

# **sensors: a summary characteristics from satellite remote Integrating retrievals of volcanic cloud**

W. I. Rose, G. J. S. Bluth and G. G. J. Ernst

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Integrating retrievals of volcanic<br>Integrating retrievals of volcanic<br>Ioud characteristics from satellite Integrating retrievals of volcanic<br>cloud characteristics from satellite<br>remote sensors: a summary regrating retrievals of volcanic<br>id characteristics from satellite<br>remote sensors: a summary

**remote sensors: a summary**<br>By W. I. Rose<sup>1</sup>, G. J. S. BLUTH<sup>1</sup> AND G. G. J. ERNST<sup>2</sup>

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<sup>2</sup>Department of Earth Sciences, University of Bristol,<br> *Resistol,* Res. 1PL UK (Corold J Frant@bristol, 98, wh) *Bristol, USA* (raman@mtu.edu; gbluth@mtu.edu)<br>*Pepartment of Earth Sciences, University of Bristol,*<br>*Bristol BS8 1RJ, UK* (Gerald.J.Ernst@bristol.ac.uk)

Volcanic eruptions are events that rapidly and suddenly disperse gases and fine par-Volcanic eruptions are events that rapidly and suddenly disperse gases and fine particles into the atmosphere, a process most conveniently studied from the synoptic satellite perspective where remote sensing offers a pract Volcanic eruptions are events that rapidly and suddenly disperse gases and fine particles into the atmosphere, a process most conveniently studied from the synoptic satellite perspective, where remote sensing offers a prac satellite perspective, where remote sensing offers a practical tool for spatial and temporal measurements. Meteorological satellites offer approximately 20 years of satellite perspective, where remote sensing offers a practical tool for spatial and<br>temporal measurements. Meteorological satellites offer approximately 20 years of<br>archived data, which can be analysed for measurements of temporal measurements. Meteorological satellites offer approximately 20 years of archived data, which can be analysed for measurements of masses of  $SO_2$  and fine volcanic ash in spatial two-dimensional arrays and integra archived data, which can be analysed for measurements of masses of  $SO_2$  and fine<br>volcanic ash in spatial two-dimensional arrays and integrated with other meteorolog-<br>ical data. The satellite data offer a tool to study vo volcanic ash in spatial two-dimensional arrays and integrated with other meteorological data. The satellite data offer a tool to study volcano-atmosphere interactions in a quantitative way. They provide information of uniq ical data. The satellite data offer a tool to study volcano-atmosphere interactions in<br>a quantitative way. They provide information of unique value for understanding the<br>fate and transport of fine silicates with significan a quantitative way. They provide information of unique value for understanding the fate and transport of fine silicates with significant health hazards and for addressing the problem of volcanic cloud hazards to jet aircra the problem of volcanic cloud hazards to jet aircraft. Studies of satellite data have demonstrated the following.

- emonstrated the following.<br>
(1) Volcanic clouds from convergent plate boundary volcanoes contain large and<br>
variable excesses of SO<sub>2</sub> Volcanic clouds from conversible excesses of  $SO_2$ .
- variable excesses of  $SO_2$ .<br>(2) The second day of atmospheric residence for volcanic clouds has significantly The second day of atmospheric residence for volcanic clouds has significantly higher  $SO_2$  than the first, suggesting that early volcanic  $H_2S$  may be converting to  $SO_2$ The secon<br>higher SC<br>to  $SO_2$ .
- to  $SO_2$ .<br>(3) Complete conversion of  $SO_2$  to sulphate in the stratosphere occurs at an e-Complete conversion of  $SO_2$  to sulphate in the stratosphere occurs at an e-<br>folding rate of approximately 120 days.  $SO_2$  loss from stratospheric volcanic<br>clouds occurs at an e-folding rate of approximately 35 days, and Complete conversion of  $SO_2$  to sulphate in the stratosphere occurs at an e-folding rate of approximately 120 days.  $SO_2$  loss from stratospheric volcanic clouds occurs at an e-folding rate of approximately 35 days, and t folding rate of approximately 120 days.  $SO_2$  loss from stratospheric volcanic<br>clouds occurs at an e-folding rate of approximately 35 days, and the  $SO_2$  loss<br>rate for volcanic clouds which only barely reach the stratosph clouds occurs at an e-folding rate of approximately 35 days, and the  $SO_2$  loss<br>rate for volcanic clouds which only barely reach the stratosphere is rapid (e-<br>folding only a few days). The latter limits the stratospheric rate for volcanic clouds v<br>folding only a few days).<br>from smaller eruptions.
- (4) Fine volcanic ash (with diameters of less than  $ca. 25 \mu m$ ) in drifting volcanic<br>clouds retrieved after 10 h or more appear to represent a small fraction (less Fine volcanic ash (with diameters of less than  $ca.25 \mu m$ ) in drifting volcanic clouds retrieved after 10 h or more appear to represent a small fraction (less than  $2\%$  of the total mass) of the total mass of magma erupte Fine volcanic ash (with diameters of less than  $ca.25 \,\mu\text{m}$ ) in drifting volcanic<br>clouds retrieved after 10 h or more appear to represent a small fraction (less<br>than 2% of the total mass of magma erupted, and also a sma clouds retrieved after 10 h or more appear to represent a small fraction (less<br>than 2% of the total mass) of the total mass of magma erupted, and also a small<br>fraction (less than 20%) of the total mass of fine ash erupte than  $2\%$  of the total mass) of the total mass of magma erupted, and also a small fraction (less than  $20\%$ ) of the total mass of fine ash erupted. This is probably explained by the fact that the total mass is greatly r fraction (less than  $20\%$ ) of the total mass of fine ash erupted. This is probably explained by the fact that the total mass is greatly reduced by aggregation processes within the volcanic cloud.

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- (5) The amounts of fine ash decrease faster in volcanic clouds of larger eruptions, supporting the self-removal processes suggested by Pinto *et al*. in 1989.
- supporting the self-removal processes suggested by Pinto *et al.* in 1989.<br>(6) Evidence for a strong role of ice in the fallout and aggregation of volcanic cloud ash is considerable. Evidence for a strong<br>ash is considerable.
- % ash is considerable.<br>(7) In many cases, volcanic clouds separate into higher  $SO_2$ -rich portions and lower In many cases, volcanic clouds separate into higher  $SO_2$ -rich portions and lower ash-rich portions. The two portions follow different trajectories and the lower, ash-rich portions are affected by interactions with moist In many cases, volcanic clouds separate into higher  $SO_2$ -rich portions and low ash-rich portions. The two portions follow different trajectories and the low ash-rich portions are affected by interactions with moist tropo

Keywords: volcanic ash; sulphur dioxide; ice; aggregation; fallout

# 1. Introduction

Volcanologists study active processes at the volcano and deposits of eruptions that are mostly proximal, typically within tens, and rarely as far as hundreds, of kilometres Volcanologists study active processes at the volcano and deposits of eruptions that are<br>mostly proximal, typically within tens, and rarely as far as hundreds, of kilometres<br>from the volcano. Meteorologists and atmospheric Volcanologists study active processes at the volcano and deposits of eruptions that are<br>mostly proximal, typically within tens, and rarely as far as hundreds, of kilometres<br>from the volcano. Meteorologists and atmospheric mostly proximal, typically within tens, and rarely as far as hundreds, of kilometres<br>from the volcano. Meteorologists and atmospheric physicists and chemists study<br>clouds and cloud processes on scales ranging from microsco from the volcano. Meteorologists and atmospheric physicists and chemists study clouds and cloud processes on scales ranging from microscopic to global. This is a paper about volcanic clouds, a study that draws from both of clouds and cloud processes on scales ranging from microscopic to global. This is<br>a paper about volcanic clouds, a study that draws from both of these groups of<br>scientists. The paper aims to integrate satellite remote sensi a paper about volcanic clouds, a study that draws from both of these groups of scientists. The paper aims to integrate satellite remote sensing measurements on volcanic clouds and to explain some of the main scientific res scientists. The pap<br>volcanic clouds and<br>obtained to date.<br>Clouds are suspe clouds and to explain some of the main scientific results that have been<br>tained to date.<br>Clouds are suspensions of particles in the atmosphere. Meteorological clouds con-<br>in particles that are mainly liquid or solid  $H_2O$ 

obtained to date.<br>Clouds are suspensions of particles in the atmosphere. Meteorological clouds contain particles that are mainly liquid or solid  $H_2O$  (hydrometeors), which are smaller than  $ca$  100 um in diameter and tha Clouds are suspensions of particles in the atmosphere. Meteorological clouds con-<br>tain particles that are mainly liquid or solid  $H_2O$  (hydrometeors), which are smaller<br>than *ca*. 100  $\mu$ m in diameter and that fall thro tain particles that are mainly liquid or solid  $H_2O$  (hydrometeors), which are smaller<br>than *ca*. 100  $\mu$ m in diameter and that fall through the atmosphere in a laminar regime<br>at velocities of less than *ca*. 0.1 m s<sup>-1</sup> than ca. 100  $\mu$ m in diameter and that fall through the atmosphere in a laminar regime<br>at velocities of less than ca. 0.1 m s<sup>-1</sup>. Larger meteorological particles fall much faster,<br>in the turbulent regime, and are called at velocities of less than  $ca.0.1 \text{ m s}^{-1}$ . Larger meteorological particles fall much faster,<br>in the turbulent regime, and are called precipitation (Rogers & Yau 1989; Houze<br>1993). Because of the slow fall speeds of thei in the turbulent regime, and are called precipitation (Rogers  $\&$  Yau 1989; Houze 1993). Because of the slow fall speeds of their particles, clouds can persist in the atmosphere for periods of hours to weeks or longer, a

**IATHEMATICAL,<br>HYSICAL<br>< ENGINEERING<br>CIENCES** atmosphere for periods of hours to weeks or longer, although they are often dynamic.<br>Volcanic clouds are much rarer features than meteorological clouds. They are initiated by explosive eruptions that release volcanic gases Volcanic clouds are much rarer features than meteorological clouds. They are initiated by explosive eruptions that release volcanic gases and hot silicate fragments called pyroclasts and form vertical buoyant columns or pl Volcanic clouds are much rarer features than meteorological clouds. They are initiated by explosive eruptions that release volcanic gases and hot silicate fragments<br>called pyroclasts and form vertical buoyant columns or plumes that rise to heights of<br>up to 50 km as heat is transferred from the hot py called pyroclasts and form vertical buoyant columns or plumes that rise to heights of<br>up to 50 km as heat is transferred from the hot pyroclasts to entrained air from the<br>surrounding atmosphere (Sparks *et al.* 1997; Gilbe up to 50 km as heat is transferred from the hot pyroclasts to entrained air from the<br>surrounding atmosphere (Sparks *et al.* 1997; Gilbert & Sparks 1998). Large amounts<br>of lower tropospheric air are entrained in these plu surrounding atmosphere (Sparks *et al.* 1997; Gilbert & Sparks 1998). Large amounts of lower tropospheric air are entrained in these plumes (Woods 1993; Glaze & Baloga 1996; Glaze *et al.* 1997), and this air typically con of lower tropospheric air are entrained in these plumes (Woods 1993; Glaze & Baloga 1996; Glaze *et al.* 1997), and this air typically contains water vapour, which saturates the rising air as it rises and condenses, formi 1996; Glaze *et al.* 1997), and this air typically contains water vapour, which satu-<br>rates the rising air as it rises and condenses, forming hydrometeors. Large pyroclasts<br>fall out of the eruption column margins quickly rates the rising air as it rises and condenses, forming hydrometeors. Large pyroclasts<br>fall out of the eruption column margins quickly (Ernst *et al.* 1996): lapilli (pyro-<br>clasts greater than 2 mm in diameter) fall back fall out of the eruption column margins quickly (Ernst *et al.* 1996): lapilli (pyro-<br>clasts greater than 2 mm in diameter) fall back to Earth within less than *ca*. 30 min<br>(Walker *et al.* 1971; Wilson & Huang 1979; Lane clasts greater than 2 mm in diameter) fall back to Earth within less than *ca*. 30 min (Walker *et al.* 1971; Wilson & Huang 1979; Lane *et al.* 1993). Ash (pyroclasts less than 2 mm in diameter) particles fall out more s (Walker *et al.* 1971; Wilson & Huang 1979; Lane *et al.* 1993). Ash (pyroclasts less than 2 mm in diameter) particles fall out more slowly, and fine ash (less than 50  $\mu$ m in diameter) falls out in the laminar flow regi than 2 mm in diameter) particles fall out more slowly, and fine ash (less than 50  $\mu$ m<br>in diameter) falls out in the laminar flow regime (Rose 1993; Bonadonna *et al.* 1998)<br>at slow velocities like the particles in meteo in diameter) falls out in the laminar flow regime (Rose 1993; Bonadonna *et al.* 1998) at slow velocities like the particles in meteorological clouds. So, like meteorological clouds, volcanic clouds can persist in the atm at slow velocities like the particles in meteorological clouds. So, like meteorological<br>clouds, volcanic clouds can persist in the atmosphere for days to weeks or longer.<br>Typically, they detach from plumes before or after clouds, volcanic clouds can persist in the atmosphere for days to weeks or Typically, they detach from plumes before or after the eruption stops and response to the three-dimensional wind patterns (Servranckx *et al.* 1999 response to the three-dimensional wind patterns (Servranckx *et al.* 1999).<br>*Phil. Trans. R. Soc. Lond.* A (2000)



Table 1. *Direct sampling studies of small particles in volcanic clouds*

1. Cadle *et al*. (1979); 2. Lazrus *et al*. (1979); 3. Rose *et al*. (1980); 4. Rose *et al*. (1982); 5. Casadevall *et al*. (1984); 6. Woods *et al*. (1985); 7. Chuan *et al*. (1986); 8. Rose *et al*. (1986); 1. Cadle *et al.* (1979);<br>5. Casadevall *et al.* (19<br>9. Rose *et al.* (1988).

# 2. What volcanic clouds are made of

Volcanic clouds contain a variety of components including

- Solemic clouds contain a variety of components including<br>
(1) volcanogenic products from the eruption, i.e. volcanic gases, pyroclasts and<br>
aerosol particles derived from reactions of volcanogenic and atmospheric mate-Inc cious contain a variety of components including<br>volcanogenic products from the eruption, i.e. volcanic gases, pyroclasts and<br>aerosol particles derived from reactions of volcanogenic and atmospheric mate-<br>rials: and volcanogenic<br>aerosol partic<br>rials; and % aerosol particles derived from reactions of volcanogenic and atmospheric mate-<br>rials; and<br>(2) products from the ambient atmosphere, such as  $H_2O$  and gaseous species and
- rials; and<br>products from the ambient atmosphere, such as  $H_2O$  and gaseous species and<br>various particles from the land and sea, including wind-blown silicates, sea salt<br>and others. products from<br>various partic<br>and others.<br>releasescanie s

various particles from the land and sea, including wind-blown silicates, sea salt<br>and others.<br>The volcanogenic components make the clouds distinctive, and they can be tracked<br>by satellite sensors for periods that range fro and others.<br>The volcanogenic components make the clouds distinctive, and they can be tracked<br>by satellite sensors for periods that range from minutes to weeks (Bluth *et al.* 1997;<br>Schneider *et al.* 1995). During this tim **MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** The volcanogenic components make the clouds distinctive, and they can be tracked<br>by satellite sensors for periods that range from minutes to weeks (Bluth *et al.* 1997;<br>Schneider *et al.* 1995). During this time, the volca by satellite sensors for periods that range from minutes to weeks (Bluth *et al.* 1997; Schneider *et al.* 1995). During this time, the volcanogenic particles mix and interact with meteorological and hydrospheric particle

Volcanogenic particles in volcanic clouds consist of ne pyroclasts, salts and acids in aerosol form. Direct sampling of volcanogenic particles has been accomplished by Volcanogenic particles in volcanic clouds consist of fine pyroclasts, salts and acids<br>in aerosol form. Direct sampling of volcanogenic particles has been accomplished by<br>balloon studies (see, for example, Rietmeijer 1993) in aerosol form. Direct sampling of volcanogenic particles has been accomplished by<br>balloon studies (see, for example, Rietmeijer 1993) and a variety of research aircraft.<br>Volcanogenic particles in volcanic clouds have bee balloon studies (see, for example, Rietmeijer 1993) and a variety of research aircraft.<br>Volcanogenic particles in volcanic clouds have been examined in a number of studies<br>(table 1) where a research aircraft with a particl Volcanogenic particles in volcanic clouds have been examined in a number of studies (table 1) where a research aircraft with a particle-collection system was flown through  $\rightarrow$  the clouds. Because of safety, only plumes a (table 1) where a research aircraft with a particle-collection system was flown t<br>the clouds. Because of safety, only plumes and relatively small volcanic cloud<br>been directly sampled in this way. The particles consist of

1. *Silicate pyroclasts representing fragments of the magma*. These are glassy pyro-<br>1. *Silicate pyroclasts representing fragments of the magma*. These are glassy pyro-<br>clasts and minerals, which represent the crystalline  $\bigcup$  1. Silicate pyroclasts representing fragments of the magma. These are glassy pyro-<br>Clasts and minerals, which represent the crystalline fraction of the magma. Their 1. Silicate pyroclasts representing fragments of the magma. These are glassy pyroclasts and minerals, which represent the crystalline fraction of the magma. Their shape is angular, and basaltic and andesitic eruptions giv clasts and minerals, which represent the crystalline fraction of the magma. Their<br>shape is angular, and basaltic and andesitic eruptions give rise to particles that<br>have moderate aspect ratios (Riley *et al.* 1999), while shape is angular, and basaltic and andesitic eruptions give rise to particles that<br>have moderate aspect ratios (Riley *et al.* 1999), while rhyolitic eruptions can gen-<br>erate an abundance of glassy pyroclasts with a platy have moderate aspect ratios (Riley *et al.* 1999), while rhyolitic eruptions can generate an abundance of glassy pyroclasts with a platy geometry and extreme aspect ratios (Rose  $\&$  Chesner 1987). The diameters of silica erate an abundance of glassy pyroclasts with a platy geometry and extreme aspect<br>ratios (Rose & Chesner 1987). The diameters of silicate pyroclasts generated during<br>explosive eruptions range from metres to micrometres. Th ratios (Rose & Chesner 1987). The diameters of silicate pyroclasts generated during<br>explosive eruptions range from metres to micrometres. Those in volcanic clouds are<br>smaller, generally less than  $ca$  50  $\mu$ m. The mass pr explosive eruptions range from metres to micrometres. Those in<br>smaller, generally less than *ca*. 50 µm. The mass proportions of si<br>diameters less than *ca*. 1 µm are very small (Rose *et al*. 1980). diameters less than  $ca.1 \mu m$  are very small (Rose *et al.* 1980).<br>*Phil. Trans. R. Soc. Lond.* A (2000)



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| sensor         | TOMS            | <b>AVHRR</b>               | <b>GOES</b>                |
|----------------|-----------------|----------------------------|----------------------------|
| wavelengths    | $312 - 380$ nm  | $10-12.5 \,\mathrm{\mu m}$ | $10-12.5 \,\mathrm{\mu m}$ |
| orbit          | polar           | polar                      | geostationary              |
| sensing target | ash, $SO2$      | ash                        | ash                        |
| archive        | $1979$ -present | $1981$ -present            | $1996$ -present            |
| scenes per day |                 | $4 - 8$                    | 48                         |

Table 2. *Sources of data for remote sensing retrievals used in the study of volcanic clouds*

scenes per day and the section of the sections of the constituents of the sections among the constituents of the secondary of the sections among the constituents of the secondary of the secondary  $\frac{1}{2}$  and  $\frac{1}{2}$  an 2. Non-silicate particles that are related to reactions among the constituents of the volcanic gases. These particles are generally smaller than the silicates, usually less than 1 um in diameter. The most common compositio 2. Non-silicate particles that are related to reactions among the constituents of the volcanic gases. These particles are generally smaller than the silicates, usually less than 1  $\mu$ m in diameter. The most common compos  $\Gamma$  volcanic gases. These particles are generally smaller than the silicates, usually less<br>is than  $1 \mu$ m in diameter. The most common composition for these is sulphate, especially  $H_2SO_4$ , which forms as submicrometre than  $1 \mu$ m in diameter. The most common composition for these is sulphate, especially  $H_2SO_4$ , which forms as submicrometre spherical droplets that also contain  $H_2O$  (typically *ca*. 25% by volume; see Zhao *et al.* ( cially  $\text{H}_2\text{SO}_4$ , which forms as submicrometre spherical droplets that also contain  $\text{H}_2\text{O}$  (typically *ca*. 25% by volume; see Zhao *et al.* (1995)). A total of at least 28 different phases have also been obse  $H_2O$  (typically *ca.* 25% by volume; see Zhao *et al.* (1995)). A total of at least 28 different phases have also been observed (see table 3 in Rose *et al.* (1982) for a partial list) including native sulphur, sulphate ferent phases have also been observed (see table 3 in Rose *et al.* (1982) for a partial list) including native sulphur, sulphates, haloids, metallic oxides, and such exotic species as silver sulphide and even native gold list) including native sulphur, sulphates, haloids, metallic oxides, and such exotic<br>species as silver sulphide and even native gold (Meeker *et al.* 1991). Overall, the<br>analogy between the observed phases and fumarolic i species as silver sulphide and even native gold (Meeker *et al.* 1991). Overall, the analogy between the observed phases and fumarolic incrustations and sublimates at gas vents (Stoiber & Rose 1974; Bernard 1985; Symonds  $\frac{1}{\alpha}$ analogy between the observed phases and fumarolic incrustations and sublimates at gas vents (Stoiber & Rose 1974; Bernard 1985; Symonds *et al.* 1987) suggests that these phases originate from reactions among the volcanic gas vents (Stoiber & Rose 1974; Bernar<br>these phases originate from reactions and<br>the atmosphere and volcanic silicates. the atmosphere and volcanic silicates.<br>Besides these two broad types, a wide variety of other, unexplained materials has

besides these two broad types, a wide variety of other, unexplained materials has<br>been observed in volcanic clouds. They largely consist of phases that are amorphous<br>and have uncertain compositions (Chuan *et al.* 1987). Besides these two broad types, a wide variety of other, unexplained materials has<br>been observed in volcanic clouds. They largely consist of phases that are amorphous<br>and have uncertain compositions (Chuan *et al.* 1987). M been observed in volcanic clouds. They largely consist of phases that are amorphous<br>and have uncertain compositions (Chuan *et al.* 1987). Many or most of these particles<br>are likely to be non-volcanic in origin, and repres and have uncertain compositions (Chuan *et al.* 1987). Many or most of these particles are likely to be non-volcanic in origin, and represent accidental material of surficial or extraterrestrial origin.

Direct sampling and analysis of gases in volcanic clouds has been done only rarely or extraterrestrial origin.<br>Direct sampling and analysis of gases in volcanic clouds has been done only rarely<br>(see, for example, Cadle *et al.* 1979), although analysis of  $CO_2$  has been done much<br>more extensively during Direct sampling and analysis of gases in volcanic clouds has been done only rarely (see, for example, Cadle *et al.* 1979), although analysis of  $CO_2$  has been done much more extensively during  $CO_2$  flux-determination su (see, for example, Cadle *et al.* 1979), although analysis of  $CO_2$  has been done much more extensively during  $CO_2$  flux-determination surveys (Harris *et al.* 1981; Gerlach *et al.* 1999). Other information about gases more extensively during  $CO_2$  flux-determination surveys (Harris *et al.* 1981; Gerlach *et al.* 1999). Other information about gases has been collected from extensive airborne remote sensing of volcanic plumes using the lach *et al.* 1999). Other information about gases has been collected from extensive airborne remote sensing of volcanic plumes using the correlation spectrometer (COSPEC) instrument. These results show that the volcanic g sive airborne remote sensing of volcanic plumes using the correlation spectrometer (COSPEC) instrument. These results show that the volcanic gases in volcanic clouds are mixed and highly diluted by the ambient atmosphere, (COSPEC) instrument. These results show that the volcanic gases<br>are mixed and highly diluted by the ambient atmosphere, and the<br>volcanic  $SO_2$  and  $CO_2$  are less than a few ppmv (McGee 1992). volcanic  $SO_2$  and  $CO_2$  are less than a few ppmv (McGee 1992).<br>3. Methods of studying volcanic clouds

3. Methods of studying volcanic clouds<br>During the late 1970s and 1980s, a number of studies of volcanic clouds were made<br>using direct sampling methods (table 1). These gave us direct data about the particles During the late 1970s and 1980s, a number of studies of volcanic clouds were made<br>using direct sampling methods (table 1). These gave us direct data about the particles<br>and gases. During this time recognition of the hazard During the late 1970s and 1980s, a number of studies of volcanic clouds were made<br>using direct sampling methods (table 1). These gave us direct data about the particles<br>and gases. During this time recognition of the hazar using direct sampling methods (table 1). These gave us direct data about the particles and gases. During this time recognition of the hazards to aircraft from volcanic cloud particles widened (Rose 1986; Bernard  $\&$  Rose and gases. During this time recognition of the hazards to aircraft from volcanic cloud particles widened (Rose 1986; Bernard  $\&$  Rose 1990), and remote sensing methods advanced. Sampling volcanic clouds directly with an instrumented aircraft is impractical because it involves risk to aircraft and because s tical because it involves risk to aircraft and because such aircraft are highly scheduled tical because it involves risk to aircraft and because such aircraft are highly scheduled<br>for research purposes and cannot be conveniently refitted and reprogrammed for rare,<br>ephemeral events like volcanic clouds (Riehle for research purposes and cannot be conveniently refitted and reprogrammed for rare,<br>ephemeral events like volcanic clouds (Riehle *et al.* 1994). Remote sensing has devel-<br>oped into a very convenient study tool, because oped into a very convenient study tool, because satellites designed to monitor and measure weather phenomena and global atmospheric change have the capability to

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optical depth (IR);<br>particle radius,<br>particle mass particle radius,

| <i>Volcanic cloud characteristics</i><br>Table 3. Data retrieved from volcanic-cloud satellite sensors, 1999 |  |                    |                                |  |  |  |  |
|--|--|--------------------|--------------------------------|--|--|--|--|
|  |  |                    |                                |  |  |  |  |
| TOMS   | $SO2$ mass                                 | $40 \mathrm{km}$   | Krueger <i>et al.</i> $(1995)$ |  |  |  |  |
| TOMS AI  | optical depth (UV)                         | $40 \mathrm{km}$   | Krotkov <i>et al.</i> $(1999)$ |  |  |  |  |
| AVHRR and GOES   | optical depth $(IR)$ ;<br>particle radius. | $ca.4 \mathrm{km}$ | Wen $& Rose(1994)$             |  |  |  |  |

<sup>a</sup> In addition to two-dimensional position data.<br><sup>b</sup> Sensor dependent Nimbus = 50 km.

map and measure many features of volcanic clouds, and have a very valuable synopthe perspective. Repetitive geometric visual observations of eruption clouds using the geostationary GOES (Sarna-Woicicki *et al.* 1981; Holasek  $k$  Self 1995) and the GMS map and measure many features of volcanic clouds, and have a very valuable synoptic perspective. Repetitive geometric visual observations of eruption clouds using the geostationary GOES (Sarna-Wojcicki *et al.* 1981; Holas tic perspective. Repetitive geometric visual observations of eruption clouds using the geostationary GOES (Sarna-Wojcicki *et al.* 1981; Holasek & Self 1995) and the GMS meteorological satellite (Sawada 1987; Holasek *et a* geostationary GOES (Sarna-Wojcicki *et al.* 1981; Holasek & Self 1995) and the GMS<br>meteorological satellite (Sawada 1987; Holasek *et al.* 1996) have shown that satellites<br>can map volcanic clouds of a wide variety of scale meteorological satellite (Sawada 1987; Holasek *et al.* 1996) have shown that satellites can map volcanic clouds of a wide variety of scales in two dimensions. This paper focuses on quantitative data retrieved from satell can map volcanic clouds of a wide variety of scales in two dimensions. This paper<br>focuses on quantitative data retrieved from satellites concerning burdens of particles<br>and  $SO_2$  and sizes of particles and integrating suc focuses on quantitative data retrieved from satellites concerning burdens of particles and  $SO_2$  and sizes of particles and integrating such data with cloud mapping. The main sources of retrieval data we have used to stud and  $SO_2$ <br>main sou:<br>table 2.<br>These main sources of retrieval data we have used to study volcanic clouds are listed in table 2.<br>These sensors have been capable of volcanic-cloud sensing for variable periods:

table 2.<br>These sensors have been capable of volcanic-cloud sensing for variable periods:<br>TOMS, 1979 to present; AVHRR, 1981 to present; GOES, 1996 to present (actually<br>GOES has been operating for much longer but only since These sensors have been capable of volcanic-cloud sensing for variable periods:<br>TOMS, 1979 to present; AVHRR, 1981 to present; GOES, 1996 to present (actually<br>GOES has been operating for much longer, but only since 1996 ha TOMS, 1979 to present; AVHRR, 1981 to present; GOES, 1996 to present (actually GOES has been operating for much longer, but only since 1996 has it used two thermal infrared (IR) bands, which allow retrievals). The result i GOES has been operating for much longer, but only since 1996 has it used two<br>thermal infrared (IR) bands, which allow retrievals). The result is that we have a<br>substantial archive of volcanic cloud data, and this archive h thermal infrared (IR) bands, which allow retrievals). The result is that we have a substantial archive of volcanic cloud data, and this archive has been used to improve our capability of sensing and measuring volcanic clou substantial archive of volcanic cloud data, and this archive has been used to improve our capability of sensing and measuring volcanic clouds. The sensors collect from<br>1 to 48 datasets for any existing volcanic clouds each day. Because of their much<br>higher frequency of data collection, the geostationary to 1 to 48 datasets for any existing volcanic clouds each day. Because of their much<br>higher frequency of data collection, the geostationary tools (currently only GOES)<br>are most useful (Rose & Schneider 1996; Davies & Rose 199 higher frequency of data collection, the geostationary tools (currently only GOES)<br>are most useful (Rose & Schneider 1996; Davies & Rose 1998). Unfortunately, only<br>relatively small eruptions have been sensed by GOES, which are most useful (Rose & Schneider 1996; Davies & Rose 1998). Unfortunately, only relatively small eruptions have been sensed by GOES, which has been in operation for only a few years. Also, NOAA has decided to suspend the relatively small eruptions have been sensed by GOES, which has been in operation<br>for only a few years. Also, NOAA has decided to suspend the two-band IR sensing<br>on future GOES satellites, which means that the volcanic clou for only a few years. Also, NOAA has decided to suspend the two-band IR sensing<br>on future GOES satellites, which means that the volcanic cloud-sensing option will<br>be diminished on GOES after 2002. Fortunately, new generati on future GOES satellites, which means that the volcanic cloud-sensing option will<br>be diminished on GOES after 2002. Fortunately, new generations of GMS, which is<br>a geostationary satellite covering the Western Pacific, wil be diminished on GOES after 2002. Fortunately, new generations of GMS, which is<br>a geostationary satellite covering the Western Pacific, will have excellent two-band<br>IR coverage of Earth's most volcanically active areas.<br>Th

geostationary satellite covering the Western Pacific, will have excellent two-band<br>coverage of Earth's most volcanically active areas.<br>The current capability for volcanic-cloud sensing can be expressed in terms of the<br>pori IR coverage of Earth's most volcanic-cloud sensing can be expressed in terms of the<br>algorithm retrievals from the above sensors (table 3). Volcanic clouds can be mapped<br>in two dimensions based on both  $SO_2$  and silicate p The current capability for volcanic-cloud sensing can be expressed in terms of the algorithm retrievals from the above sensors (table 3). Volcanic clouds can be mapped in two dimensions, based on both  $SO_2$  and silicate p algorithm retrievals from the above sensors (table 3). Volcanic clouds can be mapped<br>in two dimensions, based on both  $SO_2$  and silicate particles. The masses of  $SO_2$  and<br>fine silicates (1–12 µm radius) can be estimated. in two dimensions, based on both  $SO_2$  and silicate particles. The masses of  $SO_2$  and fine silicates (1–12  $\mu$ m radius) can be estimated. The optical depth of the volcanic cloud at  $10 \mu m$  and the effective radius of silicate particles is also retrievable.<br>4. Scientific results of volcanic-cloud studies

 $(a) SO<sub>2</sub> results$ 

(i) *Excess sulphur from convergent plate boundary volcanoes*

(i) Excess sulphur from convergent plate boundary volcanoes<br>Compilations of results of the mass retrievals of  $SO_2$  (from the TOMS instrument<br>algorithms) in volcanic clouds since 1979 were published by Bluth *et al.* (199 (1) *Excess suppur from convergent plate boundary volcanoes*<br>Compilations of results of the mass retrievals of  $SO_2$  (from the TOMS instrument<br>algorithms) in volcanic clouds since 1979 were published by Bluth *et al.* (19 algorithms) in volcanic clouds since 1979 were published by Bluth *et al.* (1993, 1997).<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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**PHILOSOPHICAL**<br>TRANSACTIONS Ğ

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** 

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**PHILOSOPHICAL**<br>TRANSACTIONS



eruption date  $SO_2 \text{ MT}^a$  magma MT wt% S S, melt (wt%)<br>
St Helens May 1980 1 312<sup>c</sup> 0.2 0.0068<br>
El Chichón May 1982 7 338<sup>d</sup> 1.1 0.02 El Chichón May 1980 1 312° 0.2 0.0068<br>
El Chichón May 1982 7 338<sup>d</sup> 1.1 0.02<br>
Ruiz November 1985 0.66 15<sup>e</sup> 2.2 0.000–0.0° 81 Helens May 1980 1 312 0.2 0.0008<br>
El Chichón May 1982 7 338<sup>d</sup> 1.1 0.02<br>
Ruiz November 1985 0.66 15<sup>e</sup> 2.2 0.009-0.07<br>
Pinatubo Iune 1991 20 9600–13.800<sup>f</sup> 0.08–0.1 0.0075

eruption date SO<sub>2</sub> MT<sup>a</sup> magma MT wt% S S, melt (wt%)<sup>b</sup>

equivalent

El Chichon May 1982<br>
Ruiz November 1985 0.66 15<sup>e</sup> 2.2 0.009-0.07<br>
Pinatubo June 1991 20 9600-13 800<sup>f</sup> 0.08-0.1 0.0075 Pinatubo June 1991 20 9600–13 800<sup>f</sup> 0.08–0.1 0.0075<br>
<sup>a</sup>Bluth *et al.* (1992, 1997); <sup>b</sup> Scaillet *et al.* (1998); <sup>c</sup> Sarna-Wojcicki *et al.* (1981); <sup>d</sup> Varekamp *et*<br> *al.* (1984): <sup>e</sup> Naranio *et al.* (1986); <sup>f</sup> Scot <sup>a</sup> Bluth *et al.* (1992, 1997); <sup>b</sup> Scaillet *et al.* (1998); <sup>c</sup> Sarna *al.* (1984); <sup>e</sup> Naranjo *et al.* (1986); <sup>f</sup> Scott *et al.* (1996).

al. (1984); <sup>e</sup>Naranjo *et al.* (1986); <sup>f</sup>Scott *et al.* (1996).<br>These results show that non-arc eruptions release higher  $SO_2$  masses than arc erup-These results show that non-arc eruptions release higher  $SO_2$  masses than arc eruptions of the same volume, a result largely explained by the higher sulphur content of more primitive basaltic non-arc magmas (Devine *et a* These results show that non-arc eruptions release higher  $SO_2$  masses than arc eruptions of the same volume, a result largely explained by the higher sulphur content of more primitive basaltic non-arc magmas (Devine *et a* tions of the same volume, a result largely explained by the higher sulphur content of more primitive basaltic non-arc magmas (Devine *et al.* 1984). They also consistently demonstrate (see, for example, Gerlach *et al.* 1 more primitive basaltic non-arc magmas (Devine *et al.* 1984). They also consistently<br>demonstrate (see, for example, Gerlach *et al.* 1996) that convergent plate boundary<br>volcanoes (CPBVs) release 1 to 2 orders of magnitu volcanoes (CPBVs) release 1 to 2 orders of magnitude more  $SO_2$  in eruptions than petrologists estimate from the volume of erupted magma and from melt-inclusion volcanoes (CPBVs) release 1 to 2 orders of magnitude more  $SO_2$  in eruptions than<br>petrologists estimate from the volume of erupted magma and from melt-inclusion<br>analyses (Palais & Sigurdsson 1989), which are thought to re petrologists estimate from the volume of erupted magma and from melt-inclusion<br>analyses (Palais & Sigurdsson 1989), which are thought to reflect the pre-eruption<br>magma content of sulphur. This 'excess emission' of sulphur analyses (Palais & Sigurdsson 1989), which are thought to reflect the pre-eruption<br>magma content of sulphur. This 'excess emission' of sulphur is also observed from<br>ground-based remote sensing (COSPEC) measurements during magma content of sulphur. This 'excess emission' of sulphur is also observed from<br>ground-based remote sensing (COSPEC) measurements during open-vent activity at<br>CPBVs (Casadevall *et al.* 1981; Andres *et al.* 1991). Recog ground-based remote sensing (COSPEC) measurements during open-vent activity at CPBVs (Casadevall *et al.* 1981; Andres *et al.* 1991). Recognition of excess sulphur CPBVs (Casadevall *et al.* 1981; Andres *et al.* 1991). Recognition of excess sulphur<br>from CPBVs has led to a re-evaluation of our understanding of where sulphur resides<br>before eruption. The advocacy of a separate  $SO_2$ -r from CPBVs has led to a re-evaluation of our understanding of where sulphur resides<br>before eruption. The advocacy of a separate  $SO_2$ -rich gas phase that coexists with<br>magma (in exsolution before eruption) has gained a co before eruption. The advocacy of a separate  $SO_2$ -rich gas phase that coexists with magma (in exsolution before eruption) has gained a consensus (Gerlach *et al.* 1996). This excess of sulphur has not been found in volcan sources (Andres *et al*. 1989), where the sulphur emission rates can be related simply This excess of sulphur has not been found in volcanoes from divergent or hot-spot<br>sources (Andres *et al.* 1989), where the sulphur emission rates can be related simply<br>to magma extrusion rates without an excess. S (and C sources (Andres *et al.* 1989), where the sulphur emission rates can be related simply<br>to magma extrusion rates without an excess. S (and Cl) in CPBVs probably has its<br>source in subducted slab sediments (Anderson 1974) and to magma extrusion rates without an excess. S (and Cl) in CPBVs probably has its<br>source in subducted slab sediments (Anderson 1974) and is perhaps supplied in excess<br>at andesitic and dacitic CPBVs through magma mixing or i source in subducted slab sediments (Anderson 1974) and is perhaps supplied in excess<br>at andesitic and dacitic CPBVs through magma mixing or incipient magma mixing.<br>Petrological evidence for magma mixing in andesitic volca at andesitic and dacitic CPBVs through magma mixing or incipient magma mixing.<br>Petrological evidence for magma mixing in andesitic volcanoes is abundant (see, for<br>example, Eichelberger 1975; Halsor & Rose 1991). Even when Petrological evidence for magma mixing in andesitic volcanoes is abundant (see, for example, Eichelberger 1975; Halsor & Rose 1991). Even when such evidence is not obvious, there may be evidence for a basaltic heat source example, Eichelberger 1975; Halsor & Rose 1991). Even when such evidence is not obvious, there may be evidence for a basaltic heat source transmitted to andesite, which could also supply excess gas (Murphy *et al.* 1999; B obvious, there may be evidence for a basaltic heat source transmitted to andesite, which could also supply excess gas (Murphy *et al.* 1999; Barclay *et al.* 1998). One important issue about excess sulphur releases is tha which could also supply excess gas (Murphy *et al.* 1999; Barclay *et al.* 1998). One<br>important issue about excess sulphur releases is that they are highly variable, and<br>they all represent proportional concentrations of m important issue about excess sulphur releases is that they are highly variable, and<br>they all represent proportional concentrations of magnatic sulphur (see column 4<br>in table 4) that are much higher (1-3 orders of magnitud they all represent proportional concentrations of<br>in table 4) that are much higher (1–3 orders of ma<br>from petrological data (see column 5 in table 4).<br>The 1982 El Chichón eruption released seven ti table 4) that are much higher (1–3 orders of magnitude) than would be expected<br>om petrological data (see column 5 in table 4).<br>The 1982 El Chichón eruption released seven times more sulphur than the 1980<br>t. St. Helens eve

from petrological data (see column 5 in table 4).<br>The 1982 El Chichón eruption released seven times more sulphur than the 1980<br>Mt St Helens event (Bluth *et al.* 1997), although its eruption volume was only<br>slightly  $(ca,$ The 1982 El Chichón eruption released seven times more sulphur than the 1980<br>Mt St Helens event (Bluth *et al.* 1997), although its eruption volume was only<br>slightly  $(ca. 10-20\%)$  higher. El Chichón released  $ca. 35\%$  as m Mt St Helens event (Bluth *et al.* 1997), although its eruption volume was only slightly  $(ca. 10-20\%)$  higher. El Chichón released  $ca. 35\%$  as much sulphur as did the Pinatubo 1991 release, although Pinatubo was an order slightly  $(ca. 10-20\%)$  higher. El Chichón released  $ca. 35\%$  as much sulphur as did<br>the Pinatubo 1991 release, although Pinatubo was an order of magnitude or more<br>greater in magma volume (Scott *et al.* 1996). The variabil the Pinatubo 1991 release, although Pinatubo was an order of magnitude or more greater in magma volume (Scott *et al.* 1996). The variability of excess sulphur has<br>been shown by Scaillet *et al.* (1998) to be associated with redox controls, wherein<br>reduced magmas with sulphides do not release large reduced magmas with sulphides do not release large sulphur excesses. Excess volreduced magmas with sulphides do not release large sulphur excesses. Excess volcanic gas information is related to volatile saturation and its significance remains undigested in our consideration of how volcanoes work, bec canic gas information is related to volatile saturation and its significance remains undigested in our consideration of how volcanoes work, because how these excesses affect the nature of eruptions has not been explored. I affect the nature of eruptions has not been explored. If excess gas information can<br>*Phil. Trans. R. Soc. Lond.* A (2000)



Figure 1. Masses of SO<sub>2</sub> in the 1992 Spurr eruptions (from Bluth *et al.* 1995). Plot resembles<br>the trends shown for other eruptions with SO<sub>2</sub> showing a mass increase in the second day (see Figure 1. Masses of  $SO_2$  in the 1992 Spurr eruptions (from Bluth *et al.* 1995). Plot resembles<br>the trends shown for other eruptions, with  $SO_2$  showing a mass increase in the second day (see<br>text for discussion) the trends shown for other eruptions, with  $SO_2$  showing a mass increase in the second day (see text for discussion).

be understood, it offers a potential window into processes that happen in convergent plate boundary magma bodies (see, for example, Harris & Rose 1996).

### (ii) *Possible co-emission of*  $H_2S$  *and*  $SO_2$  *in explosive eruptions*

TOMS measurements are made only once a day, but most of the eruptions studied TOMS measurements are made only once a day, but most of the eruptions studied<br>show higher  $SO_2$  on the second day than they do on the first (Bluth *et al.* (1995);<br>and see also figure 1). In the Hudson eruption of 15 Augu show higher  $SO_2$  on the second day than they do on the first (Bluth *et al.* (1995);<br>and see also figure 1). In the Hudson eruption of 15 August 1991, studied in detail<br>by Constantine *et al.* (2000), the second day  $SO_2$ show higher  $SO_2$  on the second day than they do on the first (Bluth *et al.* (1995); and see also figure 1). In the Hudson eruption of 15 August 1991, studied in detail<br>by Constantine *et al.* (2000), the second day  $SO_2$  mass was three times larger than<br>the first. This difference cannot be explained by t the first. This difference cannot be explained by the continuing emission of  $SO_2$ , because the first day's measurement occurred after the end of the eruption. It is unlikely to reflect an error in TOMS data analysis (Kru ICAL<br>GINEERING<br>ICES because the first day's measurement occurred after the end of the eruption. It is unlikely to reflect an error in TOMS data analysis (Krueger *et al.* 1995), which would be far less than the observed difference. It is unl unlikely to reflect an error in TOMS data analysis (Krueger *et al.* 1995), which would be far less than the observed difference. It is unlikely that the TOMS detector was saturated or suppressed by an interference from v would be far less than the observed difference. It is unlikely that the TOMS detector<br>was saturated or suppressed by an interference from volcanic ash in the  $SO_2$  signal,<br>because simulations of this effect would probably was saturated or suppressed by an interference from volcanic ash in the  $SO_2$  signal,<br>because simulations of this effect would probably result in an overestimate on the first<br>day rather than an underestimate (Krueger *et* because simulations of this effect would probably result in an overestimate on the first<br>day rather than an underestimate (Krueger *et al.* 1995). The favoured explanation<br>is that the mass increase appears to be the co-em day rather than an underestimate (Krueger *et al.* 1995). The favoured explanation<br>is that the mass increase appears to be the co-emission and subsequent oxidation<br>of H<sub>2</sub>S. This possibility has been suggested by Bluth *et* is that the mass increase appears to be the co-emission and subsequent oxidation<br>of H<sub>2</sub>S. This possibility has been suggested by Bluth *et al.* (1995), although the<br>nature of the TOMS data left much uncertainty. The conv of H<sub>2</sub>S. This possibility has been suggested by Bluth *et al.* (1995), although the nature of the TOMS data left much uncertainty. The conversion of H<sub>2</sub>S to SO<sub>2</sub> in the atmosphere, although poorly constrained for volca the atmosphere, although poorly constrained for volcanic cloud conditions, is thought<br>to be roughly an order of magnitude faster than the conversion of  $SO_2$  to  $H_2SO_4$ <br>paerosol (Graedel 1977). Therefore, it is consisten to be roughly an order of magnitude faster than the conversion of  $SO_2$  to  $H_2SO_4$ to be roughly an order of magnitude faster than the conversion of  $SO_2$  to  $H_2SO_4$ <br>aerosol (Graedel 1977). Therefore, it is consistent with the TOMS mass retrievals to<br>find such an increase from one day to the next. Dete aerosol (Graedel 1977). Therefore, it is consistent with the TOMS mass retrievals to<br>find such an increase from one day to the next. Determination of an H<sub>2</sub>S component<br>could be important, as this could indicate hydrolysi find such an increase from one day to the next. Determination of an  $H_2S$  component<br>could be important, as this could indicate hydrolysis of  $SO_2$  to aqueous  $H_2S$  by a<br>liquid-dominated magmatic system, as proposed by D could be important, as this could indicate hydrolysis of  $SO_2$  to aqueous  $H_2S$  by a<br>liquid-dominated magmatic system, as proposed by Doukas & Gerlach (1995) for<br>the Mount Spurr, Alaska eruptions of 1992. They suggest th liquid-dominated magmatic system, as proposed by Doukas & Gerlach (1995) for<br>the Mount Spurr, Alaska eruptions of 1992. They suggest that  $SO_2$  'scrubbing' by<br>this mechanism could prevent (predictive) pre-eruptive  $SO_2$  d the Mount Spurr, Alaska eruptions of 1992. They suggest that  $SO_2$  'scrubbing' by<br>this mechanism could prevent (predictive) pre-eruptive  $SO_2$  degassing from being<br>detected by routine monitoring. Also, because the proport this mechanism could prevent (predictive) pre-eruptive  $SO_2$  degassing from being detected by routine monitoring. Also, because the proportions of  $H_2S$  and  $SO_2$  in volcanic gases reflects the oxidation state, the prese detected by routine monitoring.<br>volcanic gases reflects the oxidat<br>the sulphur excess (see above). *Phil. Trans. R. Soc. Lond.* A (2000)

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<sup>1592</sup> *W. I. Ros[e, G. J. S. Bluth and G.](http://rsta.royalsocietypublishing.org/) G. J. Ernst* Downloaded from rsta.royalsocietypublishing.org

## (iii) *Rates of processes related to the fate of atmospheric*  $SO_2$  *tested*

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** Eq. (ii) Takes of processes related to the jake of all model to TOMS data to test the rates of conversion of  $SO_2$  to sulphate aerosol. They used a rate based on the decrease of  $SO_2$  in the Pinatubo volcanic cloud, large Bluth *et al*. (1997) applied a simple model to TOMS data to test the rates of Bluth *et al.* (1997) applied a simple model to TOMS data to test the rates of conversion of  $SO_2$  to sulphate aerosol. They used a rate based on the decrease of  $SO_2$  in the Pinatubo volcanic cloud, largest in the TOMS a  $SO<sub>2</sub>$  in the Pinatubo volcanic cloud, largest in the TOMS archive and corresponding to an e-folding time of 35 days, which is similar to other satellite-derived data on

 $SO_2$  in the Pinatubo volcanic cloud, largest in the TOMS archive and corresponding<br>to an e-folding time of 35 days, which is similar to other satellite-derived data on<br> $SO_2$  removal rates (30–40 days) (see table 2 in Blu to an e-folding time of 35 days, which is similar to other satellite-derived data on  $SO_2$  removal rates (30–40 days) (see table 2 in Bluth *et al.* (1997)). This rate is four times faster than the rate of sulphate build- $SO_2$  removal rates (30–40 days) (see table 2 in Bluth *et al.* (1997)). This rate is four times faster than the rate of sulphate build-up in the stratosphere following Pinatubo and El Chichón eruptions, however. This lag times faster than the rate of sulphate build-up in the stratosphere following Pinatubo<br>and El Chichón eruptions, however. This lag in build-up of sulphate (about 120 days<br>e-folding) is thought to reflect multiple reactions and El Chichón eruptions, however. This lag in build-up of sulphate (about 120 days<br>e-folding) is thought to reflect multiple reactions in the conversion process. The<br>conversion of  $SO_2$  to sulphate is the result of a ser e-folding) is thought to reflect multiple reactions in the conversion process. The conversion of  $SO_2$  to sulphate is the result of a series of reactions, while the TOMS measurements of  $SO_2$  only reflect the first of the measurements of  $SO_2$  only reflect the first of these, which is the destruction of  $SO_2$ .<br>Thus, one of the later reactions must be rate limiting in this case. Rates of removal of  $SO_2$  for smaller eruptions are much faste Thus, one of the later reactions must be rate limiting in this case. Rates of removal<br>of  $SO_2$  for smaller eruptions are much faster than 35 days e-folding, however, often<br>being only a few days (Bluth *et al.* 1997). This of  $SO_2$  for smaller eruptions are much faster than 35 days e-folding, however, often<br>being only a few days (Bluth *et al.* 1997). This faster rate of removal is also associated<br>with very little stratospheric aerosol buil being only a few days (Bluth *et al.* 1997). This faster rate of removal is also associated<br>with very little stratospheric aerosol build-up, which suggests that eruption columns<br>that do not rise much higher than the tropo with very little stratospheric aerosol build-up, which suggests that eruption columns<br>that do not rise much higher than the tropopause (with volcanic explosivity index not<br>more than 4; see Newhall & Self (1982)) are subje that do not rise much higher than the tropopause (with volcanic explosivity index not<br>more than 4; see Newhall  $\&$  Self (1982)) are subject to highly efficient self-removal<br>processes (Pinto *et al.* 1989). Conversely, it more than 4; see Newhall & Self (1982)) are subject to highly efficient self-removal<br>processes (Pinto *et al.* 1989). Conversely, it is thought (Bekki *et al.* 1996) that gas-<br>to-particle conversion may be considerably sl  $\overline{5}$ processes (Pinto *et al.* 1989). Conversely, it is thought (Bekki *et al.* 1996) that gasto-particle conversion may be considerably slower when there has been extremely high stratospheric loading (e.g. the Toba scenario), to-particle conversion may be considerably slower whigh stratospheric loading (e.g. the Toba scenario), b data to measure an eruption with this large a scale. (*b*) *Ash results*

# (b) Ash results<br>(i) *Masses of very fine particles*

The two-band IR algorithms used on GOES and AVHRR detectors only sense The two-band IR algorithms used on GOES and AVHRR detectors only sense<br>particles between  $ca$ . 1 and 12  $\mu$ m in radius. This provides important data on those<br>materials that have high surface area/mass and which can theref The two-band IR algorithms used on GOES and AVHRR detectors only sense<br>particles between  $ca$ . 1 and 12  $\mu$ m in radius. This provides important data on those<br>materials that have high surface area/mass and which can theref particles between  $ca$ . 1 and 12  $\mu$ m in radius. This provides important data on those materials that have high surface area/mass and which can therefore potentially catal-<br>yse atmospheric reactions. It also provides an i materials that have high surface area/mass and which can therefore potentially catal-<br>yse atmospheric reactions. It also provides an insight into the fate and transport of<br>those volcanic particles with potentially the grea those volcanic particles with potentially the greatest impact on health, because recent reports have tended to emphasize the significance of particulate material with diamthose volcanic particles with potentially the greatest impact on health, because recent<br>reports have tended to emphasize the significance of particulate material with diam-<br>eters less than 10 (PM10) or 2.5  $\mu$ m (PM2.5). reports have tended to emphasize the significance of particulate material with diameters less than 10 (PM10) or  $2.5 \mu m$  (PM2.5). Health standards for PM10 and PM2.5 have been revised downward recently, reflecting the dis eters less than 10 (PM10) or 2.5  $\mu$ m (PM2.5). Health standards for PM10 and PM2.5<br>have been revised downward recently, reflecting the discovery that particularly small<br>particles are not caught in the oesophagus and ente have been revised downward recently, reflecting the discovery that particularly small particles are not caught in the oesophagus and enter the lungs. Studies of dust hazards in Idaho (Norton & Gunter 1999) have demonstrat particles are not caught in the oesophagus and enter the lungs. Studies of dust hazards in Idaho (Norton & Gunter 1999) have demonstrated the effects of distal ashfall<br>on health. They show that the PM10 and PM2.5 splits of ards in Idaho (Norton & Gunter 1999) have demonstrated the effects of distal ashfall<br>on health. They show that the PM10 and PM2.5 splits of fine particles on Idaho<br>farms (600–900 km from Mt St Helens) are dominated by Mt on health. They show that the PM<br>farms (600–900 km from Mt St Hele<br>and more after the 1980 eruption.<br>Infrared satellite data offer a tool Infrared satellite data offer a tool for studying the fate and transport of fine ash<br>Infrared satellite data offer a tool for studying the fate and transport of fine ash<br>unted in explosive eruptions. The satellite measurem

and more after the 1980 eruption.<br>Infrared satellite data offer a tool for studying the fate and transport of fine ash<br>erupted in explosive eruptions. The satellite measurements appear to show that the<br>masses of fine ash i Infrared satellite data offer a tool for studying the fate and transport of fine ash erupted in explosive eruptions. The satellite measurements appear to show that the masses of fine ash in volcanic clouds are less than a erupted in explosive eruptions. The satellite measurements appear to show that the masses of fine ash in volcanic clouds are less than a few per cent of the total mass of ash produced in the eruptions (table 5). This perce masses of fine ash in volcanic clouds are less than a few per cent of the total mass<br>of ash produced in the eruptions (table 5). This percentage is probably much less<br>than the total percentage of fine particles in the erup of ash produced in the eruptions (table 5). This percentage is probably much less<br>than the total percentage of fine particles in the eruption, because we know that<br>large amounts of fines fall out as part of aggregated mate than the total percentage of fine particles in the eruption, because we know that large amounts of fines fall out as part of aggregated materials in ash blankets near the vent. For example, a fallout sample from Wells Bay, large amounts of fines fall out as part of aggregated materials in ash blankets near<br>the vent. For example, a fallout sample from Wells Bay, Alaska (only 300 km from<br>the Crater Peak vent of Mount Spurr), which erupted in the vent. For example, a fallout sample from Wells Bay, Alaska (only 300 km from<br>the Crater Peak vent of Mount Spurr), which erupted in August 1992 (McGimsey,<br>personal communication; Riley *et al.* 1999), contains *ca*. 25 *Phil. Trans. R. Soc. Lond.* A (2000)



hours since eruption

Figure 2. Evolution of volcanic cloud total mass/unit area (a measure of average volcanic cloud density) as measured by TOMS and AVHRR data for the June 1992 Spurr eruption (from Figure 2. Evolution of volcanic cloud total mass/unit area (a measure of average volcanic cloud<br>density) as measured by TOMS and AVHRR data for the June 1992 Spurr eruption (from<br>Shannon 1997). The plot resembles the trend density) as measured by TOMS and AVHRR data for the June 1992 Spurr eruption (from<br>Shannon 1997). The plot resembles the trends shown for other eruptions with rapidly decreasing<br>ash density in the first 36 h, followed by ash density in the first 36 h, followed by similar slow decreases in both ash and  $SO_2$  after that (see text for discussion). Table 5. *Fine ash* (*radius* <sup>1</sup>*{*<sup>12</sup> m) *masses in volcanic clouds from satellites*

| volcano    | date           | total ash<br>erupted<br>$(\times 10^6 \text{ t})$ | maximum<br>fine ash<br>$(\times 10^6 \text{ t})$ | %    | height $(km)^a$ |
|------------|----------------|---|--|------|-----------------|
| Spurr      | June 1992      | $21.1^{\rm b}$                                    | 0.44   | 2.1  | 14.5            |
| Spurr      | August 1992    | $21.3^{\rm b}$                                    | 0.42   | 2.0  | 13.7            |
| Spurr      | September 1992 | $23.3^{\rm b}$                                    | 0.61   | 2.6  | 13.9            |
| El Chichón | April 1982     | $910^{\circ}$                                     | $6.5^{\circ}$                                    | 0.7  | 32              |
| Láscar     | April 1993     | $345^{\rm d}$                                     | $4.8^{\circ}$                                    | 1.4  | 18              |
| Hudson     | August 1991    | 7600 <sup>f</sup>                                 | 2.9 <sup>g</sup>                                 | 0.04 | 18              |

Fudson August 1991 7600<sup>f</sup> 2.9<sup>g</sup> 0.04 18<br>
bNeal *et al.* (1995); <sup>c</sup> Schneider *et al.* (1999); <sup>d</sup>Viramonte (1995); <sup>e</sup> Shocker *et al.* (2000); <sup>f</sup> Scasso<br>
et al. (1994): <sup>g</sup> Constanting *et al.* (2000) <sup>a</sup>Maximum column height observed (above<br><sup>b</sup>Neal *et al.* (1995); <sup>c</sup>Schneider *et al.* (1999<br>*et al.* (1994); <sup>g</sup>Constantine *et al.* (2000).

*et al.* (1994); <sup>g</sup>Constantine *et al.* (2000).<br>in diameter (PM10), and *ca.* 1.5% of ash finer than 2.5  $\mu$ m in diameter (PM2.5). Also<br>the masses of fine ash, as measured by satellite decrease rapidly in the first 1.5 in diameter (PM10), and ca. 1.5% of ash finer than  $2.5 \mu m$  in diameter (PM2.5). Also<br>the masses of fine ash, as measured by satellite, decrease rapidly in the first 1.5 days<br>and then decrease much more slowly (figure 2). in diameter (PM10), and ca. 1.5% of ash finer than 2.5  $\mu$ m in diameter (PM2.5). Also<br>the masses of fine ash, as measured by satellite, decrease rapidly in the first 1.5 days<br>and then decrease much more slowly (figure 2) the masses of fine ash, as measured by satellite, decrease rapidly in the first 1.5 days<br>and then decrease much more slowly (figure 2). From this we conclude that as much<br>as  $75{\text -}90\%$  of fine ash falls out of volcanic and then decrease much more slowly (figure 2). From this we conclude that as much<br>as 75–90% of fine ash falls out of volcanic clouds in the first 36 h, and is deposited in<br>ash blankets and, sometimes, within regions of sec as  $75-90\%$  of fine ash falls out of volcanic clouds in the first  $36$  h, and is deposited in ash blankets and, sometimes, within regions of secondary thickness maxima of ash blankets. Only a small fraction of this fine blankets. Only a small fraction of this fine ash continues with the volcanic cloud.<br>(ii) *Ash fallout patterns described* 

Fallout of silicates from volcanic clouds can be quantified with remote sensing data. The fallout of large particles (greater than 1 mm in diameter) in the turbulent flow regimes can be observed by ground-based weather radar systems, which are optimized for large particles (precipitation) (Harris *et al.* 1981; Harris  $\&$  Rose 1983; data. The fallout of large particles (greater than 1 mm in diameter) in the turbulent-<br>flow regimes can be observed by ground-based weather radar systems, which are<br>optimized for large particles (precipitation) (Harris *et* flow regimes can be observed by ground-based weather radar systems, which are optimized for large particles (precipitation) (Harris *et al.* 1981; Harris & Rose 1983; Rose *et al.* 1995). The radar data depict the rapid f optimized for large particles (precipitation) (Harris *et al.* 1981; Harris & Rose 1983; Rose *et al.* 1995). The radar data depict the rapid fall of materials that deposit in the proximal ash blankets, and *ca*. 30 min a Rose *et al.* 1995). The radar data depict the rapid fall of materials that deposit in the proximal ash blankets, and  $ca. 30$  min after eruption the C-band radar signal returns to background, because only particles with d *Phil. Trans. R. Soc. Lond.* A (2000) *Phil. Trans. R. Soc. Lond.* A (2000)

ERING **ATHEMATICAL** 

1594 *W. I. Rose, G. J. S. Bluth and G. G. J. Ernst*<br>still airborne (Rose *et al.* 1995). During the first three hours or so after the eruption<br>stops, the volcanic cloud may contain enough particles to be optically opaque still airborne (Rose *et al.* 1995). During the first three hours or so after the eruption stops, the volcanic cloud may contain enough particles to be optically opaque in the IR (Schneider *et al.* 1995). The mass measur **IATHEMATICAL,<br>HYSICAL<br>¿ ENGINEERING**<br>CIENCES still airborne (Rose *et al.* 1995). During the first three hours or so after the eruption<br>stops, the volcanic cloud may contain enough particles to be optically opaque in<br>the IR (Schneider *et al.* 1995). The mass measure stops, the volcanic cloud may contain enough particles to be optically opaque in<br>the IR (Schneider *et al.* 1995). The mass measurements of fine particles in volcanic<br>clouds determined from IR data decrease rapidly for *c* the IR (Schneider *et al.* 1995). The mass measurements of fine particles in volcanic<br>clouds determined from IR data decrease rapidly for *ca*. 36 h after eruption (figure 2),<br>even though these particles will not fall out clouds determined from IR data decrease rapidly for  $ca$ . 36 h after eruption (figure 2), even though these particles will not fall out rapidly as single particles (note that a simple spherical silicate ash particle with a even though these particles will not fall out rapidly as single particles (note that a simple spherical silicate ash particle with a diameter of  $ca$ .  $25 \mu m$  would fall out from 14 km in 36 h). This is viewed as direct ev simple spherical silicate ash particle with a diameter of  $ca. 25$ <br>14 km in 36 h). This is viewed as direct evidence for aggregs<br>mass decrease are greater for large eruptions (see figure 4).<br>A key observation from table 5

mass decrease are greater for large eruptions (see figure 4).<br>A key observation from table 5 and figure 4 is the apparent negative correlation between eruption intensity and the  $wt\%$  of fine ash retrieved in the cloud: lower mass fractions of fine ash remain in clouds from big eruptions. This can be rationalized as follows.

- Sollows.<br>(1) More intense eruption columns characterized by higher upward velocities are<br>more efficient at re-entraining particles than low-intensity eruptions columns S.<br>More intense eruption columns characterized by higher upward velocities are<br>more efficient at re-entraining particles than low-intensity eruptions columns<br>(Ernst et al. 1996). More intense eruption<br>more efficient at re-e<br>(Ernst *et al.* 1996).
- (Ernst *et al.* 1996).<br>
(2) More intense eruptions also have higher eruption rates, so that the volume of fragmented ash is higher. However, the case of the series of the series of the fragmented ash is higher.
- (2) More fragmented ash is higher.<br>
(3) More fragmentation results in more electric charge generated in the volcanic<br>
conduit by fracto-emission (Lane *et al.* 1993). ragmented asn is nigher.<br>More fragmentation results in more electric channel conduit by fracto-emission (Lane *et al.* 1993).
- (3) More fragmentation results in more electric charge generated in the volcanic<br>conduit by fracto-emission (Lane *et al.* 1993).<br>(4) Higher columns also entrain more moist air (Glaze *et al.* 1997) and experience<br>higher t Higher columns also entrain more moist air (Glaze *et al.* 1997) and experience<br>higher temperature gradients leading to the formation of hydrometeors (Rose *et*<br>al. 1995: Herzog *et al.* 1998) resulting in further charge g *Alteriangleries* Higher columns also entrain more moist air (Glaze *et al.* 1997) and experience higher temperature gradients leading to the formation of hydrometeors (Rose *et al.* 1995; Herzog *et al.* 1998), resulting higher temperature gradients leading to the formation of hydrometeors (Rose *et al.* 1995; Herzog *et al.* 1998), resulting in further charge generation by processes analogous to those that generate electric charges in th al. 1995; Herzog et al. 1998), resulting in further charge generation by processes
- $(5)$  As a result of items  $(1)-(4)$ , more intense eruption columns result in more effi-As a result of items  $(1)$ – $(4)$ , more intense eruption columns result in more efficient particle removal by ash aggregation and premature fallout of aggregates as icy pyroclasts (Rose *et al.* 1995) As a result of items  $(1)$ – $(4)$ , more inte<br>cient particle removal by ash aggregat<br>as icy pyroclasts (Rose *et al.* 1995).

This is viewed as support for self-removal processes as envisioned by Pinto *et al.* (1989), and demonstrates that aggregation probably happens in the coarse proximal fallout as well as farther from the vent. This is viewed as support for self-remov (1989), and demonstrates that aggregatio fallout as well as farther from the vent.<br>After ca 36 h, the apparent ash mass l (1989), and demonstrates that aggregation probably happens in the coarse proximal fallout as well as farther from the vent.<br>After  $ca. 36$  h, the apparent ash mass loading of volcanic clouds does not change

fallout as well as farther from the vent.<br>After  $ca.36$  h, the apparent ash mass loading of volcanic clouds does not change<br>greatly, and the clouds may drift for several more days in the prevailing winds at<br>various levels. After  $ca.36$  h, the apparent ash mass loading of volcanic clouds does not change<br>greatly, and the clouds may drift for several more days in the prevailing winds at<br>various levels. The fine ash that remains in the cloud is greatly, and the clouds may drift for several more days in the prevailing winds at<br>various levels. The fine ash that remains in the cloud is only a small fraction (less<br>than 20%) of the maximum detected, and the burden of various levels. The fine ash that remains in the cloud is only a small fraction (less<br>than 20%) of the maximum detected, and the burden of fine particles, which has<br>fallen to about one-fifth of its maximum after 36 h, fol than 20%) of the maximum detected, and the burden of fine particles, which has<br>fallen to about one-fifth of its maximum after 36 h, follows a trend that is similar to<br> $SO_2$  from then on (figure 2). Studies of the trajecto fallen to about one-fifth of its maximum after 36 h, follows a trend that is similar to  $SO_2$  from then on (figure 2). Studies of the trajectory of the June 1992 Spurr clouds by Shannon (1997) has shown that the lower par  $SO_2$  from then on (figure 2). Studies of the trajectory of the June 1992 Spurr clouds<br>by Shannon (1997) has shown that the lower parts of these clouds thin greatly and<br>become undetectable after ash falls, presumably beca by Shannon (1997) has shown that the lower parts of these clouds thin greatly and<br>become undetectable after ash falls, presumably because ash particles are scavenged<br>by hydrometeors (see also Rose *et al.* 1995; Textor 199 become undetectable after ash falls, presumably because ash particles are scavenged<br>by hydrometeors (see also Rose *et al.* 1995; Textor 1999). Thus, the final fate of the<br>remaining fine ash is closely related to the loca by hydrometeors (see also Rose *et al.* 1995; Textor 1999). Thus, the final fate of the remaining fine ash is closely related to the local weather of the upper troposphere (see also Bursik 1998).

# (iii) *Meteorology and volcanic clouds*

Remote sensing of the Rabaul eruption clouds of 1994 showed that the stratospheric cloud contained much ice (up to  $200{-}300$  Mt), a result explained by the

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Figure 3. Mean effective radius of volcanic clouds of El Chichón in 1982 (Schneider *et al.* 1999)<br>and Hudson in 1991 (Constantine *et al.* 2000) as a function of time measured using AVHRR Figure 3. Mean effective radius of volcanic clouds of El Chichón in 1982 (Schneider *et al.* 1999)<br>and Hudson in 1991 (Constantine *et al.* 2000) as a function of time, measured using AVHRR<br>data. The sizes of El Chichón si Figure 3. Mean effective radius of volcanic clouds of El Chichón in 1982 (Schneider *et al.* 1999) and Hudson in 1991 (Constantine *et al.* 2000) as a function of time, measured using AVHRR data. The sizes of El Chichón s and Hudson in 1991 (Con<br>data. The sizes of El Chic<br>(see text for discussion).

strong interaction of sea water with the erupted magma (Rose *et al*. 1995). This strong interaction of sea water with the erupted magma (Rose *et al.* 1995). This study heightened the awareness of meteorological processes in volcanic clouds, and new model simulations have demonstrated that ice is like strong interaction of sea water with the erupted magma (Rose *et al.* 1995). This<br>study heightened the awareness of meteorological processes in volcanic clouds, and<br>new model simulations have demonstrated that ice is like study heightened the awareness of meteorological processes in volcanic clouds, and<br>new model simulations have demonstrated that ice is likely to be abundant at lev-<br>els above  $ca$  6 km in eruption clouds, even when there i mew model simulations have demonstrated that ice is likely to be abundant at levels above  $ca$ . 6 km in eruption clouds, even when there is no seawater interaction (Herzog *et al.* 1998). This prediction is consistent with els above *ca.* 6 km in eruption clouds, even when there is no seawater interaction (Herzog *et al.* 1998). This prediction is consistent with experimental data (Rogers & Yau 1989) on heterogeneous nucleation of ice on vo (Herzog *et al.* 1998). This prediction is consistent with experimental data (Rogers & Yau 1989) on heterogeneous nucleation of ice on volcanic ash showing nucleation from temperatures of  $-13 \text{ °C}$  (*ca.* 5 km in height & Yau 1989) on heterogeneous nucleation of ice on volcanic ash showing nucleation<br>from temperatures of  $-13 \degree C$  (*ca.* 5 km in height). Recycling of icy particles within<br>the eruption column on a time-scale of less than 1 from temperatures of  $-13 \text{ }^{\circ}\text{C}$  (*ca.* 5 km in height). Recycling of icy particles within the eruption column on a time-scale of less than 1 h can allow ice-ice nucleation at even lower levels (Lane-Serff 1995). In the eruption column on a time-scale of less than 1 h can allow ice-ice nucleation at<br>even lower levels (Lane-Serff 1995). In the absence of external ground or seawater<br>involvement, ice originates within the eruption colum even lower levels (Lane-Serff 1995). In the absence of external ground or seawater<br>involvement, ice originates within the eruption column because of entrainment of<br>moist lower tropospheric air that rises, condenses and fre involvement, ice originates within<br>moist lower tropospheric air that in<br>Baloga 1996; Glaze *et al.* 1997).<br>The simulation models of erunt. sist lower tropospheric air that rises, condenses and freezes (Woods 1993; Glaze & aloga 1996; Glaze *et al.* 1997).<br>The simulation models of eruptions that include microphysical processes (Herzog al. 1998: Textor 1999) s

*Baloga 1996; Glaze et al. 1997).*<br>The simulation models of eruptions that include microphysical processes (Herzog *et al. 1998; Textor 1999)* show that icy hydrometeors will form from fine ash nuclei in volcanic clouds bu The simulation models of eruptions that include microphysical processes (Herzog *et al.* 1998; Textor 1999) show that icy hydrometeors will form from fine ash nuclei in volcanic clouds, but these hydrometeors may be aggre *et al.* 1998; Textor 1999) show that icy hydrometeors will form from fine ash nuclei<br>in volcanic clouds, but these hydrometeors may be aggregates with an ash content<br>of above 80 wt% (Textor 1999). This may explain why vo in volcanic clouds, but these hydrometeors may be aggregates with an ash content<br>of above 80 wt% (Textor 1999). This may explain why volcanic clouds usually show<br>silicate IR signals with negative brightness temperature di of above 80 wt% (Textor 1999). This may explain why volcanic clouds usually show<br>silicate IR signals with negative brightness temperature difference (BTD) (10–11  $\mu$ m<br>BTD) because of the high wt% of silicate even in the silicate IR signals with negative brightness temperature difference (BTD) (10–11  $\mu$ m<br>BTD) because of the high wt% of silicate even in the icy ashballs. However, the<br>effective radii of many drifting volcanic clouds are r BTD) because of the high wt% of silicate even in the icy ashballs. However, the effective radii of many drifting volcanic clouds are relatively large and increase with time, especially when there are abundant high meteoro effective radii of many drifting volcanic clouds are relatively large and increase with<br>time, especially when there are abundant high meteorological clouds present, as was<br>the case for the Hudson eruption (Constantine *et*  $\blacktriangleright$  time, especially when there are abundant high meteorological clouds present, as was  $\blacktriangleright$  the case for the Hudson eruption (Constantine *et al.* 2000; figure 3). We interpret this to be the result of the formation of hybrid ash-ice hydrometeors (icy ashballs), which still have the spectral signal of ash. Thus, we can infer that ice possibly plays  $\bigcap$  an important role in fallout, particularl which still have the spectral signal of ash. Thus, we can infer that ice possibly plays  $\rightarrow$  cloud. important role in fallout, particularly in the first 36 h in the life of the volcanic<br>oud.<br>Significantly, in the model studies that consider tropical atmospheric conditions<br>ferzog et al. 1998), the ice often disappears (m

(Herzog *et al.* 1998), the ice often disappears (melts and evaporates) before the ash (Herzog *et al.* 1998), the ice often disappears (melts and evaporates) before the ash reaches the ground a fact that explains why dire Significantly, in the model studies that consider tropical atmospheric conditions (Herzog *et al.* 1998), the ice often disappears (melts and evaporates) before the ash reaches the ground, a fact that explains why direct (Herzog *et al.* 1998), the ice often disappears (melts and evaporates) before the ash reaches the ground, a fact that explains why direct evidence for ice in ash blankets is elusive. There is the potential that ice can b reaches the ground, a fact that explains why direct evidence for ice in ash blankets<br>is elusive. There is the potential that ice can be preserved on the ground in some<br>conditions (i.e. phreatoplinian eruptions at high lati is elusive. There is the potential that ice can be preserved on the ground in some conditions (i.e. phreatoplinian eruptions at high latitudes). This was illustrated during the late November 1963 eruptions at Surtsey, Icel *Phil. Trans. R. Soc. Lond.* A (2000)

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**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** hours of residence<br>Figure 4. Two plots comparing the rates of total retrieved mass decreases for larger volcanic<br>clouds (El Chichón and Hudson, see above) with smaller ones (three 1992 Spurr clouds, see Figure 4. Two plots comparing the rates of total retrieved mass decreases for larger volcanic<br>clouds (El Chichón and Hudson, see above) with smaller ones (three 1992 Spurr clouds, see<br>helow). The smaller clouds decrease at clouds (El Chichón and Hudson, see above) with smaller ones (three 1992 Spurr clouds, see below). The smaller clouds decrease at a much slower rate (see text for discussion).

pyroclasts onto local ships was described as hail showers with a grain of ash within<br>each hailstone (Thorarinsson 1966) pyroclasts onto local ships was description<br>each hailstone (Thorarinsson 1966).<br>Understanding the meteorology is roclasts onto local ships was described as hail showers with a grain of ash within<br>ch hailstone (Thorarinsson 1966).<br>Understanding the meteorology is essential in interpreting the data, because the<br>currence of high clouds,

each hailstone (Thorarinsson 1966).<br>Understanding the meteorology is essential in interpreting the data, because the<br>occurrence of high clouds, such as those that form above the Andes in the roaring<br>forties (Constantine Understanding the meteorology is essential in interpreting the data, because the occurrence of high clouds, such as those that form above the Andes in the roaring forties (Constantine *et al.* 2000), can create difficulti forties (Constantine *et al.* 2000), can create difficulties for the IR remote sensing measurements. The spectral signal of ice in volcanic clouds is dominant when there is a hydrospheric source of water in addition to th forties (Constantine *et al.* 2000), can create difficulties for the IR remote sensing measurements. The spectral signal of ice in volcanic clouds is dominant when there is a hydrospheric source of water in addition to th measurements. The spectral signal of ice in volcanic clouds is dominant when there<br>is a hydrospheric source of water in addition to the atmospheric entrainment of water<br>(Rose *et al.* 1995). In addition to the Rabaul examp (Rose *et al.* 1995). In addition to the Rabaul example (above), the pyroclastic flow eruptions of Soufrière Hills, Montserrat frequently reach the sea and exchange much of their heat with seawater. The rise of this water  $\bullet$  eruptions of Soufrière Hills, Montserrat frequently reach the sea and exchange much clouds that interact and rise together with the volcanic ash clouds and increase of their heat with seawater. The rise of this water vapour creates meteorological clouds that interact and rise together with the volcanic ash clouds and increase the potential for hydrometeor formation and turbulent conve the potential for hydrometeor formation and turbulent convection (Mayberry *et al.* 2000). This incorporation of large amounts of hydrospheric water into the volcanic cloud may be quite important because there are many vol 2000). This incorporation of large amounts of hydrospheric water into the volcanic cloud may be quite important because there are many volcanoes near the ocean or lakes, and the latent heat contributions can change the cha

| $SO_2$ height (km)<br>ash height (km)<br>reference<br>eruption<br>date<br>El Chichón<br>April 1982<br>$22 - 26$<br>$19 - 21$<br>August 1991<br>Hudson<br>$10 - 14$<br>$14 - 18$<br>2<br>April 1993<br>$12 - 18$<br>Láscar<br>>18<br>3<br>Soufrière Hills<br>December 1997<br>$4 - 14$<br>ca.15<br>4 | Table 6. Examples of gas-ash separations of volcanic clouds |  |  |  |  |  |  |  |
|---|---|--|--|--|--|--|--|--|
|   |   |  |  |  |  |  |  |  |
|   |   |  |  |  |  |  |  |  |

Volcanic cloud characteristics<br>Table 6. *Examples of gas-ash separations of volcanic clouds* 

1, Schneider *et al*. (1999); 2, Constantine *et al*. (1999); 3, Shocker *et al*. (2000); 4, Mayberry *et al*. (2000).

 $\Box$  al. (2000).<br> $\Box$  greatly. When hydrometeors become dominant, the eruption cloud may resemble a greatly. When hydrometeors become dominant, the eruption cloud may resemble a giant thunderstorm, or, in the extreme cases of megaeruptions into a lake or the sea (e.g. Toba. 75 ka or Krakatau, 1883), the results could gen greatly. When hydrometeors become dominant, the eruption cloud may resemble a giant thunderstorm, or, in the extreme cases of megaeruptions into a lake or the sea (e.g. Toba, 75 ka or Krakatau, 1883), the results could ge giant thunderstorm, or, in the extreme cases of megaeruptions into (e.g. Toba, 75 ka or Krakatau, 1883), the results could generate a la hypercane (the runaway hurricane of Emmanuel *et al.* (1995)). Ca hypercane (the runaway hurricane of Emmanuel *et al.* (1995)).<br>
(*c*) *Integrated data* 

(i) *Separation of gas and ash*

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Use of both IR and UV sensors in studies of the same volcanic clouds enables more Holistic studies. One highlight of the studies of the same volcanic clouds enables more<br>holistic studies. One highlight of the studies of this type (see, for example, Rose *et*<br>al. 1995: Schneider *et al.* 1999: Shannon 19 Use of both IR and UV sensors in studies of the same volcanic clouds enables more<br>holistic studies. One highlight of the studies of this type (see, for example, Rose *et*<br>*al.* 1995; Schneider *et al.* 1999; Shannon 1997; *al.* 1995; Schneider *et al.* 1999; Shannon 1997; Constantine *et al.* 2000; Shocker *et al.* 2000; Mayberry *et al.* 2000) is that many eruptions exhibit separation of SO<sub>2</sub> and volcanic ash typically almost immediately al. 1995; Schneider et al. 1999; Shannon 1997; Constantine et al. 2000; Shocker et al. 2000; Mayberry *et al.* 2000) is that many eruptions exhibit separation of  $SO_2$  and volcanic ash, typically almost immediately after eruption. The  $SO_2$  ends up higher in the atmosphere than the ash and is then moved volcanic ash, typically almost immediately after eruption. The  $SO<sub>2</sub>$  ends up higher in the atmosphere than the ash and is then moved by higher-level winds in a different separation. data studied to date, only the relatively small Spurr eruptions do not show this separation.<br>In all cases where separation is observed, the  $SO_2$  and ash-rich clouds are appar-

ICAL<br>Gineering<br>ICES Exparation.<br>In all cases where separation is observed, the  $SO_2$  and ash-rich clouds are apparently already well separated vertically on the first satellite image available. The effect<br>of windshear is to make the separati In all cases where separation is observed, the  $SO_2$  and ash-rich clouds are apparently already well separated vertically on the first satellite image available. The effect of windshear is to make the separation of the tw ently already well separated vertically on the first satellite image available. The effect<br>of windshear is to make the separation of the two clouds evident without any further<br>vertical splitting apparent for either cloud a of windshear is to make the separation of the two clouds evident without any further<br>vertical splitting apparent for either cloud as time goes by (Schneider *et al.* 1999).<br>The causes of this separation and its implicatio

vertical splitting apparent for either cloud as time goes by (Schneider *et al.* 1999).<br>The causes of this separation and its implications are mostly unexplored. Since the  $SO_2$  comes largely from an exsolved gas phase be The causes of this separation and its implications are mostly unexplored. Since the  $SO<sub>2</sub>$  comes largely from an exsolved gas phase before eruption (see above), it may be that it separates largely from the ash during that it separates largely from the ash during eruption, and it may even be released selectively before much of the ash. This scenario is consistent with measurements that it separates largely from the ash during eruption, and it may even be released selectively before much of the ash. This scenario is consistent with measurements of electrical potential field during explosive activity selectively before much of the ash. This scenario is consistent with measurements<br>of electrical potential field during explosive activity at Sakurajima Volcano, Japan<br>(Lane & Gilbert 1992). At Sakurajima, a gas-rich cloud of electrical potential field during explosive activity at Sakurajima Volcano, Japan (Lane & Gilbert 1992). At Sakurajima, a gas-rich cloud precedes an ash-rich cloud<br>during the vulcanian eruptions documented. It may be th (Lane & Gilbert 1992). At Sakurajima, a gas-rich cloud precedes an ash-rich cloud<br>during the vulcanian eruptions documented. It may be that the sedimentation of ash<br>within the umbrella cloud that forms in the upper parts during the vulcanian eruptions documented. It may be that the sedimentation of ash within the umbrella cloud that forms in the upper parts of the drifting volcanic cloud <br>
dynamically triggers separation in a fluid dynamic within the umbrella cloud that forms in the upper parts of the drifting volcanic cloud<br>dynamically triggers separation in a fluid dynamic process (Holasek *et al.* 1996).<br>However, we realize that the experiments of Holasek dynamically triggers separation in a fluid dynamic process (Holasek *et al.* 1996).<br>However, we realize that the experiments of Holasek *et al.* (1996) are inconclusive<br>because the simulated process of particle-fluid sepa However, we realize that the experiments of Holasek *et al.* (1996) are inconclusive because the simulated process of particle–fluid separation would be expected on the same time-scale that the effects of the tank walls i because the simulated process of particle–fluid separation would be expected on the same time-scale that the effects of the tank walls induce a return flow in the tank and force the breakdown of particle–fluid separation. same time-scale that the effects of the tank walls induce a return flow in the tank and<br>force the breakdown of particle-fluid separation. The process envisioned by Holasek<br>*et al.* (1996), however, is also suggested by tr force the breakdown of particle–fluid separation. The process envisioned by Holasek *et al.* (1996), however, is also suggested by tropical volcanic-cloud simulations that incorporate hydrometeors (Herzog *et al.* 1998), a *et al.* (1996), however, is also suggested by tropical volcanic-cloud simulations that incorporate hydrometeors (Herzog *et al.* 1998), and the presence of hydrometeors is expected to enhance the process by accelerating expected to enhance the process by accelerating the sedimentation of ash. A third<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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**PHILOSOPHICAL**<br>TRANSACTIONS

<sup>1598</sup> *W. I. Ros[e, G. J. S. Bluth and G.](http://rsta.royalsocietypublishing.org/) G. J. Ernst* Downloaded from rsta.royalsocietypublishing.org



hours since eruption<br>Figure 5. Volcanic-cloud-area and optical-depth measurements plotted against time for the<br>June 1992 Spurr event (from Shannon 1997). Ash-cloud area and optical depth measured from Figure 5. Volcanic-cloud-area and optical-depth measurements plotted against time for the<br>June 1992 Spurr event (from Shannon 1997). Ash-cloud area and optical depth measured from<br>AVHRR and SO<sub>2</sub> area measured from TOMS da June 1992 Spurr event (from Shannon 1997). Ash-cloud area and optical depth measured from AVHRR and  $SO<sub>2</sub>$  area measured from TOMS data (see text for discussion).

AVHRR and SO<sub>2</sub> area measured from TOMS data (see text for discussion).<br>process that could explain the separation is scavenging or absorption of  $SO_2$  by ice<br>in the cloud, especially at levels below the top. This process process that could explain the separation is scavenging or absorption of  $SO_2$  by ice<br>in the cloud, especially at levels below the top. This process was suggested for the<br>Rabaul eruption by Rose *et al.* (1995) and is con process that could explain the separation is scavenging or absorption of  $SO_2$  by ice<br>in the cloud, especially at levels below the top. This process was suggested for the<br>Rabaul eruption by Rose *et al.* (1995) and is con in the cloud, especially at levels below the top. This process was suggested for the Rabaul eruption by Rose *et al.* (1995) and is consistent with most of the other cases in table 6. It differs from the other explanation Rabaul eruption by Rose *et al.* (1995) and is consistent with most of the other cases<br>in table 6. It differs from the other explanations because it involves removal of  $SO_2$ <br>rather than dynamic separation. We are optimis in table 6. It differs from the other explanations because it in rather than dynamic separation. We are optimistic that we can<br>by continuing our remote sensing and experimental studies. by continuing our remote sensing and experimental studies.<br>(ii) *Morphology and dynamics of volcanic clouds* 

**MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>& ENGINEES** Figure 5 shows an example of area measurements of volcanic clouds. Data on cloud shapes, widths and distances are also readily available along with changes with time. shapes, widths and distances are also readily available along with changes with time.<br>The possibilities for studies of the sizes and shapes of volcanic-cloud sequences to<br>define the cloud-spreading dynamics has already bee The possibilities for studies of the sizes and shapes of volcanic-cloud sequences to The possibilities for studies of the sizes and shapes of volcanic-cloud sequences to define the cloud-spreading dynamics has already been demonstrated by Sparks *et al.* (1986, 1997) and Volon (1997). A discussion of some define the cloud-spreading dynamics has already been demonstrated by Sparks  $et$  al. (1986, 1997) and Volon (1997). A discussion of some of the research issues and processes of volcanic plume or cloud-shape changes (e.g. d al. (1986, 1997) and Volon (1997). A discussion of some of the research issues and<br>processes of volcanic plume or cloud-shape changes (e.g. draughting and bending)<br>was given by Bursik (1998), while preliminary studies of processes of volcanic plume or cloud-shape changes (e.g. draughting and bending)<br>was given by Bursik (1998), while preliminary studies of plume bifurcation have<br>been made by Ernst *et al.* (1994) and Rose *et al.* (1995). was given by Bursik (1998), while preliminary studies of plume bifurcation have<br>been made by Ernst *et al.* (1994) and Rose *et al.* (1995). Photoinclimetric studies of<br>satellite data have been used to extract three-dimen been made by Ernst *et al.* (1994) and Rose *et al.* (1995). Photoinclimetric studies of satellite data have been used to extract three-dimensional patterns of dispersion and movement (Glaze *et al.* 1999), while Shannon ( satellite data have been used to extract three-dimensional patterns of dispersion and<br>movement (Glaze *et al.* 1999), while Shannon (1997) and Mayberry *et al.* (2000)<br>have combined the UV and IR satellite data (table 3) movement (Glaze *et al.* 1999), while Shannon (1997) and Mayberry *et al.* (2000) have combined the UV and IR satellite data (table 3) with trajectory analysis to develop three-dimensional patterns. Evidence for thermal d have combined the UV and IR satellite data (table 3) with trajectory analysis to develop three-dimensional patterns. Evidence for thermal disequilibrium for eruption clouds has also been documented from satellite data, wit develop three-dimensional patterns. Evidence for thermal disequilibrium for eruption<br>clouds has also been documented from satellite data, with implications for eruption<br>column models (Woods & Bursik 1991; Woods & Self 199  $\bullet$ clouds has also been documented from satellite data, with implications for eruption<br>column models (Woods & Bursik 1991; Woods & Self 1992). Geometrically corrected<br>satellite images are used to derive the lateral spreading *all* column models (Woods & Bursik 1991; Woods & Self 1992). Geometrically corrected satellite images are used to derive the lateral spreading of umbrella clouds (Sparks *et al.* 1986) as well as cloud radial velocities ( satellite images are used to derive the lateral spreading of umbrella clouds (Sparks *et al.* 1986) as well as cloud radial velocities (see, for example, Volon 1997), and then these datasets are compared with theoreticalal. 1986) as well as cloud radial velocities (see, for example, Volon 1997), and then<br>these datasets are compared with theoretical-model predictions (Bursik *et al.* 1992;<br>Woods *et al.* 1995; Sparks *et al.* 1997). Compar these datasets are compared with theoretical-model predictions (Bursik *et al.* 1992; Woods *et al.* 1995; Sparks *et al.* 1997). Comparison between theory and lateral spreading data for the 18 May 1980 Mt St Helens cloud

cloud spreading was dominated by gravity flow, advection of the cloud by wind, and outfalling particles within the first few hours of spreading, with atmospheric diffusion playing a very minor role (Sparks *et al.*, 1997) **ATHEMATICA** 

playing a very minor role (Sparks *et al.* 1997). This is in direct contradiction with the suggestion of Heffter (1996) that advection-diffusion models could adequately outfalling particles within the first few hours of spreading, with atmospheric diffusion playing a very minor role (Sparks *et al.* 1997). This is in direct contradiction with the suggestion of Heffter (1996) that advecti playing a very minor role (Sparks *et al.* 1997). This is in direct contradiction with the suggestion of Heffter (1996) that advection–diffusion models could adequately describe this stage of spreading. However, such advection–diffusion models can be useful to describe the second stage of spreading, after th describe this stage of spreading. However, such advection-diffusion models can b<br>useful to describe the second stage of spreading, after the turbulence level in th<br>volcanic cloud becomes dominated by atmospheric turbulence

# volcanic cloud becomes dominated by atmospheric turbulence (see Bursik 1998).<br>5. Potential improvements

5. Potential improvements<br>As satellite detectors evolve and improve, as the algorithms used to retrieve data<br>develop, and as more users learn to interpret the data, we expect that our ability As satellite detectors evolve and improve, as the algorithms used to retrieve data develop, and as more users learn to interpret the data, we expect that our ability to study volcanic clouds will improve. The following is As satellite detectors evolve and improve, as the algorithms used to retrieve data develop, and as more users learn to interpret the data, we expect that our ability to study volcanic clouds will improve. The following is develop, and as more users learn to interp<br>to study volcanic clouds will improve. The<br>improvements that are now within reach. (*a*) *Cross validation of methods*

We have only very occasionally the opportunity to study TOMS and GOES or We have only very occasionally the opportunity to study TOMS and GOES or AVHRR data collected at exactly the same time. One such example is one of the Spurr volcanic clouds studied by Krotkov *et al.* (1999). This compari We have only very occasionally the opportunity to study TOMS and GOES or AVHRR data collected at exactly the same time. One such example is one of the Spurr volcanic clouds studied by Krotkov *et al.* (1999). This comparis AVHRR data collected at exactly the same time. One such example is one of the Spurr volcanic clouds studied by Krotkov *et al.* (1999). This comparison helps us improve the algorithms used in retrievals and also to unders Spurr volcanic clouds studied by Krotkov *et al.* (1999). This comparison helps us improve the algorithms used in retrievals and also to understand the environmental variables that sometimes prevent full retrieval of IR d improve the algorithms used in retrievals and also to understand the environmental variables that sometimes prevent full retrieval of IR data. Validation of volcanic-cloud<br>retrievals is crucially important, especially for the hazards considerations regarding<br>public heath and fine particles and ash hazar retrievals is crucially important, especially for the hazards considerations regarding<br>public heath and fine particles and ash hazards to aircraft. Although we hope for<br>direct sampling studies for validation (see, for exam public heath and fine particles and as<br>direct sampling studies for validation<br>logistically difficult to arrange them. (*b*) *Geostationary positioning of detectors*

The availability of GOES two-band IR data clearly demonstrates the advantage of The availability of GOES two-band IR data clearly demonstrates the advantage of<br>the stare mode in the study of rapidly changing volcanic clouds (Rose & Schneider<br>1996: Davies & Rose 1998). Unfortunately this capability wi The availability of GOES two-band IR data clearly demonstrates the advantage of<br>the stare mode in the study of rapidly changing volcanic clouds (Rose & Schneider<br>1996; Davies & Rose 1998). Unfortunately, this capability wi the stare mode in the study of rapidly changing volcanic clouds (Rose & Schneider 1996; Davies & Rose 1998). Unfortunately, this capability will be lost in 2002 and the TOMS has never been placed on a geostationary platfo 1996; Davies & Rose 1998). Unfortunately, this capability will be lost in 2002 and<br>the TOMS has never been placed on a geostationary platform. A NASA proposal<br>(VOLCAM) to demonstrate the use of a geostationary platform wi the TOMS has never been placed on a geostationary platform. A NASA proposal (VOLCAM) to demonstrate the use of a geostationary platform with both UV and IR detectors is currently being negotiated among US agencies for poss (VOLCAM) to demonstrate the use of a geostationary platform with both UV and<br>IR detectors is currently being negotiated among US agencies for possible funding,<br>which could result in favourable positioning of one or both of IR detectors is currently being negotiated among US agencies for possible funding,<br>which could result in favourable positioning of one or both of the detectors on a<br>geostationary platform in about 2003. This would result i which could result in favourable positioning of one or both of the detectors on a geostationary platform in about 2003. This would result in much better temporal resolution of integrative satellite data on volcanic clouds, geostationary platform in<br>resolution of integrative sa<br>data for detailed studies. (*c*) *Volcanic-cloud-height determinations*

Currently, we use tra jectory analysis to constrain the heights of volcanic clouds  $\begin{bmatrix} 1 & 0 \end{bmatrix}$  constraint determinations<br>but do not have an independent way of determining the altitude of the cloud top.<br>The TOMS instrument can potentially determine cloud top pressure by using the Currently, we use trajectory analysis to constrain the heights of volcanic clouds<br>but do not have an independent way of determining the altitude of the cloud top.<br>The TOMS instrument can potentially determine cloud top pre but do not have an independent way of determining the altitude of the cloud top.<br>The TOMS instrument can potentially determine cloud top pressure by using the<br>'ring effect' (filling-in of solar Fraunhofer lines by rotation The TOMS instrument can potentially determine cloud top pressure by using the 'ring effect' (filling-in of solar Fraunhofer lines by rotational Raman scattering). The algorithm compares radiance differences between cloud 'ring effect' (filling-in of solar Fraunhofer lines by rotational Raman scattering). The algorithm compares radiance differences between cloud and clear areas within the Fraunhofer lines to those in a flat spectral region algorithm compares radiance differences between cloud and clear areas within the

*Phil. Trans. R. Soc. Lond.* A (2000)

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pressure using the Ca, H and K lines in the solar spectrum. Future designs of TOMS pressure using the Ca, H and K lines in the solar spectrum. Future designs of TOMS<br>instruments, such as the one planned for VOLCAM, will initiate this ability, which<br>will help our three-dimensional understanding of volcani pressure using the Ca, H and K lines in the solar spectrum. Future of instruments, such as the one planned for VOLCAM, will initiate the will help our three-dimensional understanding of volcanic clouds. will help our three-dimensional understanding of volcanic clouds.<br>(*d*) *Improvements in the IR detection of volcanic clouds* 

Unlike the TOMS detector, which has not shown any false alarms, the two-band IR Unlike the TOMS detector, which has not shown any false alarms, the two-band IR detectors can give erroneous or misleading results, especially when the atmospheric conditions are not ideal. High clouds beneath the volcani Unlike the TOMS detector, which has not shown any false alarms, the two-band IR detectors can give erroneous or misleading results, especially when the atmospheric conditions are not ideal. High clouds beneath the volcanic detectors can give erroneous or misleading results, especially when the atmospheric<br>conditions are not ideal. High clouds beneath the volcanic cloud (Constantine *et*<br>*al.* 1999) reduce the thermal contrast between the vol conditions are not ideal. High clouds beneath the volcanic cloud (Constantine *et*  $al$ . 1999) reduce the thermal contrast between the volcanic cloud and the subsurface radiator. In the first few hours of volcanic clouds, al. 1999) reduce the thermal contrast between the volcanic cloud and the subsurface radiator. In the first few hours of volcanic clouds, high optical depth prevents retrieval of particle size and mass data (Schneider *et a* radiator. In the first few hours of volcanic clouds, high optical depth prevents retrieval<br>of particle size and mass data (Schneider *et al.* 1995). When the lower atmosphere<br>is moist, as is the case for most tropical eru of particle size and mass data (Schneider *et al.* 1995). When the lower atmosphere is moist, as is the case for most tropical eruptions, such as Montserrat, the high water vapour absorption of IR wavelengths produces a s is moist, as is the case for most tropical eruptions, such as Montserrat, the high<br>water vapour absorption of IR wavelengths produces a shift of BTDs unless the<br>differential absorption effects are corrected for. This latte water vapour absorption of IR wavelengths produces a shift of BTDs unless the differential absorption effects are corrected for. This latter problem has been targeted for correction and can be effectively minimized if inf differential absorption effects are corrected for. This latter problem has been targeted<br>for correction and can be effectively minimized if information about the water vapour<br>content of the first 3 km of atmosphere is kno for correction and can be effectively minimized if information about the water<br>content of the first 3 km of atmosphere is known (Yu & Rose 2000). We expert<br>wo-band algorithms can improve these atmospheric corrections mark ntent of the first 3 km of atmosphere is known (Yu & Rose 2000). We expect that o-band algorithms can improve these atmospheric corrections markedly.<br>In the very near future there will be new capability for volcanic clouds

two-band algorithms can improve these atmospheric corrections markedly.<br>In the very near future there will be new capability for volcanic clouds as part of<br>EOS AM-1, launched in December 1999. The moderate resolution imagi In the very near future there will be new capability for volcanic clouds as part of EOS AM-1, launched in December 1999. The moderate resolution imaging spectrom-<br>eter (MODIS) detector, with improved spatial resolution (2 EOS AM-1, launched in December 1999. The moderate resolution imaging spectrom-<br>eter (MODIS) detector, with improved spatial resolution (250–1000 m) and multi-<br>spectral IR bands, including coverage of the critical  $10-12.5$ eter (MODIS) detector, with improved spatial resolution (250–1000 m) and multi-<br>spectral IR bands, including coverage of the critical 10–12.5  $\mu$ m region, will offer<br>great opportunities for improvements in ash retrievals spectral IR bands, including coverage of the critical  $10-12.5 \mu m$  region, will offer<br>great opportunities for improvements in ash retrievals. It will also enable sensing<br>of  $SO_2$  (Realmuto *et al.* 1997) and sulphate aero great opportunities for improvements in ash retrievals. It will also enable sensing<br>of  $SO_2$  (Realmuto *et al.* 1997) and sulphate aerosols (Yu & Rose 2000). ASTER<br>(advanced spaceborne thermal emission and reflection radi of  $SO_2$  (Realmuto *et al.* 1997) and sulphate aerosols (Yu & Rose 2000). ASTER (advanced spaceborne thermal emission and reflection radiometer) is another EOS instrument with even better spatial (15–90 m) and spectral re instrument with even better spatial  $(15-90 \text{ m})$  and spectral resolution in the IR than MODIS, and it will allow very-high-resolution coverage of a small number of volcanic clouds. Although more vulnerable to environment MODIS, and it will allow very-high-resolution coverage of a small number of volcanic MODIS, and it will allow very-high-resolution coverage of a small number of volcanic<br>clouds. Although more vulnerable to environmental conditions that adversely affect<br>accurate detection and retrievals, IR data are availab **MATHEMATICAL,<br>PHYSICAL<br>& ENGINEERING<br>SCIENCES** clouds. Although more vulnerable to environmental conditions that adversely affect<br>accurate detection and retrievals, IR data are available during the night-time, when<br>UV detectors will not work. We expect that IR will alw UV detectors will not work. We expect that IR will always be a significant part of volcanic-cloud monitoring.

# (*e*) *Early sulphate in volcanic clouds*

(e) Early sulphate in volcanic clouds<br>Using a multispectral IR method, Yu & Rose (2000) have shown that  $SO_2$  is<br>rtly converted to sulphate aerosol during the first 24 h of atmospheric residence Using a multispectral IR method, Yu & Rose (2000) have shown that  $SO_2$  is partly converted to sulphate aerosol during the first 24 h of atmospheric residence.<br>This conclusion is also consistent with the observation of sc Using a multispectral IR method, Yu & Rose  $(2000)$  have shown that  $SO_2$  is partly converted to sulphate aerosol during the first 24 h of atmospheric residence.<br>This conclusion is also consistent with the observational o partly converted to sulphate aerosol during the first 24 h of atmospheric residence.<br>  $\geq$  This conclusion is also consistent with the observation of scavenged sulphate on  $\geq$  fresh volcanic ash (Rose 1977) and with th This conclusion is also consistent with the observation of scavenged sulphate on<br>fresh volcanic ash (Rose 1977) and with the observational data on volcanic clouds<br>summarized above and in table 1. The rate of sulphate form fresh volcanic ash (Rose 1977) and with the observational data on volcanic clouds<br>summarized above and in table 1. The rate of sulphate formation is consistent with<br>the rate of  $SO_2$  mass decreases in volcanic clouds such summarized above and in table 1. The rate of sulphate formation is consistent with<br>the rate of  $SO_2$  mass decreases in volcanic clouds such as El Chichón (Bluth *et*<br>*al.* 1997), and suggests that the catalysis of sulphat the rate of  $SO_2$  mass decreases in volcanic clouds such as El Chichón (Bluth *et al.* 1997), and suggests that the catalysis of sulphate formation resulting from the presence of large amounts of volcanic ash early in vol al. 1997), and suggests that the catalysis of sulphate formation resulting from the presence of large amounts of volcanic ash early in volcanic clouds is minimal. The presence of sulphate aerosols is potentially vital for presence of large amounts of volcanic ash early in volcanic clouds is minimal. The presence of sulphate aerosols is potentially vital for the formation of aggregates,<br>because, by analogy with reactions associated with fumarolic incrustations (Stoiber &<br>Rose 1974; Symonds *et al.* 1987), they can react wi because, by analogy with reactions associated with fumarolic incrustations (Stoiber & Rose 1974; Symonds *et al.* 1987), they can react with the silicate surfaces and form an effective chemical cement that enhances aggreg Rose 1974; Symonds *et al.* 1987), they can react with the silicate surfaces and form an effective chemical cement that enhances aggregation. Alternatively, chemical reaction is not required to bind particles: mere evapor effective chemical cement that enhances aggregation. Alternatively, chemical reaction<br>is not required to bind particles: mere evaporation of sulphate/chloride solution films<br>are expected to precipitate salts that can bind are expected to precipitate salts that can bind the particles (Gilbert & Lane 1994).<br>*Phil. Trans. R. Soc. Lond.* A (2000)

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**PHILOSOPHICAL**<br>TRANSACTIONS

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# *Volcanic cloud characteristics*<br>(*f*) *Interaction of ash and gases*

We have already discussed the accumulation of sulphate aerosols on ash particles We have already discussed the accumulation of sulphate aerosols on ash particles<br>and the role of ice that forms on ash surfaces and scavenges gases such as  $SO_2$ <br>and HCl (Tabazedeh & Turco 1993), but direct adsorption of We have already discussed the accumulation of sulphate aerosols on ash particles<br>and the role of ice that forms on ash surfaces and scavenges gases such as  $SO_2$ <br>and HCl (Tabazedeh & Turco 1993), but direct adsorption of and the role of ice that forms on ash surfaces and scavenges gases such as  $SO_2$ <br>and HCl (Tabazedeh & Turco 1993), but direct adsorption of gases such as  $SO_2$  on<br>ash particles may also be important (Oskarsson 1980). We h and HCl (Tabazedeh & Turco 1993), but direct adsorption of gases such as  $SO_2$  on ash particles may also be important (Oskarsson 1980). We have begun studies of this process in laboratory experiments (Gu *et al.* 1999). L ash particles may also be important (Oskarsson 1980). We have begun studies of this process in laboratory experiments (Gu *et al.* 1999). Like many of the processes that occur in volcanic clouds, we can evaluate and study this process in laboratory experiments (Gu *et al.* 1 that occur in volcanic clouds, we can evaluate and improved data frequency, particularly in the UV. improved data frequency, particularly in the UV.<br>(*q*) *Widespread use of satellite data on volcanic clouds* 

The widespread use of volcanic-cloud remote sensing is likely because of its potential to reduce the hazards of volcanic clouds to aircraft (Casadevall 1994). However, The widespread use of volcanic-cloud remote sensing is likely because of its potential to reduce the hazards of volcanic clouds to aircraft (Casadevall 1994). However, this application will require technology and training tial to reduce the hazards of volcanic clouds to aircraft (Casadevall 1994). However,<br>this application will require technology and training to be regionalized and placed in<br>centres around the world near the volcano observa this application will require technology and training to be regionalized and placed in centres around the world near the volcano observatories, weather stations and airports affected. In recent years, this work has been pr centres around the world near the volcano observatories, weather stations and air-<br>ports affected. In recent years, this work has been proceeding in the regional volcanic<br>ash advisory centres (VAACs).

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