A Meteorological Approach to Calculate Volcanic Cloud Parameters

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1. Introduction

Here we present a theoretical approach to calculate volcanic cloud total water content (TWC), temperature and density from satellite observations of ash and SO2 masses, motivated by a need to better model volcanic cloud destabilisation and sedimentation mechanisms. Using parcel theory, a recently emplaced volcanic cloud can be modeled as a closed-system homogeneous fluid parcel with 3 components: Dry air, ash, and magmatic water. Mass of water entrained during plume rise is ignored, providing a minimum value for TWC. Parcel dimensions are measured after emplacement and account for the volume of entrained air. Magmatic water mass is calculated from knowledge of typical gas ratios in source volcano emissions and satellite-based measurement of SO₂ in the volcanic cloud of interest. Other volcanic gases are ignored in the calculation because concentrations are low and densities are relatively similar to atmospheric gases.

2. Parcel theory

- Predicts changes in the physical properties of an unconfined sample, or parcel, of atmospheric components.
- In the simplest case, there is no mixing between the parcel and ambient atmosphere.
- As an air parcel rises, it expands and cools: molecules in the expanding parcel collide with neighbours and expend molecular kinetic energy. Alternately, a subsiding parcel warms as it sinks.
- An underlying assumption is that cooling caused by expansion or heating from compression occurs so rapidly that these temperature changes outweigh other mechanisms of heat exchange, such as heat conduction or absorption and emission of solar radiation.
- Phase changes of water add additional complexity as condensation and freezing supplies heat to the parcel, while sublimation and evaporation removes heat.

Cloud density and temperature is approximated using the ideal gas law under the following assumptions: (1) The volcanic cloud is in dynamic equilibrium; (2) fine ash (1-25 μ m) and magmatic water are not removed by sedimentation by the time of analysis; (3) the volumetric fraction of magmatic water and volcanic ash is so small that displaced air is negligible in the parcel density determination.

3. Mass of magmatic water

A. Petrographic method

To calculate total magmatic water erupted, we take the following approach. First we calculate DRE mass erupted from field investigations of the tephra blanket and other deposits. We then assume that: (1) the water released is proportional to the erupted magma mass; (2) all of the water that was in magma is liberated during eruption; and (3) chemical analysis of melt inclusions in the magma estimates the mass of magmatic water. We ignore water incorporated into the cloud through entrainment by the convecting plume.

B. Gas ratio method

Mass of water in a volcanic cloud can also be estimated using known H 20/SO2 from volcanic gas vents sampled at source volcanoes, and satellite measurements of SO₂ mass in a volcanic cloud. SO₂ is a common component of volcanic plumes and clouds, but normally has low background concentrations in the atmosphere. For this reason, SO2 and other volcanic gases can be detected using satellite sensors such as AVHRR, TOMS or MODIS.

4. Total cloud water mixing ratio

Calculating volcanic cloud dimensions

The volume of a volcanic cloud V_{vc} can be approximated using the following expression:

$$V_{vc} = \int \int A_{vc} dz \tag{1}$$

where A_{vc} is the cloud area and z is cloud thickness. Cloud area is measured in georeferenced satellite images by calculating the integral of pixel area that corresponds to the volcanic cloud. Cloud thickness is estimated from trajectory modeling in the absence of direct measurements.

Total cloud water mixing ratio (TWC)

The mass of magmatic water erupted, estimated above, is used to calculate total cloud water mixing ratio for a volcanic cloud using satellite-based measurements of the characteristics of a volcanic cloud. Assuming that all the cloud water is initially in vapour form, mixing ratio w describes the mass of water vapour per unit mass of dry air. In the first step, we calculate the total water content TWCof the volcanic cloud per unit volume.

$$TWC = m_v / V_{vc} \tag{2}$$

where m_v is mass of magmatic water vapour. Mixing ratios for the volcanic cloud can then be calculated:

 $w = TWC/\rho_d$ (3)

where the density of dry ambient air ρ_d is determined using the equation of state for an ideal gas:

$$\rho_d = p/RT_d \tag{4}$$

and where p is ambient pressure, R is the gas constant for dry air (287.05 J kg⁻¹ K⁻¹) and T_d is ambient temperature.

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5. Volcanic cloud temperature and density

For simplicity and in the absence of measurements of entrained air mass, it is assumed that the mass of dry air in the volcanic cloud m_d is equal to the mass of ambient atmosphere at the same pressure. In this case, the cloud is modelled as though ash particles and water vapour are added to pre-existing atmosphere. Volcanic cloud density ρ_{vc} is then:

 $\rho_{vc} = (m_d + m_v + m_a)/V_{vc} \qquad =$

where ρ'_d , ρ'_v , and ρ'_a are the respective partial densities of dry air, water vapour and ash: these are the densities that would result if the mass of each component occupied the cloud volume individually (Wallace and Hobbs [1977], p. 51). Using remote sensing techniques, the ash burden of a given volcanic cloud can be directly measured.

The partial density of suspended ash particles can be calculated from remote sensing ash retrievals and volcanic cloud volume:

 $\rho_a' = m_a / V_{vc}$

where m_a is mass of ash in the cloud. This quantity is independent of and water components of the cloud parcel. To calculate the temperatu equation of state:

 $T = p/R_m \rho_{vc}$

where R_m is the individual gas constant for moist air, which depends on mixing ratio according to:

 $R_m = R(1 + 0.6w)$

The volcanic cloud is slightly denser than the ambient atmosphere as it contains solid particles and magmatic water, so for the volcanic cloud to be in dynamic equilibrium with the ambient atmosphere, it would need to be warmer. Volcanic cloud equilibrium temperature T_{vc} is:

$$T_{vc} = T_d + (T_d - T_d)$$

6. Which water phase will be stable in the volcanic cloud?



Figure 1. (a) Standard atmosphere temperature; (b) water phase diagram; (c) equilibrium vapour pressure curve for liquid water and ice.

In the atmosphere, water freezes by heterogeneous ice nucleation at temperatures between -3 °C to -40°C, or by homogeneous ice nucleation at <-40°C. Saturation describes a state of dynamic equilibrium between different phases of a substance. In the case of pure water, the density and pressure of the saturated vapour over either a liquid or solid phase depends on temperature. These variables can be calculated at a specific temperature with respect to vapour, liquid and ice phases.

Measurements of cloud temperature, pressure and water content can be used to calculate vapour pressure e:

 $e = \rho_v R_v T_{vc}$

where R_v is the individual gas constant for water vapour (461.5 J kg⁻¹ K⁻¹). In our approach, water vapour density ρ_v is equivalent to TWC, which is related to vapor pressure by the following expression:

 $\rho_v = e/R_v T_{vc}$

Modifying equation 2.11 in Rogers and Yau [1989] yields the following expression for calculation of saturation vapour pressure with respect to ice e_i :

 $e_i(T) = e_{i_0} e^{(L_s/R_v[1/T_0 - 1/T])}$

where e_{i_0} is the saturation vapour pressure at T_0 , determined empirically, and L_s is the latent heat of sublimation of water (2.8×10⁶ J kg⁻ ¹). For example, if $e = e_i$, the vapour phase will be in equilibrium with the solid phase and hydrometeors will neither grow or sublimate. However, ice crystals exposed to an atmosphere where the actual vapour pressure is less than the saturation vapour pressure with respect to ice, i.e. $e < e_i$, will tend to sublimate. We can rearrange the vapour pressure expression to calculate a saturation vapour density ρ_i :

 $\rho_i = e_i / R_v T_v$

From this, ice water content *IWC* can be calculated:

IWC = TWC -

$$\equiv \rho_d' + \rho_v' + \rho_a' \tag{5}$$

(6)
pressure and can be added to the density contributed by the dry air
are of the volcanic cloud at the same pressure
$$T$$
, we use the
(7)

(8)



(10)





с	(13)	
$- ho_i$	(14)	

7. Example calculation: 17 September 1992 Crater Peak eruption, Mt. Spurr, Alaska.

Crater Peak and Mount Spurr are located ~125 km west of Anchorage, Alaska. Crater Peak erupted on 16-17 September 1992 (in addition to 27 June and 18 August 1992). The cloud was observed and measured by satellite-based sensors less than 10 minutes after the end of the eruption (3.7 hour old cloud [Rose et al., 2001]). Many sources of observational data exist for the volcanic cloud and associated fallout deposit from this eruption including radar [Rose et al., 1995], satellite remote sensing [Bluth et al., 1995; Rose et al., 2001; Schneider et al., 1995] and field-focused studies [McGimsey et al., 2002; Neal et al., 1995].

Satellite observations of the Spurr eruptions



Figure 2. AVHRR 3.7 hour old September Spurr cloud imaged at 1240 UT on 17 September 1992 [Schneider et al., 1995].

SO₂ peaks were commonly observed in the clouds on the second day after eruption. The favoured hypothesis is that ice sequestered SO₂ during the eruption, which was later released as the ice in the cloud sublimated, due to mixing with ambient atmosphere [Rose et al. 2001].

Characteristics of September Spurr eruption fallout

A second MPUA maximum begins	
182 km from the vent and extends to 365 km downwind [McGimsey et al. 2002].	
Secondary maximum has a bimodal grainsize distribution, consistent with the fallout of aggregates of 100-300 μ m diameter composed dominantly of 10-30 μ m ash [Rose et al. 2001].	62°0 61°00'

Figure 3. Mass accumulation map from McGimsey et al. [2002].

Calculated characteristics of 3.7 hour 17 September 1992 Spurr volcanic cloud

Mass of magmatic water erupted

 $TWC = 7.1 \times 10^{-2} \text{ g m}^{-3}$ Total cloud water: $w = 2.3 \cdot 10^{-1} \text{ g kg}^{-1}$

Total cloud ice water content:

8. Conclusions

(1) The 17 September 1992 Spurr volcanic cloud contained at least 0.2 g kg⁻¹ water, of which ~86 % was ice and the remaining ~14 % was in the vapour phase (ignoring entrained lower tropospheric water vapour, and assuming water phases are in equilibrium, vapour is saturated and no precipitation occurred before 3.7 hours).

(2) IWC in the September 1992 Spurr cloud was 0.06 g m⁻³. An IWC value of ~0.1 g m³ is typical for a tropical cirrus anvil cloud at a similar height, but is ~60 times greater than typical synoptically-formed cirrus values [T. Garrett, personal communication, 2005].

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	00:48	Plume height 12200 m (NWS radar).				
	00:50	Intense incandescence observed.				
	02:21	Maximum	n plume height 13900 m	(NWS radar).		
	03:39	End of er	uption.			
	Eruption chronology from <i>Eichelberger</i> [1995]; times are in AKS ⁻					
ible a	2 Septemb	er Spurr	eruption cloud char	racteristics		
loud a	rea		3.4×10 ¹⁰ m ²	1		
loud t	hickness		1×10 ³ m	(estimate)		
loud v	olume		3.4×10 ¹³ m ³	(estimate)		
odelle	ed cloud level		12159 m	2		
mbien	t temperature		211 K	3		
mbien	t pressure		19100 Pa	3		
mbien	t atmospheric	density	3.154×10 ⁻¹ kg m ⁻³	(calculated)		
xtrapo	lated cloud as	sh mass	4.5×10 ⁸ kg	1		
allout	(DRE)		15×10 ⁶ m ³	4		
sh der	nsity		2600 kg m ³	4		
sh spe	ecific heat cap	acity	1150 ± 250 J kg ⁻¹ K ⁻¹	5		
otal mass erupted		3.9×10 ¹⁰ kg	(calculated)			

Table 1. September Spurr eruption chronology

Plume height 10700 m (PIREPS and NWS radar)

Start of eruption.

Sources – (1) *Rose et al.* [2001]: (2) based on *Eichelberger et al.* [1995 Nye et al. [1995]; (7) Wallace [2004]; (8) Emissions sampled at Augustine Volcano, Alaska, by Symonds et al. [1992]

3 wt %

12.1

2×10⁸ kg

Magma water conter

SO₂ mass

H₂O: SO₂



d:	Petrographic method = ~1.1×10 ⁹ kg
	Gas ratio method = 2.4×10⁹ kg

 ρ_i = 9.2 ×10⁻⁶ kg m⁻³ IWC: 6.1 ×10⁻⁵ kg m⁻³

Ash partial density:

 ρ'_a = 1.3×10⁻⁵ kg m⁻³

 ρ_{vc} = 3.155×10⁻¹ kg m⁻³ Volcanic cloud density: (~0.03 % denser than ambient atmosphere)

 T_{vc} = ~211.1 K Volcanic cloud temperature: (~0.05 % warmer than ambient atmosphere)

(3) Under these assumptions, total ice mass in the 3.7 hour September 1992 Spurr cloud was ~2×10⁹ kg.

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