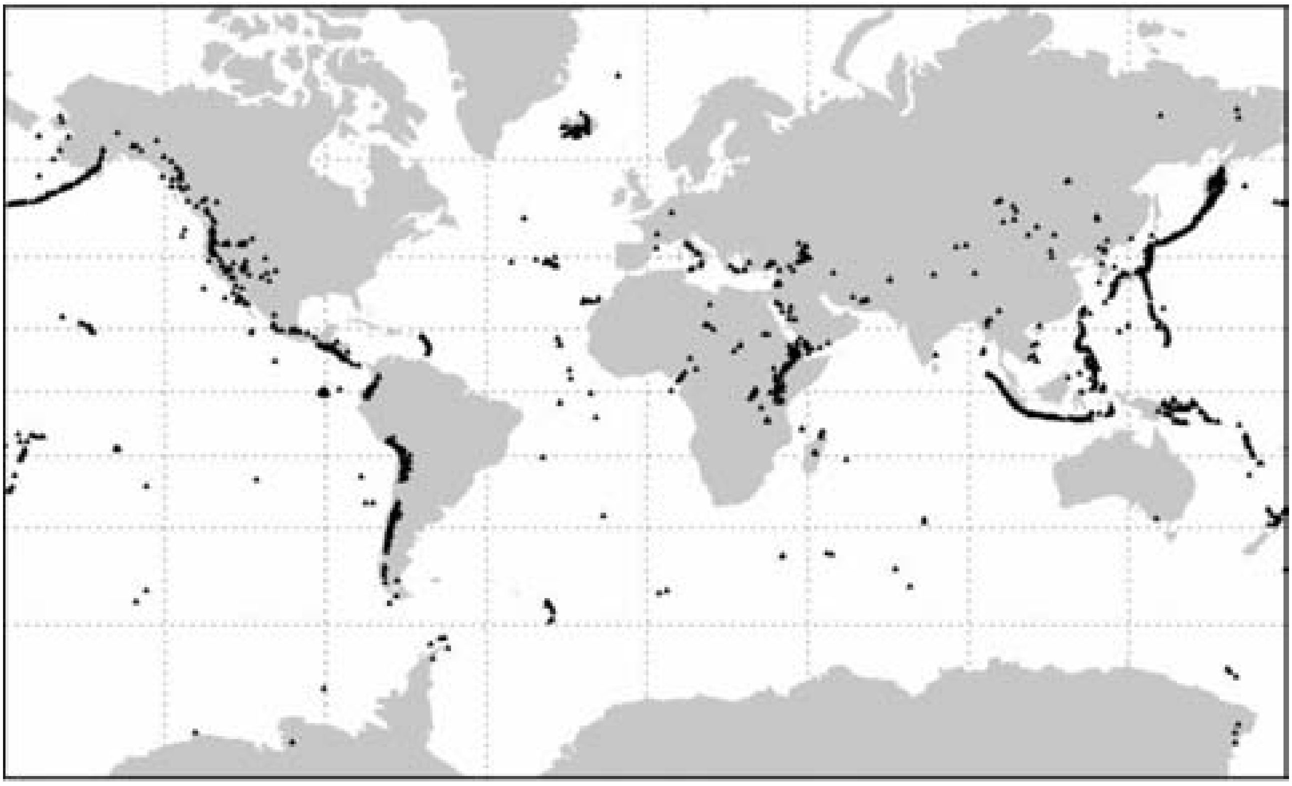

Figure 5.1 Location of volcanoes thought to have been active in the last 10,000 years (Holocene). Volcanic belts cover 0.6% of the Earth's surface. (Source: Smithsonian Institution, Global Volcanism Program)

The impact of a volcano on the atmosphere can be characterised in terms of the erupted magma. Globally, most of the magma mass erupted is of basaltic composition. Basaltic magma is rich in magnesium and iron, and contains comparatively little silica. In general, this magma type is characterised by a low gas content and eruptions are mostly effusive. They consist of a high portion of carbon dioxide (CO_2) and sulphur in the gas fraction. Long-lasting basaltic lava streams can cover large areas (e.g. the Deccan traps in India and the Laki fissure in Iceland). Eruptions of basaltic magma contribute only a small fraction to volcanic sulphur emissions into the atmosphere, and only in rare cases reach the stratosphere.

Felsic magma stems from differentiation processes (i.e. chemical fractionation) in the magma chamber or from the melting of crust material. This highly differentiated magma is rich in silica and alkalis. It contains a higher content of dissolved gases, especially water, and eruptions are generally more explosive but low in sulphur content. Extreme eruptions of felsic magmas include several hundreds to thousands of cubic kilometres of ash emissions in a short time. Bishops Tuff, Fish Canyon Tuff and Toba Tuff are examples of these deposits.

Magmas of intermediate silica content are called andesitic magmas, and are typical of volcanoes at convergent plate boundaries where subduction is the fundamental plate tectonic process. Felsic and andesitic volcanoes erupt less frequently than basaltic volcanoes. They can release large amounts of magma and energy on short time scales, often injecting ashes and gases directly into the stratosphere. In addition, many permanently emit gases during non-explosive phases. As they possess intermediate concentrations of sulphur but are generally explosive, eruptions of subduction zone volcanoes contribute the largest part to the total global volcanic sulphur emission.

5.1.2 Volcanic Emissions

Volcanoes emit gases and particles into the free troposphere, in part because the source height is above the planetary boundary layer, and also because emissions are strongest during eruptions and eruption clouds can reach considerable heights above the crater, ranging from a few hundred metres to some tens of kilometres. Volcanic sulphur emissions to the troposphere make up in the order of 10-20% of total sulphur emissions from manmade and natural sources. However, their long lifetime (they are emitted into the free troposphere where removal processes are less effective) may lead their contribution to equal that of manmade sources with respect to the sulphur burden.

In addition to the release of a number of gases, an explosive eruption blasts molten and solid rock fragments (tephra) into the air. The largest fragments (bombs) fall back to the ground near the vent, usually within 3-5 km. The smallest rock fragments (ash) continue rising into the air, forming an eruption column. Fine volcanic ash injected into the stratosphere is characterised by grain sizes in the micrometer range. In the troposphere these particles are quickly lost through sedimentation and rainout, typically on a timescale of a few days. In the stratosphere, ash is efficiently removed by sedimentation within about a month following an eruption (Pinto et al., 1989).

The composition of volcanic gases at the volcanic vent varies widely, depending on the magma type and the individual volcano's state of activity. Water vapour (H_2O) is the most prevalent volcanic gas, contributing between 50 and 90% by volume; however the contribution to the global H_2O atmospheric concentration is negligible. The second most important volcanic gas is carbon dioxide (CO_2), which comprises 1-40% of the emitted gas by volume. Volcanic emissions contribute less than 1% to the total global CO_2 emission in the long term mean but can provide a substantial contribution in the case of a large scale and sustained basaltic eruption (Cadle, 1980, and Gerlach, 1991).

Typically, sulphur gases contribute 2-35% to volcanic gas emissions by volume. They are the most relevant species to the climatic impact of volcanic events. The dominant sulphur component is sulphur dioxide, with yearly emissions ranging from 1.5-50 Tg. The main halogen component of volcanic emissions is hydrogen chloride (HCl), contributing about 1-10% by volume (Symonds et al., 1988). The upper limit for volcanic emissions of HCl is 0.4-11 Tg per year (Symonds et al., 1988, and Cadle, 1980). This is approximately equal to anthropogenic HCl emissions but HCl emissions from oceans are orders of magnitude higher. HCl is highly soluble and is therefore rapidly washed out of the atmosphere. Hence small eruptions and silent degassing will not be of importance for atmospheric composition with regard to halogens. Volcanoes constitute potentially a very important source of atmospheric bromine. The global volcanic BrO source is between 6,500 and 140,000 tonnes per year and so may exceed anthropogenic CH_3Br (approx. 100,000 tonnes Br per year, Butler and Rodriguez, 1996) as a source of atmospheric bromine. Traces of hydrogen bromide (HBr) are contained in volcanic emissions: typically about 10^{-6} parts per volume. The inclusion of the bromine in HBr and other chemical forms (e.g. HOBr) makes the total volcanic bromine emission higher than the above figure indicates. Hydrogen fluoride (HF) usually comprises less than 1 ppmv in volcanic gas emissions: the annual global emission is 0.06-6 Tg (Symonds et al., 1988). HF is not of importance in general, but during specific events (e.g. Laki 1783, Mt. Hudson 1991), HF emissions may be extreme and lead to severe environmental contamination that is hazardous to plants and livestock.

5.2 WHAT ARE THE POLICY RELATED ISSUES?

5.2.1 Direct Atmospheric Impacts of Volcanic Eruptions

Volcanic eruptions can produce lethally high, local atmospheric concentrations of volcanic ash, acidic gases and secondary particles. The impact of long-lived effusive eruptions can be extended to a regional scale. For example, one of the greatest environmental disasters in history occurred in

1783-4 as a result of the Laki fissure eruption in Iceland. The eruption lasted 9 months, expelled 15 km^3 of lava and ash, and released more than 100 million tonnes of sulphur, chlorine and fluorine gases, and particles into the atmosphere. The eruption affected the climate over the whole of the northern hemisphere and was followed by widespread agricultural crop failures. In addition the volcanic emissions may have caused or aggravated respiratory illnesses. Over 20% of the Icelandic population died during and in the immediate aftermath of the eruption due to climatic effects and contamination of soil induced by the Laki eruption.

Aircraft that encounter ash from explosive volcanic eruptions can experience engine failure and damage to a number of aviation subsystems. Between 1980 and 1994, eighty jet aeroplanes were damaged by unexpected encounters with drifting clouds of volcanic ash in flight corridors and at airports. Ash clouds, which are hazardous to aircraft, exhibit radar reflectivity several orders of magnitude smaller than that of severe weather and consequently do not appear on on-board radar. Visual recognition of a volcanic hazard may be difficult as ash clouds commonly resemble normal weather clouds.

5.2.2 Indirect Effects

Volcanically emitted gases (SO_2, H_2O, H_2S, CO_2 and HCl) can alter the radiative and chemical balance of the atmosphere and so perturb climate and atmospheric circulation. In addition, sulphur containing gases (principally SO_2) are converted to sulphuric acid, which subsequently condenses to form small droplets or aerosols which lead to acid rain.

5.2.2.1 The Troposphere

Volcanic sulphur emissions in the troposphere have a disproportionate effect on the atmosphere: this has been shown by numerical experiments with an atmospheric general circulation model that includes a simplified sulphur cycle (Graf et al., 1997). SO_2 is transformed into H_2SO_4 within days in the troposphere, but with e-folding times of a month in the stratosphere. The fastest transformation occurs in the lower troposphere. Sulphate aerosols in the atmosphere absorb and emit in the longwave, heating the layer, in which they reside and increasing the downward flux of radiation at the surface (for a review see Robock, 2000). In addition, aerosols scatter incoming solar radiation and thereby lead to a net cooling at the surface.

Sulphate aerosols in the troposphere act as cloud condensation nuclei and modify the radiative properties and the lifetime of clouds (Twomey, 1974). The increase in the number of cloud droplets due to an increased number of condensation nuclei leads to an increase in cloud albedo and thus enhances surface cooling. The rate of precipitation or rain suppression in deep convective clouds may also be affected and consequently the spatial and temporal distributions of latent heat release may change. This could have a significant effect on global circulation, as shown for aerosols in general by Nober et al. (2003).

In the tropics, during tropopause folds at mid-latitudes, volcanic sulphate aerosol particles can be transported vertically across the tropopause. Important lidar data show that in more than 50% of observations, the stratospheric aerosol layer has penetrated the tropopause and influenced the formation and maintenance of cirrus clouds in the upper troposphere (Ansmann et al., 1993). Graf et al. (1997) suggested that sulphate aerosol in the upper troposphere is important for cirrus formation. Unusually high cloud particle number concentrations (600 l^{-1}) and extremely supercooled drops at 223-233K were observed in the year following the eruption of Mt. Pinatubo (Sassen, 1992, and Sassen et al., 1995). Song et al. (1996) suggested that the interannual variability of global high level clouds is related to explosive volcanism. The amount and persistence of such clouds increased by as much as 10% following the eruptions of El Chichón and Mt. Pinatubo, mainly at mid-latitudes. These anomalies lasted several years. Thus, violent volcanic eruptions lead to a change in radiative properties of cirrus clouds. Their impact on climate is still not known as this depends on changes in cloud microphysics: the scattering of solar radiation leads to enhanced cooling whilst the absorption of terrestrial radiation leads to warming.

5.2.2.2 The Stratosphere

Emissions of halogen species are significant (e.g. Varekamp et al., 1984, Westrich and Gerlach, 1992 and Bureau et al., 2000) as their direct injection into the stratosphere could lead to catastrophic ozone loss (Prather, 1992). No severe increase of halogens was observed in the stratosphere after the eruption of Mt. Pinatubo (Mankin et al., 1992, Wallace and Livingston, 1992); however, after the eruption of El Chichón in 1982, a clear increase in chlorine concentration was detected (Mankin and Coffey, 1983, and Woods et al., 1985).

Sulphate aerosols in the stratosphere can serve as sites for heterogeneous reactions that convert passive chlorine compounds (HCl, HOCl and $ClNO_3$) into active ones (ClO and Cl) (chlorine activation). After the Mt. Pinatubo eruption, the surface layer of the stratospheric sulphate aerosol was about 300 times higher than usual with peak concentrations of $>3x10^{-7}$ cm^2/cm^3 (Jäger et al., 1995, and Thomason et al., 1997). The critical value for ozone destruction of 10^{-7} cm^2/cm^3 was reached (Jäger et al., 1995, and Ansmann et al., 1993) for more than one year in northern hemisphere mid-latitudes. Heterogeneous reactions deplete ozone in the presence of halogens like chlorine and bromine (Michelangeli et al., 1989, Hofmann and Solomon, 1989, Granier and Brasseur, 1992, and Solomon et al., 1996). Since the human-induced increase in chlorine concentration in the stratosphere has peaked, the ozone destruction at volcanic aerosol sites will probably decrease over the next few decades.

The radiative effects of stratospheric volcanic aerosols can cause climate perturbations for several years, which include cooling at all latitudes in summer and complex cooling-warming patterns at higher latitudes in winter. Radiation changes also affect the biosphere by changing the ratio of diffuse to direct solar radiation.

5.3 WHAT ARE THE CURRENT CAPABILITIES?

An eruption is the culmination of long-term magmatic evolution beneath a volcano. An accurate understanding of where a given volcano is in its eruptive cycle and how its magma system is evolving requires the collection of a long time-series of high quality data. The character of volcanic activity also varies according to the type of volcano although individual volcanoes are capable of several different kinds of activity and eruption regimes, which depend on the evolution of the magmatic feeding system and the physical state of the volcanic edifice. The types of measures which should be taken by civil defence authorities can vary quite considerably with the type of activity. Science is sufficiently advanced that it is possible to classify volcanoes according to the types of activity that they are likely to produce. However we are not currently in a position to predict with confidence the kind of eruption that will occur when a given volcano shows signs of unrest.

During an eruption, the determination of gas and particle concentrations in a plume is extremely difficult due to the cloud's opacity and the inherent risks of directly observing and sampling the volcanic cloud. Volcanic emissions can be studied remotely by airborne and ground-based instruments and through satellite observations.

5.3.1 Land-based Networks

There is a well-developed network of geophysical observations of the Earth's volcanic activity based on seismometry and the monitoring of individual volcanoes.

Lidars give excellent vertical distributions of aerosols but until recently, could only operate under clear-sky conditions and during the night. The distribution of lidar observatories is uneven, with only one instrument in operation between 19°N and 23°S (it is located at Bandung, Indonesia, which is plagued by bad weather). There are at least three lidar networks world-wide, one in Asia (Uchino and Fujimoto, 1992) and two in Europe (Fiocco et al., 1996, and Bösenberg et al., 1998) but only one of these (EARLINET, Bösenberg et al., 1998) operates using standardised instruments and processing software.

5.3.2 Satellite Observations

In recent years, the launch of new satellites and new developments in remote-sensing techniques have expanded the capability to monitor volcanoes from space (Rose et al., 2000). Satellites have even detected SO_2 from several eruptions that were not known from ground observations. Satellite observations (e.g. by TOMS, AVHRR, GOME and SCIAMACHY) of SO_2 and ash particles are only useful in relation to strong sources (Bluth et al., 1993). SO_2 is the only volcanic gas to be monitored operationally via satellites to date. Since the first TOMS data in 1979, which could only measure the presence of SO_2 from larger eruptions, improved instruments and retrieval algorithms can now detect SO_2 gas from smaller eruptions and the passive degassing of some volcanoes, provided the detection limit of 5-20 Kt SO_2 is exceeded. Of particular importance is the global SO_2 data from HIRS 2 that has been deployed aboard National Oceanic and Atmospheric Administration (NOAA) satellites for the past 25 years. This instrument is sensitive to SO_2 but has yet to be analysed.

Eleven instruments deployed on satellites in the past 30 years have included stratospheric aerosol measurements: SAM II, SAGE, SAGE II, SAGE III, CLAES, HALOE, ILAS, ISAMS, POAM, POAM II and POAM III. The majority of these instruments are limited-time research instruments without a monitoring capacity. In addition, the solar occultation instruments have a very sparse spatial measurement pattern (typically 24 observations per day), being able to measure at satellite sunrise and sunset only.

Recently launched instruments (MODIS, ASTER, AIRS and SEVIRI) offer the potential to provide volcano monitoring. SEVIRI in particular offers advantages for the European region as it is a geostationary satellite with relatively rapid temporal coverage. New spaceborne lidars are about to be launched (CALIPSO) which will be helpful in monitoring aerosols in remote areas. However, the space-time coverage (in the range of ca. 300 km every third day in lower latitudes) will not be sufficient for early warning.

5.4 IS THIS A RATIONAL SYSTEM?

There is a clear operational requirement from the perspectives of cost, accessibility and the uniqueness of measurements for spaceborne sensors to observe the hazardous phenomena of volcanoes. Of the many proposed and operational satellite instruments, many must be discounted with regards to routine volcano monitoring because they:

- Take days or even months to sample volcanic locations and could thus miss a significant volcanic event
- Are not sensitive to SO_2
- Do not have the ability to discriminate between normal water / ice clouds from freshly formed volcanic clouds

Nevertheless there is an opportunity to exploit existing instrumentation; some examples of surveillance techniques and methods to build on are as follows:

- GPS and satellite interferometric methods to observe large-scale deformation patterns and identify areas of strain localisation. The inversion of long term GPS data from a volcanic region can reveal how deformation is localising and where resumed activity is likely.
- Ground and space-based spectrometric techniques to monitor gas and ash emissions.
- Automated observation tools and tele-operated instruments for real-time and all-weather surveillance with standardised data acquisition and processing protocols to enable the linkage of networks and sensors in response to an event.
- Thermal band remote sensing of surface temperature, changes in which are related to renewed activity.
- Detailed simulations of activity, such as the behaviour of an ash plume subject to larger-scale atmospheric circulation, are feasible but must be made more efficient.

Local ground-based networks can provide rapid warning of immediate volcanic danger. However the mechanisms to deal with three major volcanic hazards have not yet been established. These are as follows:

- The threat to aircraft in remote and sparsely populated areas, e.g. the North Asia – North America flight corridor above the Aleutian Islands. The International Civil Aviation Organization (ICAO) has set up a network of Volcanic Ash Alert Centers (VAACs) to provide forecasts of ash cloud dispersion to the civil aviation industry. The European region is covered by two VAACs, run by the UK Meteorological Office (UKMO) and METEO-France in Toulouse. Currently, VAACs provide the best advisory service of remote volcanic clouds to air traffic, but improvements are needed.
- The threat to European countries from a sustained volcanic eruption such as Laki in 1753. For example in the UK, the government response to such an event would involve a number of national agencies (e.g. the UKMO, Department for Environment, Food and Rural Affairs (DEFRA), Department for Health and the Department of Transport) as well as local government civil defence. On a European level there is no strategy in place to deal with the consequences of a sustained eruption that would dramatically impact on human health, transport and food supplies.
- The climate perturbation in the years following a large volcanic eruption has not often been predicted. Prediction requires knowledge of the source strength and location of injected atmospheric trace gases, especially SO_2.
- Volcanic eruptions near inhabited areas threaten lives and result in serious socio-economic impact. Tens of thousands perished last century and the world population at risk from direct volcano hazards now exceeds five hundred million. Existing operational instrumentation has some ability to provide volcano monitoring; considering the potential risk to life and property, the current level of monitoring is inadequate.