Estimates of the Dynamics of Volcano Eruption Column Using Real-time AVHRR Data

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Abstract

Using real-time AVHRR infrared data, it is shown a quantitative model capable to estimate plume dynamic parameters such as emplacement temperatures related with the total energy of the column, gas weight fraction, bulk density of the mixture, cloud rise velocity, etc. The model opens new possibilities to generate in real-time important dynamic parameters of volcano eruption columns.

Introduction

Volcanic plumes are one of the most spectacular of natural phenomena. Fundamentally they represent convective transfer of substantial amounts of heat, from the Earth´s interior in a very short period of time. They also transfer particles, gases, and aerosols to the surface environments of the Earth. The focused convective flows that constitute volcanic plumes involve a rich variety of dynamical processes that are both fascinating and challenging to study (Sparks et al, 1997).

Volcanic activity at Popocatépetl (19.02 N, 98.62 W, 5426 m) during March-July 2003 was comprised principally of multiple exhalations (some with significant ash), volcano tectonic earthquakes and explosions. Daily exhalations averaged 50 events during July. The largest explosive events in July were recorded on 1,15, 19 and 25. The event of 19 July caused light ash fall as far as the southern metropolitan area of Mexico City (Smithsonian Institution, 2003).

The short-lived Vulcanian-style explosion of 19 July occurred at 9:21 local time (see Fig. 1) which was fortuitously captured by AVHRR 1 km LAC (local area coverage) multispectral scenes during the NOAA-17 satellite pass received at our ground NOAA satellite receiving station in real-time (Galindo and Domínguez, 2003)

In Volcanology satellite images have been used to estimate volcanic eruption column height and plume top temperature (Sparks et al, 1997). On the other hand, theoretical work based on turbulent gravitational convection forms the basis of the investigation of plume behavior (Sparks, 1986), however, field determinations of the physical parameters from volcanic explosion clouds are made using high sampling photographic records (1 frame per second) (Rose et al, 1978, Wilson and Self, 1980).

19 Jul 2003 09:24, (19 Jul 2003, 14:24 GMT)

19 Jul 2003 09:26, (19 Jul 2003, 14:26 GMT)

19 Jul 2003 09:31, (19 Jul 2003, 14:31 GMT)

Fig 1. Explosion eruption of Popocatépetl volcano at 09:15 a.m. local time. July 19, 2003

In this paper an attempt is made to estimate plume dynamic parameters such as emplacement temperatures related with the total energy of the eruption column gas weight fraction, bulk density of the mixture, cloud rise velocity, etc., from the real-time AVHRR middle and thermal infrared data.

Estimates of eruption column height

AVHRR digital images of the 9:15 a.m. (local time) NOAA-16 satellite pass have been used to estimate eruption column height. The shadow method (Glaze et al 1989) was applied to one of the images with known control references. Using basic geometry it was estimated the column height by measuring the length of the shadow cast ($\approx$ 13 km) on the Earth´s surface. The sun angle ($h = 29.2°$) was determined as usual as a function of solar declination, latitude, and local hour angle, Then the cast shadow of the highest point of the cloud was determined, $H = 7.3$ km.

Temperature and irradiance distribution of the explosion cloud

The temperature of the plume was determined as brightness temperature $\Delta T_{34} = T_3 - T_4$ from the AVHRR channel-3 and channel-4 temperatures. Channel-4 temperature,T_4 represents the ambient temperature (Harris et al, 1995 , Galindo and Dominguez, 2003). The irradiance of the plume was obtained with the aid of the inverted Planck´s equation.

Figure 2 shows the irradiance distribution of the volcanic cloud. It is observed that there are three nuclei of maximum irradiance. The largest one is located at the western part of the summit, it continues to the second nuclei located outside of the summit at the southeast. The smallest nuclei but the most intense is seen outside the summit at the northwest direction. The latter nuclei it is also seen in the visible and near infrared channels -1 and –2 indicating, besides reflected sunlight, energy emission in the 0.725 to 1.10 μm waveband. Following Planck´s law, thermal emittance at these wavelengths indicates the presence of an extremely hot surface together with. ash emission in very discrete amounts was also detected at the southeast side of the summit (Figure 3).

The model of a discrete volcanic explosion cloud

In what follows an attempt is made to estimate several dynamic parameters of volcanic explosion clouds from the satellite irradiance data.

To test the validity of the approach and results here presented we shall follow the model of Wilson and Self (1980) who analyzed photographic records of 10 volcanic eruption clouds during the 1978 eruption of Fuego Volcano in Guatemala.

The motion of a discrete explosion cloud as it emerges from the vent can be studied if the following simple approximations are made:

(1) the cloud decompresses to atmospheric pressure quickly,
(2) the cloud is treated as a rigid, incompressible vertical cylinder

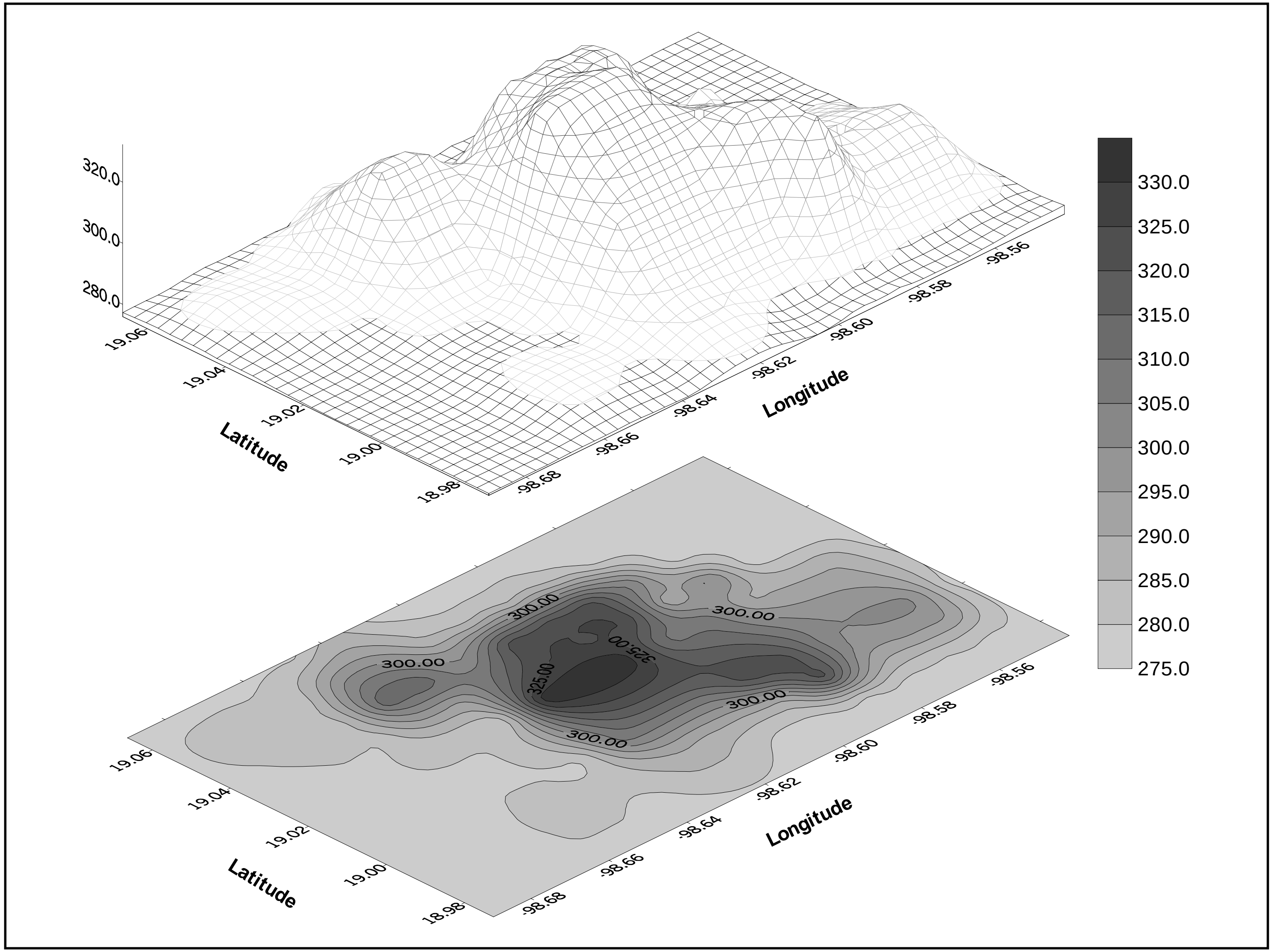

Fig. 2. Effective infrared brightness temperature [K] distribution of the explosion plume as it was detected by NOAA-15 satellite pass at 9:15 local time

Channel-1. Visible

Channel-2. Near infrared

Channel-3. Middle infrared

🟩 Ash emission

🟨 Square crater area

Fig. 3. Explosion eruption of Popocatépetl volcano as detected by AVHRR NOAA-15 at 09:15 a.m. local time. July 19, 2003

{the latter approximation is valid if velocities are well below the speed of sound but becomes increasingly inadequate with time after emergence as spatial gradients develop in pyroclastic number density, particle size, water vapor content, and temperature (Wilson and Self, 1980)}.

The equations of motion for the vertical cylinder are found by equating the product of mass and acceleration to the total forces acting on the cloud: atmospheric drag, gravity, and buoyancy.

After some parameterizations of the basic equations, Wilson and Self (1980) have obtained expressions in terms of the quotient β/α. Where β is the bulk density of the mixture (kgm^{-3}) and α (kgm^{-3}) represents the density on environment.

For a vertical cylinder the equivalent equation is

$$\beta/\alpha = (g - 3\ C_c\ W^2/2H)/(g + du/dt) \qquad (1)$$

Here the upward acceleration of the cloud is du/dt (negative if the cloud is decelerating), and the dimensionless drag coefficient C_c for a cylinder is about 1.0, W is the relative velocity of the leading edge of the cloud and the air, and u the velocity of the cloud center. H = 7.3 km is the cylinder height, i.e., the obtained estimate of eruption column height

The relation of β/α to other parameters can be investigated by considering the behavior of temperature within the eruption clouds.

After few seconds of rise, a cloud consists essentially of incorporated air plus those particles that have not fallen out of the cloud. As the air temperature rises from an ambient temperature θ_a to a new value θ, the air density will decrease from α to $(\alpha\theta_a/\theta)$.

If the gas weight fraction of the cloud is n, the particle weight fraction is (1- n) and the bulk density β is given by

$$1/\beta = (n/\alpha(\theta_a/\theta)) + (1 - n)/\rho \qquad (2)$$

where ρ is the density of the gas (kgm^{-3}), i.e.,

$$\alpha/\beta = n\ (\theta_a/\theta) + \alpha\ (1 - n)/\rho \qquad (3)$$

i.e.,

$$1/\beta = n/\alpha\ (\theta_a/\theta) + (1 - n)/\rho \qquad (4)$$

If the clasts removed from the cloud an any stage contribute negligible heat to the cloud. Then θ is obtained by equating the heat loss by clasts

$$[(1 - n)\ S_s\ (\theta_s - \theta)]$$

to the heat gained by air

$$[n\, S_a\, (\theta - \theta_a)],$$

$$\theta/\theta_a = [n\, S_a/S_s + (1- n)\, \theta_s/\theta_a]/[1 + n\, (S_a/S_s - 1)] \quad (5)$$

where S_a and S_s are the specific heats at constant pressure of air and rock, the adopted values being 0.24 and 0.20 cal/g/K, respectively.

A simplification can be made to (3) because all values of β/α encountered in the cases analyzed by Wilson and Self (1980) are greater than 0.5 and mostly close to 1; at the height of the summit of Fuego, but ρ is about 2 g cm^{-3}, so α/ρ is < 0.001; hence $(1 – n)\, \alpha/\rho$ is always $<< \alpha/\beta$ and can be neglected, giving

$$\alpha/\beta = n\, \theta/\theta_a, \quad (6)$$

At the height of the summit of Popocatépetl volcano α is about 8.194×10^{-4} g cm^{-3}. At the umbrella region of the volcanic cloud α is about
5.25×10^{-4} g cm^{-3}.

Air temperature at the summit of Popocatépetl volcano was estimated using channel-4 temperature, T_4 outside of the volcanic cloud, i.e., $T_4 = \theta_a =$.
Whereas $\theta_s = 337$ K is the temperature of the rocks, i.e., the maximum temperature detected at the main nuclei of Figure 3, i.e., at the gas thrust region and the minimum temperature of the plume is taken as the new reference temperature $\theta = 291$ K measured within the convective region.

Having done that, the algorithm runs and calculates n, from equation 4. Given a range of value for n, equations 4-6 can be used to estimate successive values of β/α from brightness temperatures of θ/θ_a.

Wilson and Self (1980) assumed "in situ" values for θ_s/θ_a, i.e., if $\theta_s = 1373$ K (1100 °C) and $\theta_a = 273$ K (0 °C), then $\theta_s/\theta_a = 5.0$, if θ_s is as low as 1123 K (850 °C) and θ_a is as large as 288 K (15 °C).These two values probably bracket the range of reasonable possibilities.

Results

A comparison of β/α for the explosions of Fuego volcano (Wilson and Self, 1980). and Popocatépetl volcano is shown in Table 1. Since the agreement is quite good, then one can use the cloud rise velocity u calculated for Fuego.

The middle infrared irradiance emitted from the volcanic cloud and detected by the AVHRR channel-3 is proportional to the total energy that the cloud is emitting into the atmosphere, then the detected brightness temperatures θ_s/θ_a should be proportional to those "in situ" values considered by

Theoretical

θs/θa = 4

n	θ / θa	β / α
0.01	3.98	25.156
0.05	3.87	5.162
0.10	3.75	2.669
0.30	3.21	1.037
0.50	2.64	0.758
0.70	2.02	0.707
0.80	1.69	0.738
0.90	1.35	0.820
0.95	1.18	0.893
0.99	1.04	0.975
1.00	1.00	1.000

θs/θa = 4.5

n	θ / θa	β / α
0.01	4.47	22.367
0.05	4.35	4.594
0.10	4.20	2.378
0.30	3.58	0.931
0.50	2.91	0.687
0.70	2.19	0.652
0.80	1.81	0.691
0.90	1.41	0.786
0.95	1.21	0.871
0.99	1.04	0.969
1.00	1.00	1.000

Our results

θs/θa = 4

n	θ / θa	β / α
0.02	3.93	13.603
0.06	3.80	4.676
0.09	3.67	2.888
0.19	3.33	1.559
0.29	3.00	1.133
0.40	2.67	0.937
0.51	2.33	0.840
0.63	2.00	0.800
0.74	1.67	0.806
0.87	1.33	0.862
1.00	1.00	1.000

θs/θa = 4.5

n	θ / θa	β / α
0.01	3.98	35.651
0.05	3.83	5.315
0.90	3.68	2.956
0.11	3.60	2.442
0.22	3.23	1.378
0.34	2.85	1.028
0.46	2.48	0.873
0.59	2.10	0.807
0.72	1.73	0.801
0.86	1.35	0.858
1.00	1.00	1.002

Table 1. Comparison of theoretical eruption cloud data (Wilson & Self, 1980) against data obtained from measurements of infrared brightness temperature

Wilson and Self (1980). A comparison of our results with the theoretical eruption cloud parameters. shows a very good agreement..

Conclusions

Besides the estimates of volcanic eruption column height and plume top temperature, satellite brightness temperatures can be used to estimate some parameters related with the plume dynamics, such as thermal energy, gas weight fraction, bulk density of the mixture and cloud rise velocity.

Brightness temperature of the volcanic cloud is proportional to the total emitted energy from the volcanic cloud. Therefore, upwelling middle infrared radiation data at the gas thrust region can be “calibrated” to estimate total emitted energy and related dynamic parameters of a explosion cloud

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