

# Ice in Volcanic Clouds: When and Where?

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*Volcanic clouds* are suspensions of particles, analogous to meteorological clouds. In volcanic clouds the particles include volcanic ash, *hydrometeors* (raindrops, snow, hail, graupel, sleet, etc), sulfate aerosols and particles that are mixtures or conglomerations of all the other particle types present. *Ash fall* is analogous to rain, hail or snow, and consists of large ash particles in descent. Ash fall occurs most markedly from the high energy first stage of volcanic clouds, with or without precipitation, near the vent and soon (<1hr) after eruption (Rose et al, 2000). Volcanic clouds exhibit a second stage of evolution, lasting a day or so, where rapid physical and chemical changes occur and when ash fall

This paper explores published data from remote sensing and other sources concerning the existence of ice particles in volcanic clouds, to attempt to reveal patterns in its variability. We use data from a variety of satellite sensors and using several different algorithms for retrieval of information about ice, ash, sulfate and SO<sub>2</sub> (Table 1), applied to eruptions of the last few decades.

If one type of particle is dominant in the volcanic cloud, it is challenging to use these remote sensing algorithms to quantify the subordinate particles. We discuss in this paper cases when ice is the dominant particle type, when ash is dominant and when ash and ice are similar in mass proportions.

**Table 1** Algorithms used for volcanic cloud sensing retrievals, see also Watson et al (2004)

Name	Sensor (s)	Objective	Reference(s)
2 band BTD	GOES, AVHRR, MODIS	Mass of fine (> 15 μm radius) ash, Particle size	Wen & Rose, 1994; Yu et al, 2002 (atmospheric corrections) Rose et al, 1995 (ice retrievals)
8.6 μm SO <sub>2</sub>	MODIS, ASTER	SO <sub>2</sub> mass	Realmuto et al, 1997
7.3 μm SO <sub>2</sub>	MODIS, HIRS/2	SO <sub>2</sub> mass	Prata et al, 2003 (HIRS/2) Prata et al, in prep (MODIS)
UV SO <sub>2</sub>	TOMS	SO <sub>2</sub> mass	Krueger et al, 1995
Multiband IR	MODIS	Fine ash, ice, sulfate masses	Yu & Rose, 2000

GOES = Geostationary Operational Environmental Satellite; AVHRR= Advanced Very High Resolution Radiometer; MODIS= Moderate Resolution Imaging Spectroradiometer; ASTER= Advanced Spaceborne Thermal Emission and Reflection Radiometer; TOMS= Total Ozone Mapping Spectrometer

occur and when ash fall (and precipitation) is muted and controlled by aggregation of ash particles too small to fall by themselves. A third stage of volcanic clouds lasts several more days and consists of drifting over hundreds or thousands of km and very slow fallout (Rose et al, 2003).

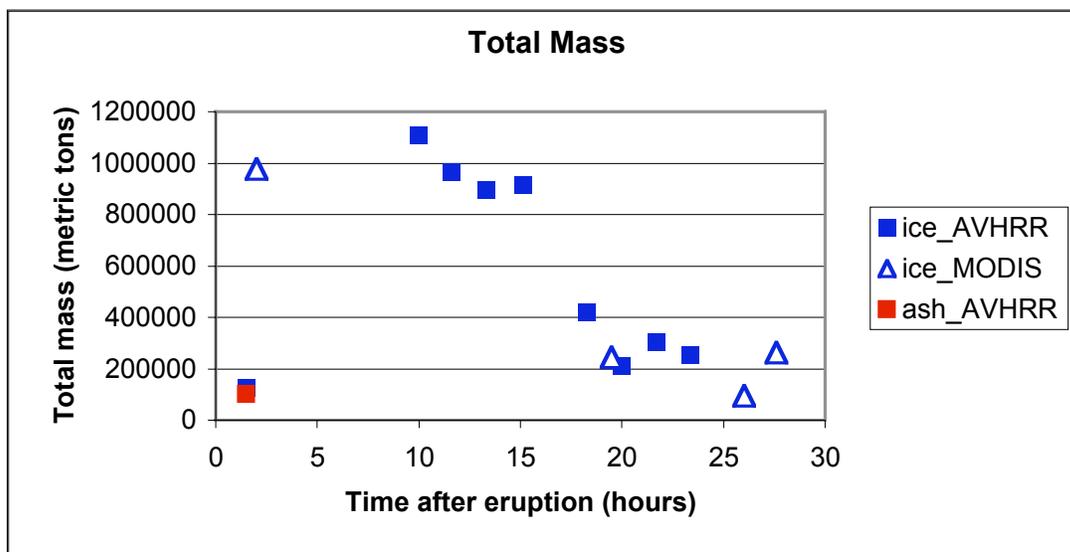
## Ice Dominant Volcanic Clouds Rabaul, Papua New Guinea 1994

The Rabaul eruption was the event which made us realize that ice could be the dominant particle in volcanic clouds. The eruption came from dual vents on opposite sides of a caldera breached by the ocean and resulted in a 20 km high eruption cloud

which was detected by satellite sensors such as the polar orbiting AVHRR. Numerous conventional photographs from the Space Shuttle (<http://www.geo.mtu.edu/volcanoes/rabaul/shuttle/>) show that this cloud had a bright white color like a meteorological cloud. Infrared remote sensing showed that the cloud contained >2 MT of ice. Salty rain falls occurred in a wide arc N and NW of the volcano and there were wet ash and mud falls which contained sea salt, although ash could not be detected by satellite remote sensors. The Vulcan vent (the main source of the Rabaul eruptions) was itself breached, and so the ocean flowed directly into the active vent during eruption. Thus the ice in the great cloud may have largely been the result of evaporation of the ocean (Rose et al, 1995). Remote sensing also revealed that the Rabaul volcanic cloud contained relatively low levels of SO<sub>2</sub> (80 ± 50 kT), which suggested that ice sequestered much of the volcanic gas and removed it from the volcanic cloud by precipitation in the early stage of the volcanic cloud. Overall this example showed that ice could reduce the residence time of both ash and SO<sub>2</sub> in the volcanic cloud, an idea suggested by Pinto et al (1989).

### Hekla, Iceland 2000

The Hekla eruption was a small (ash volume ~ 0.01 km<sup>3</sup>; total magma volume ~0.17 km<sup>3</sup> and mass about 3x10<sup>5</sup> MT) fissure eruption of lava preceded by a brief (1-2 hr) explosive phase that produced an eruption cloud which suddenly reached 10-12 km. Meteorological radar was a useful monitoring tool to document the explosive eruption and the growth of ice in the volcanic cloud (Lacasse et al, 2004). The volcanic cloud was mapped by a variety of satellite sensors as it drifted N of Hekla toward Svalbard for 2 days (Rose et al, 2003). It was also traversed by a research aircraft with in situ atmospheric sensors. In spite of the small scale of the eruption, the Hekla volcanic cloud contained >1 MT of ice and 160-240 kT of SO<sub>2</sub>. Ash was a minor component and was detected by remote sensors only in the first hour of the eruption (~100 kT or .1 Tg). The ice mass in the volcanic cloud declined by an order of magnitude before the aircraft encounter 35 hours after eruption (figure 1).



**Figure 1:** Time based determinations of particle masses determined using the multispectral IR retrieval of Yu & Rose (2000) for the Hekla Volcanic Cloud (Rose et al, 2003).

### **Examples where ice is clearly subordinate Spurr, Alaska 1992**

Crater Peak, Mount Spurr Alaska had 3 similar VEI=3 eruptions in 1992. Each resulted in a volcanic cloud which reached the lower stratosphere (~14 km asl) and had eruptive volumes of about 0.01-0.02 km<sup>3</sup> (Rose et al, 2001). All three events were studied with AVHRR sensors which enabled us to estimate masses of several hundreds of kilotonnes of fine (<15 μm radius) ash particles. These particle masses declined markedly during the first 18-24 hours due to aggregate formation and fallout. No ice could be detected with remote sensing in any of these clouds. We used atmospheric profile information and a numerical model called ATHAM which includes microphysical processes (Textor et al, 2003) to determine the likely amounts of ice in the Spurr volcanic clouds and found that the model results showed that ice concentrations in the Spurr Clouds were of the order of a few % of the fine ash concentrations. One factor that limits the ice is the low concentrations of H<sub>2</sub>O in tropospheric air at high latitudes, which limits the entrained water vapor in the column. The low proportions of ice in Spurr volcanic clouds may limit the fallout of icy aggregates which accelerate ash removal in other clouds. We also note that the Spurr clouds did not show separation of ash and SO<sub>2</sub> (See discussion in Rose et al, 2001).

### **Cleveland, Alaska 2001**

Cleveland is a stratovolcano 1730 m high located 1500 km SW of Anchorage in the east central Aleutians. With 11 eruptions since 1893 and ash eruptions in 1987 and 1994, it is relatively active. As it is unmonitored seismically and remote, satellite observations of thermal anomalies and eruption clouds play a vital role in monitoring (Dean *et al*, 2004). In 2001, Cleveland erupted on February 19, March 11 and March 19. On February 19, the largest of the three events produced ash eruptions that lasted 8-9 hours and which were observed by satellite sensors (GOES, AVHRR and MODIS) for 48 hours. The fine (<15 μm radius) ash masses in this volcanic cloud was found to be ~30 kT and the SO<sub>2</sub> mass was ~10 kT. There was a slight separation of ash and SO<sub>2</sub>, suggesting that the SO<sub>2</sub> was emitted

earlier and higher. No ice signal could be detected. The most important new observation about the Cleveland eruption was the enhanced sensitivity of the infrared detection from the large satellite zenith angles (Gu et al, in prep).

### **Other ice subordinate examples.**

We have observed more examples of ash dominant volcanic clouds, such as Augustine, 1986 (Holasek & Rose, 1991) and Kluichevskoi, 1994 (Rose et al, 1995). We note that these examples are all at latitudes >40, which suggests that tropospheric water vapor, which is much higher at tropical latitudes, influences volcanic cloud ice through the entrainment process (Glaze et al, 19xx).

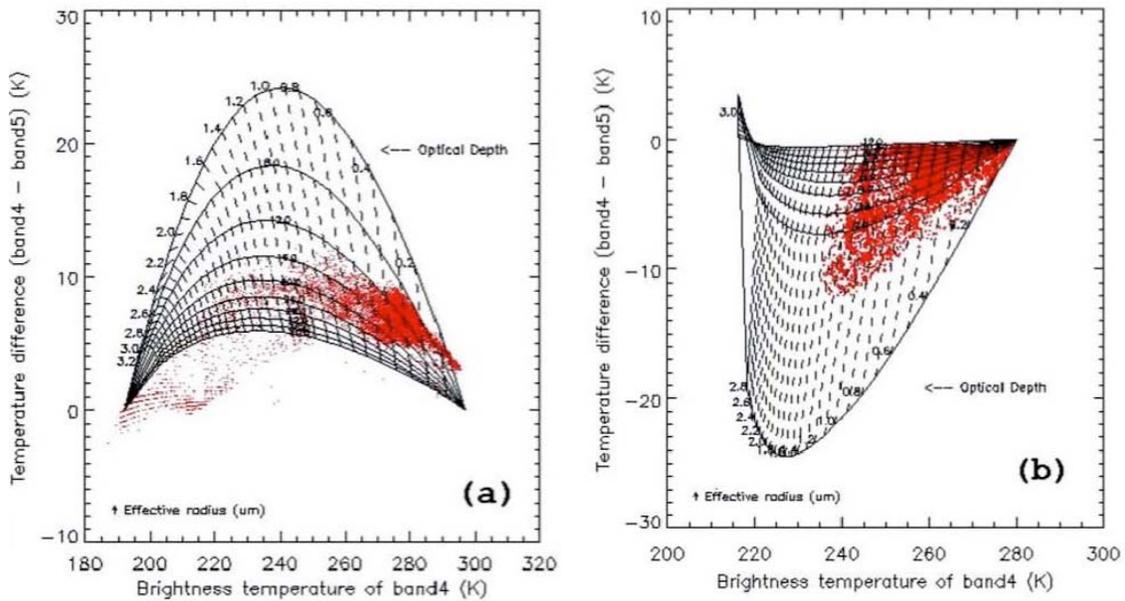
### **Subequal Proportions of ice and ash in volcanic clouds**

#### **Pinatubo, Philippines 1991**

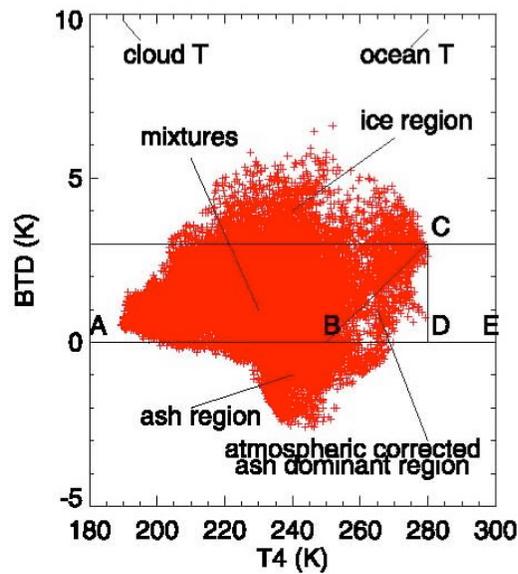
The largest eruption of the past 25 years, Pinatubo produced truly global scale atmospheric changes from its climactic eruption on 15 June 1991 (McCormick et al, 199x). About 80 MT of ice, about 50 MT of fine ash (<15 μm radius), and 18-19 MT of SO<sub>2</sub> were found in Pinatubo's huge volcanic cloud by Guo et al (2004a, 2004b). The coexistence of ice and fine ash makes retrieval using the two band BTM method of Wen & Rose difficult or impossible (Figure 2). This observation highlights an important issue for volcanic cloud detection, and provides a need for further development of multispectral infrared retrieval algorithms such as Yu & Rose (2000). The effects of ice in the Pinatubo cloud were marked: 1. SO<sub>2</sub> was apparently significantly sequestered by ice (Figure 3) during the first day of atmospheric residence (Guo et al, 2004a) and 2. The ice and the ash fell out of the cloud quickly (about 90% removed in 3 days) and at very similar rates, suggesting that they fell out as ice/ash aggregates (Guo et al, 2004b).

#### **Soufrière Hills, Montserrat, 26 December 1997**

On 26 December 1997, the volcanic dome at Soufrière Hills, Montserrat collapsed catastrophically, producing a debris avalanche.



**Figure 2:** Brightness temperature difference (BTD) of band 4 ( $\lambda=11 \mu\text{m}$ ) and Band 5 ( $\lambda=12 \mu\text{m}$ ) data from AVHRR plotted against band 4 brightness temperature for two eruption clouds: a: Rabaul, 19, Sept, 1994, which was interpreted as ice dominant and b: Kluchevskoi, 1 October 1994, which was interpreted and ash dominant (Rose et al, 1995).



**Figure 3:** BTD plot, as in figure 2, but for the volcanic cloud of Pinatubo, 15 June 1991. This volcanic cloud is extremely variable and plots mainly in region labeled "mixtures", and only partly in the fields labeled "ash region" and "ice region". Compare with figure 2.

a pyroclastic density current and an ash cloud which rose to 15 km (Sparks et al, 2003). Because the density current carried hot andesite directly to the sea, the evaporation of the ocean led to the formation of a volcanogenic meteorological cloud, which also rose to stratospheric levels. The mapping of two stratospheric clouds and their particle masses (~45 kT fine ash (<15  $\mu\text{m}$  radius) in the volcanic cloud; ~150 kT ice in the volcanogenic meteorological cloud) was demonstrated by Mayberry *et al* (2003). The two clouds overlapped in their two dimensional extent as they drifted SE for more than 6 hours.

### **El Chichón, Mexico 1982**

The El Chichón eruption consisted of 3 large phases (the first and smallest on March 29 and the other two on April 4, 1982). The April 4 events produced a volcanic cloud which dramatically separated into a higher (22-26 km high) westward-drifting SO<sub>2</sub> rich volcanic cloud and a lower (19-21 km high) which contained most of the fine ash erupted (Schneider *et al*, 1999). The April 4 events produced ~ 7 MT of SO<sub>2</sub> and about 7 MT of fine ash (<15  $\mu\text{m}$  radius) and the mass map of the cloud is obscured along its eastern edge (figure 4). By analogy with the Pinatubo example, we suggest that this is due to ice, which is present in proportions subequal to fine ash. The existence of ice may also explain the very rapid ash fallout observed by the satellite sensors, where >90% was lost in 3 days.

### **Conclusions**

Ice is present in all cold volcanic clouds and this has important implications for hazards. For detection using infrared remote sensing, ice presence in the volcanic cloud interferes with volcanic ash, which means that the simplest detection schemes (2 band brightness temperature differencing) may be less sensitive or even ineffective.

Ice may be dominant, subordinate or subequal to ash in terms of mass in volcanic clouds and we have found good examples of each of these cases in the last 25 years. High

latitude volcanoes are likely to be ice poor, perhaps because entrainment of tropospheric H<sub>2</sub>O by the eruption column is limited by the drier high latitude troposphere.

Besides entrained tropospheric water vapor, sources of H<sub>2</sub>O for volcanic cloud ice includes, magma, various hydrospheric reservoirs (ocean, crater lakes, glaciers, groundwater) and hydrothermal systems.

Ice in volcanic clouds enhances ash fallout by forming composite aggregates.

Ice forms immediately after eruption, and then decreases markedly by an order of magnitude in only a few days, apparently sublimating as well as precipitating from the drifting volcanic cloud.

Ice sequesters SO<sub>2</sub>, and can remove it by precipitation or release it during sublimation, so that SO<sub>2</sub> masses in volcanic clouds have been observed to increase for 1-2 days after eruption.

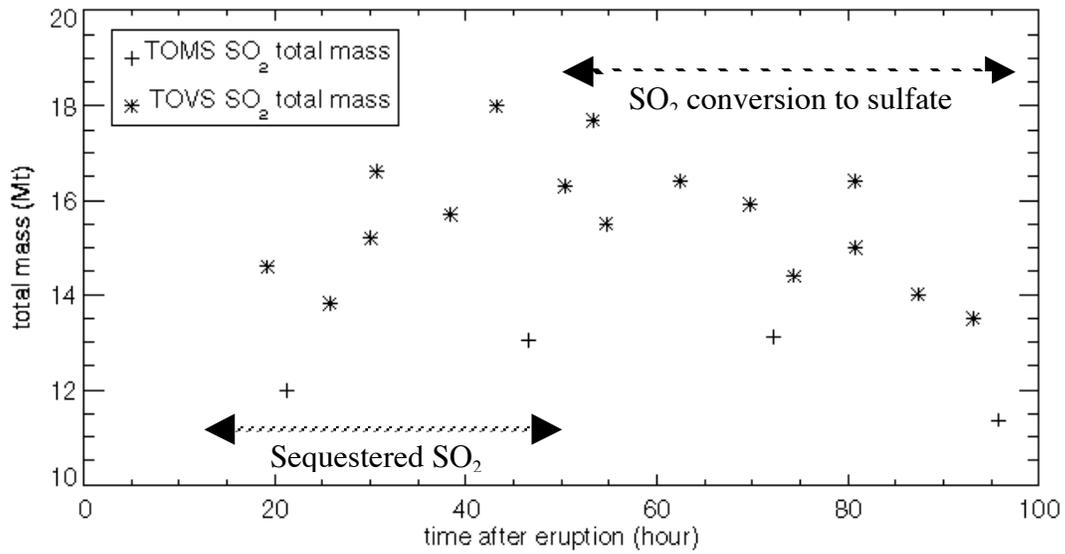
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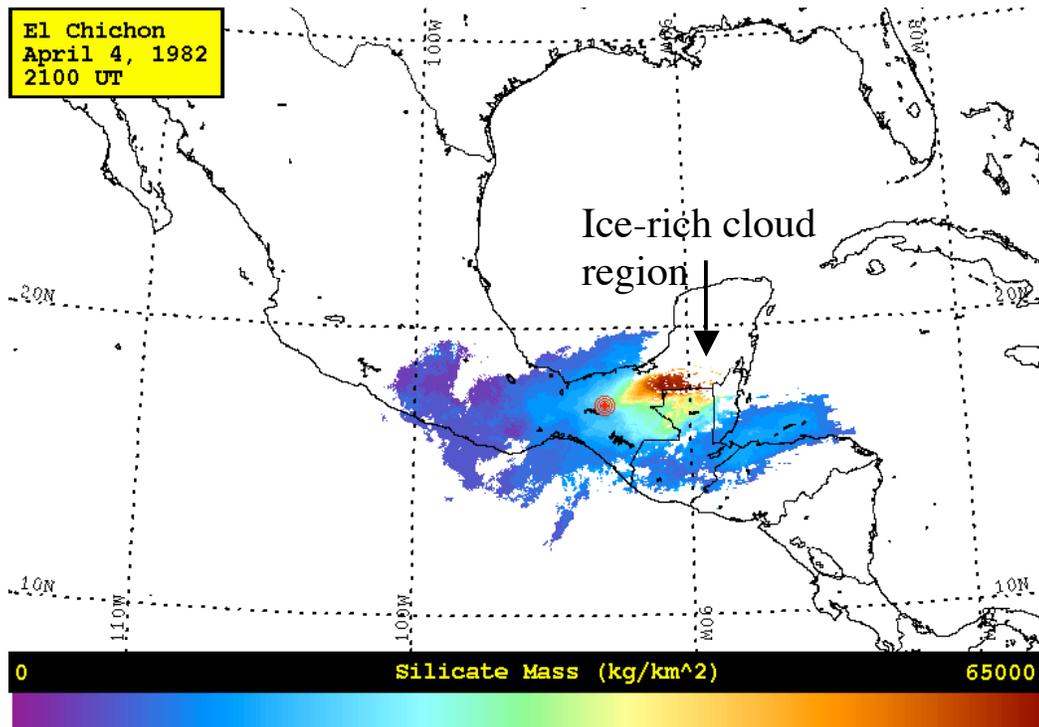
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**Figure 4:** Plot of SO<sub>2</sub> mass retrievals for the 15 June 1991 eruption of Pinatubo, showing time periods where SO<sub>2</sub> sequestration is dominant and where SO<sub>2</sub> conversion is dominant. (from Guo et al, 2004b)



**Figure 5:** Map of fine ash (<15 μm radius) burden for the El Chichón eruption cloud of 4 April 1982, showing a region where the ash signal is masked by large ice masses. Note how contours of similar burden are terminated. From Schneider et al (1999).

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