Influence of the coarse solid aerosol particles on the evolution of a volcanic plume

L.S. Ivlev, Yu.A. Dovgalyuk,* and N.E. Veremei*

Research and Development Institute of Physics at the St.-Petersburg State University, St. Petersburg
** A.I. Voeikov Main Geophysical Observatory, St. Petersburg*

Received February 9, 2000

We study the dynamic characteristics of a volcanic plume that is being a vertical cylindrical convective jet above a crater depending on the intensity of aerosol emission, particle size, and density of the particulate matter. In computations, the nonstationary numerical model of a convective jet is used. It is shown that the rate of the convective flow decreases with the increasing intensity of aerosol emission.

Introduction

We considered the evolution of a volcanic emission plume (VEP) being a vertical convective jet of cylindrical shape in the case of no aerosol emission. We studied the dependence of VEP dynamic characteristics on the perturbation of temperature fields and the speed of medium motion in the surface atmospheric layer, as well as on the temperature stratification of the atmosphere and the jet radius. Ignoring the emission of eruption products is an idealization that is far from actual conditions. That is why the set of equations should be supplemented with the equation that describes aerosol spread in the troposphere and the effect of aerosol on the VEP dynamics should be taken into account.

In this work we apply numerical simulation to the study of the spread of coarse aerosol particles in a convective jet and their influence on the dynamic characteristics of the VEP evolving in the atmosphere at a given altitude profiles of temperature and pressure without the account for condensation of water vapor. It is assumed that air pressure inside the VEP $p(z)$ instantaneously becomes equal to the pressure in the unperturbed ambient atmosphere $\bar{p}(z)$. The pressure difference between the VEP and the ambient medium is taken into account only in calculating buoyancy.

1. Basic equations of the numerical model

In calculations we used the 1.5D numerical model of a convective nonstationary jet containing suspended aerosol particles. The model was developed and then improved in the A.I. Voeikov Main Geophysical Observatory. The set of hydrothermodynamics equations complemented with the equation of balance of the aerosol mass was averaged over the horizontal cross section of the cylindrical zone of radius R, within which the VEP evolves. The lower boundary of the cylinder is at the surface level ($z = 0$), while the upper one is at some altitude $z = H$ at which the medium remains unperturbed. Both inside and outside this zone all physical parameters change in space only with altitude. The convective jet does not perturb the atmosphere beyond the cylinder, but the VEP and the ambient medium are permanently interacting because of the ordered entrainment and turbulent mixing.

The set of equations of the model includes

– the equation of motion

$$\frac{\partial w}{\partial t} = -\, w \frac{\partial w}{\partial z} - \frac{2\alpha^2}{R}\, |w| w - \frac{2}{R}\, \tilde{v}\, (\tilde{w} - w) + g\, \frac{T_\text{v} - \bar{T}_\text{v}}{\bar{T}_\text{v}} + a + gQ_\text{p}; \tag{1}$$

– the equation of continuity

$$\frac{2}{R}\, \tilde{u} + \frac{1}{\rho_\text{a}} \frac{\partial}{\partial z} (\rho_\text{a}\, w) = 0; \tag{2}$$

– the heat influx equation

$$\frac{\partial T}{\partial t} = -w \left(\frac{\partial T}{\partial z} - \gamma_\text{a}\right) - \frac{2\alpha^2}{R}\, |w| (T - \bar{T}) - \frac{2}{R}\, \tilde{u}\, (\tilde{T} - T); \tag{3}$$

– the equation of balance of the aerosol mixing ratio (Q_p)

$$\frac{\partial Q_\text{p}}{\partial t} = -(w - v_\text{p}) \frac{\partial Q_\text{p}}{\partial z} - \frac{2\alpha^2}{R}\, |w| (Q_\text{p} - \bar{Q}_\text{p}) - \frac{2}{R}\, \tilde{u}\, (\tilde{Q}_\text{p} - Q_\text{p}) + \frac{Q_\text{p}}{\rho_\text{a}} \frac{\partial}{\partial z} (\rho_\text{a}\, v_\text{p}) + F; \tag{4}$$

– the equation of hydrostatics

$$\frac{\partial p}{\partial z} = -\, \rho_\text{a}\, g; \tag{5}$$

– the ideal gas equation

$$p = R_\text{a}\, \rho_\text{a}\, T. \tag{6}$$

Here t is time; w and $\tilde{u}$ are the vertical and radial components of the medium velocity, respectively; T is the absolute temperature; T_v is the virtual temperature; p is the air pressure; α is the turbulent mixing coefficient; g is the acceleration due to gravity; ρ_a is the air density; γ_a is the dry adiabatic temperature lapse rate; R_a is the gas constant of dry air; a is the constant acceleration of the medium in the surface atmospheric layer within the cylindrical zone; F is the intensity of aerosol emission into the convective jet; v_p is the weighted mean sedimentation rate of aerosol particles (the radius of aerosol particles (r_p) and their density (ρ_p) are assumed the same for all particles, that is, monodisperse aerosol of homogeneous composition is considered). The overbar and tilde label the parameters corresponding to the outer region of the cylinder and its boundary, respectively.

This scheme is completed with a set of the initial and boundary conditions and the numerical scheme of solution (forward in time and upward opposite the flow[1–4]).

2. Statement of the problem

The state of an unperturbed atmosphere is taken as the initial conditions: the linear vertical temperature profile $\bar{T}(z)$ ($\partial\bar{T}/\partial z = \gamma_1$ at $z < 1$ km and $\partial\bar{T}/\partial z = \gamma_2$ at $z > 1$ km) and the pressure profile $p(z)$ determined by the profile $\bar{T}(z)$ according to Eqs. (5) and (6), as well as the characteristics of volcanic perturbation of the near-ground layer, namely, the air overheating in the inner region of the cylinder with respect to the ambient medium (ΔT) and the constant acceleration a caused by the emission of volcanic gases into the atmosphere (the values of ΔT and a do not change with time).

Besides, the following input parameters are used in calculations (at fixed characteristics of the perturbation and the unperturbed atmosphere):

1) the intensity of the volcanic aerosol emission f (mass of aerosol particles emitted from a crater per 1 s per 1 m^2 of the horizontal cross section of the jet; $F = f/(\rho_a \Delta z)$, where Δz is the altitude step);

2) the density of particulate matter ρ_p;

3) particle radius r_p.

The following VEP characteristics were calculated:

1) the maximum value in the altitude profile of the upward flow rate $W(t)$;

2) the vertical speed averaged over the atmospheric column of radius R

$$\bar{w}(t) = \frac{1}{H}\int_0^H w(z, t)\,dz;$$

3) the level of volcanic convection $h(t)$ (the maximum altitude at which w exceeds 0.5 m/s).

The numerical calculations showed that in some time $\tau \simeq 10 - 15$ min after the beginning of perturbation, the parameters $W(t)$, $\bar{w}(t)$, and $h(t)$ reach some steady-state values. The aim of this work is to study the dependence of the steady-state values of these parameters (W_s, $\bar{w}_s$, and h_s) on f, ρ_p, and r_p at the preset parameters of perturbation and the ambient atmosphere.

3. Calculated results

The particles suspended in air produce an effect toward slowing down the convective jet. This is explained by the fact that aerosol particles experiencing dynamic resistance from the medium while falling act themselves on the medium with the force equal in value and opposite in sign and thus entrain some volume of the air downward. Consequently, having calculated the force of air resistance F_r, we obtain the force with which the aerosol particles act on the medium.

It is assumed that particles move relative air with the established speed v_p. Consequently, the forces acting on them are in equilibrium. Ignoring electrostatic effects, we obtain $F_r = m_p g$, where $m_p g$ is the force of gravity acting on the aerosol particles. By replacing the total mass of particles m_p with the corresponding mixing ratio, we have the term gQ_p in the equation of the medium motion (1).

Numerical calculations confirmed the slowing-down effect of particles on the air jet (the vertical profile $w(z)$ in Fig. 3 shows that the upward flow rate decreases with the increasing intensity of the aerosol emission f).

Figure 1 illustrates the dependence of W_s, $\bar{w}_s$, and h_s on f (at the fixed values of ρ_p and r_p). As f increases up to some critical value f_{cr}, the intensity of convection decreases smoothly. As f reaches f_{cr}, the values of W_s, $\bar{w}_s$, and h_s decrease sharply down to almost zero level, whereas the intensity of aerosol sedimentation at the surface level I_p sharply increases by almost an order of magnitude (from 2 to 11 mm/h). This is explained by the fact that starting from some value of f the mechanical pressure of particles on air increases so that heated air from the lower layer can no longer penetrate into the atmospheric layers above it, and the upward flow is not formed; instead, a slight downward motion of air establishes. The increase of I_p is explained by the appearance of the downward flow entraining aerosol particles in the lower layers of the troposphere (see the $Q_p(z)$ profile in Fig. 3). The dotted curves in Figs. 2 and 3 illustrate the vertical profiles of $w(z)$ and $Q_p(z)$, respectively, at $f > f_{cr}$; f_{cr} for this case is roughly 12.5 g/(m^2·s).

The radius of aerosol particles in calculations varies from 10 to 125 μm. The dependence of f_{cr} on r_p obtained is shown in Fig. 4*a*. As the particle size increases, f_{cr} also increases smoothly. This is explained by the fact that large particles have higher sedimentation rate than the small ones, and they leave the atmosphere faster due to sedimentation. Thus, the mixing ratio of aerosol particles decreases as compared to fine particles, the mechanical pressure of aerosol on the medium reduces, and more intense emission of particles from the crater is needed to suppress the upward flow.

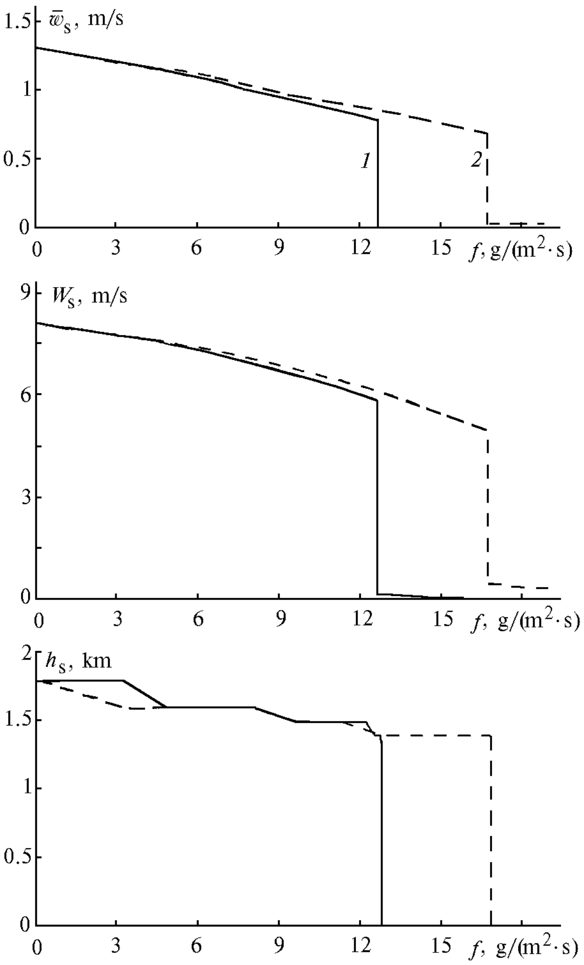

Fig. 1. Dependence of $\bar{w}_s$, W_s, and h_s on the intensity of aerosol emission at $r_p = 20$ μm (solid curve) and 100 μm (dashed curve). $a = 1.0$ m/s^2, $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $R = 1000$ m, $\Delta T = 5$°C, $\rho_p = 2$ g/cm^3.

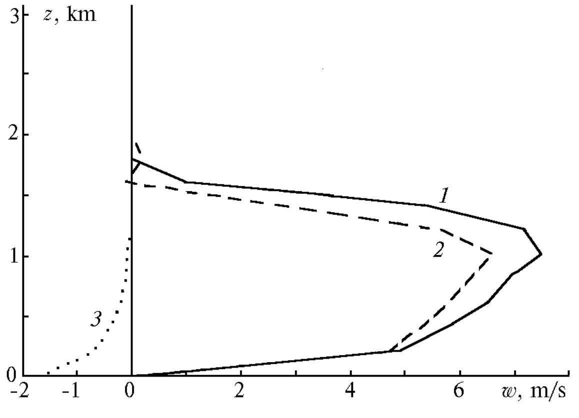

Fig. 2. Altitude profile of the vertical component of the medium motion velocity $w(z)$ at $f = 5$ (curve *1*), 10 (*2*), and 20 g/(m^2·s) (*3*). $\Delta T = 5$°C, $a = 1.0$ m/s^2, $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $R = 1000$ m, $\rho_p = 2$ g/cm^3.

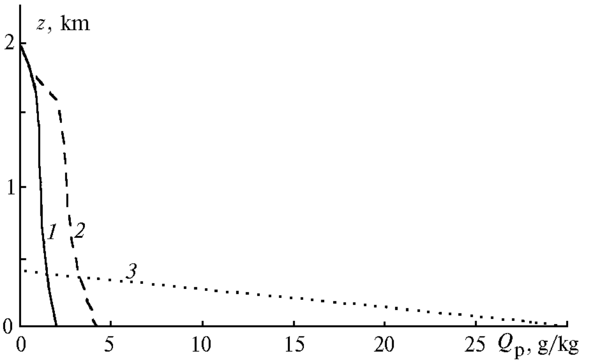

Fig. 3. Vertical profile of the mixing ratio of aerosol particles $Q_p(z)$. All conditions are the same as in the case presented in Fig. 2.

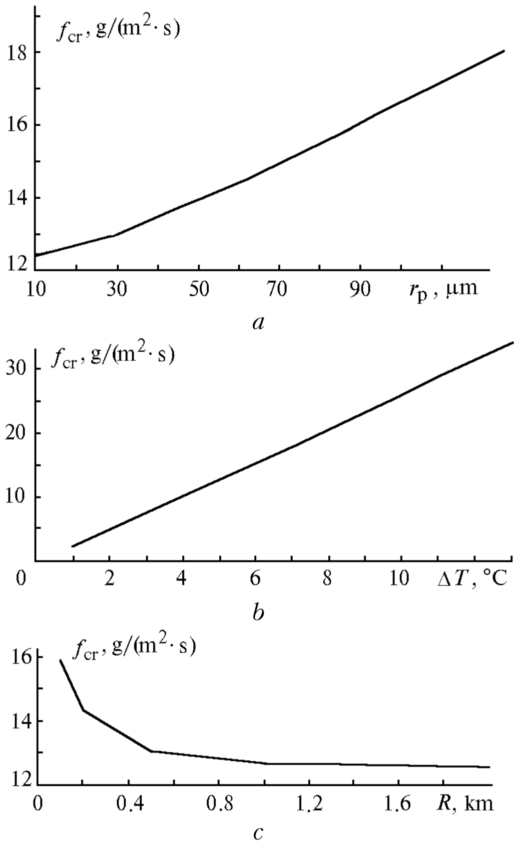

Fig. 4. Dependence of f_{cr} on radius of aerosol particles, overheat at the level $z = 0$, and jet radius at $a = 1.0$ m/s^2, $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $R = 1000$ m, $\rho_p = 2$ g/cm^3; $\Delta T = 5$°C (*a*, *c*); $r_p = 20$ μm (*b*, *c*).

Similar effect is observed when the density of particulate matter changes, which also influences the gravitational sedimentation rate. However, as ρ_p changes in a narrow range corresponding to the observed data ($1 - 3$ g/cm^3), this effect manifests itself only weakly.

The calculations showed that W_s, $\bar{w}_s$, and h_s at $f \neq f_{cr}$ only slightly depend on the particle size and density. Thus, at the same initial data as in the case presented in Fig. 1, W_s and $\bar{w}_s$ vary within 3 – 5% while r_p changes from 20 to 100 μm. This indicates that these VEP characteristics are only little sensitive to the altitude distribution of aerosol particles, which depends on their sedimentation rate.

Obviously, the influence of aerosols on the jet dynamics must be most pronounced at small perturbations, since the smaller the contribution of the two last but one terms expressing the action of overheat and mechanical acceleration of the medium by volcano in Eq. (1), the smaller is the value of f_{cr}. Figure 4*b* illustrates the dependence of the critical intensity of aerosol emission, at which the upward flow is destroyed, on ΔT (other initial conditions are given there too). Thus, at $\Delta T = 13°C$ the upward flow is destroyed at the emission intensity $f = f_{cr} = 34$ g/(m²·s), and at $\Delta T = 3°C$, i.e., in the case of weaker perturbation, f_{cr} is only 8 g/(m²·s).

The dependence of f_{cr} on the jet radius R is shown in Fig. 4*c*. At $R > 100$ m $f_{cr}(R) \simeq$ const, but at R about several hundreds meters f_{cr} starts to increase slightly with the decreasing R, because at small R the exchange of substances between the VEP and the ambient medium through the lateral boundary of the jet plays a significant role, and the loss of aerosol increases due to particle outflow into the atmosphere. This effect is observed even though the decrease of the jet radius (all other conditions being the same) leads to a decrease in the intensity of the convective flow due to energy outflow into the ambient medium.

Conclusions

The numerical model of a nonstationary convective jet containing solid aerosols has been implemented on the IBM–PC–AT, VAX, and SUN computers. The influence of coarse aerosol particles on the evolution of a convective jet generated by volcanic eruption (volcanic plume) has been studied within the framework of this model.

The following conclusions have been drawn based on the numerical calculations:

1) suspended particles have a marked slowing down effect on the evolution of a convective jet at the intensity of aerosol emission about 10^{-3} – 10^{-2} kg/(m²·s) and higher;

2) there exists some critical value f_{cr} of the aerosol emission intensity f (about 10^{-2} kg/(m²·s)), dependent on the convective flow rate, horizontal cross section of the jet, and sedimentation rate of aerosol particles; as this value is exceeded, the forces acting on the atmosphere from the volcano are fully compensated for by the force of mechanical pressure of particles on the medium, and the upward flow is replaced by the downward one;

3) as the volcanic perturbation of the atmosphere decreases, the critical intensity of aerosol emission decreases, because the lower total mass of aerosol particles is needed to destroy the weaker convective flow;

4) f_{cr} increases with the increasing sedimentation rate of particles as their radius and (or) density increases because of the decrease of the total aerosol mass in the jet due to sedimentation of aerosol particles; as the particle size increases from 10 to 100 μm, f_{cr} increases roughly 1.5 times;

5) the stable downward flow at small jet radius (about 100–500 m) is established at higher values of f, since the outflow of aerosol particles into the ambient medium plays a significant role in this case.

References

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