Numerical simulation of a volcanic plume evolution with no condensation

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The evolution of a volcanic plume being a vertical cylindrical convective jet is considered in the atmosphere at the given altitude profiles of temperature and pressure. The dependence of vertical airflow rate and the level of convection on the parameters of volcanic perturbation and unperturbed atmosphere is studied with the use of the numerical model of a nonstationary convective jet. The process of water vapor condensation is ignored.

Introduction

Besides the global influence on climate, volcanic eruptions give rise to local phenomena; in particular, they perturb temperature fields, pressure, and medium velocity near an active volcano. A *volcanic plume* (VP) is an example of such a perturbation.

In Refs. 3 and 4, the stationary axially symmetric model of a volcanic plume has been developed in the approximation of a homogeneous atmosphere. The model is applicable if the pressure inside the VP is much higher than the ambient pressure. The advantages of this model are its simplicity (the analytical solution of the set of equations has been found) and the possibility to describe the inner structure of the VP, while its most significant disadvantage is too simplified description of the state of the ambient medium. This model is inapplicable if the pressure inside the plume is comparable with the atmospheric pressure.

In this paper we describe a 1.5D numerical model of a nonstationary convective jet evolving in the atmosphere at the preset altitude profiles of temperature and pressure. This model is used to consider the evolution of the VP being a vertical jet of a cylindrical shape ignoring the processes of volcanic aerosol emission and water vapor condensation. The use of this model is justified when studying the influence of factors not connected with phase transformations of water in the atmosphere on the convective flow dynamics at a sufficiently low content of water vapor in the air.

The aim of this work is to study the influence of volcanic perturbation and the state of the unperturbed atmosphere on the dynamic characteristics of the VP by the method of numerical simulation.

1. Numerical model

In calculations we used the 1.5D numerical model of a nonstationary convective jet developed at the A.I. Voeikov Main Geophysical Observatory.[1,2]

The following simplifying assumptions were introduced when simulating the VP evolution:

1. All processes connected with the plume evolution proceed within a cylindrical zone of a given radius R.

2. The air pressure inside the jet $p(z)$ instantaneously becomes equal to the pressure of the unperturbed atmosphere $\bar{p}(z)$. The pressure difference between the VP and the ambient medium is taken into account only in buoyancy calculations.

3. No condensation of water vapor takes place in the atmosphere.

The set of equations of the model is averaged over the horizontal cross section of the cylindrical zone in which the VP 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 VP 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

$$\frac{\partial w}{\partial t} = -w\frac{\partial w}{\partial z} - \frac{2\alpha^2}{R}|w|\,w - \frac{2}{R}\tilde{u}\,(\tilde{w} - w) + g\,\frac{T_v - \bar{T}_v}{\bar{T}_v}; \quad (1)$$

– the equation of continuity

$$\frac{2}{R}\tilde{u} + \frac{1}{\rho_a}\frac{\partial}{\partial z}(\rho_a w) = 0; \quad (2)$$

– the heat inflow equation

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

– the equation of hydrostatics

$$\frac{\partial p}{\partial z} = - -\rho_a\, g; \quad (4)$$

– the ideal gas equation

$$p = R_a \rho_a T. \quad (5)$$

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. The overbar and tilde label the parameters corresponding to the outer region of the cylinder and its boundary, respectively.

This set is completed with the initial and boundary conditions. The unperturbed altitude profiles of temperature and pressure are taken as the initial conditions. The temperature profile in the ambient medium is set as follows:

$$\bar{T}(z) = \bar{T}(0) + \gamma_1 z \quad (0 < z \le z_1),$$

$$\bar{T}(z) = \bar{T}(z_1) + \gamma_2 z \quad (z_1 < z < H),$$

where $z_1 = 1$ km, γ_1 and γ_2 are the temperature lapse rates in the layers $0 < z \le z_1$ and $z_1 < z < H$, respectively (γ_1 and γ_2 are independent of z). The pressure profile $\bar{p}(z)$ is determined by the temperature profile $\bar{T}(z)$ in accordance with the Eqs. (4) and (5).

As a numerical scheme of solution, the modified scheme "forward in time and upward opposite the flow"[1,2] was used.

The volcanic perturbation of the temperature field is simulated as air overheat (ΔT) inside the cylinder at the level $z = 0$ (for simplicity it was assumed that the crater is at the surface level, what is often the case), that is, within the cylindrical zone at the moment $t = 0$ the temperature profile is the following:

$$T(0) = \bar{T}(0) + \Delta T \quad (z = 0)\ ,$$

$$T(z) = \bar{T}(z) \quad (z \ne 0)\ .$$

In addition to the overheat, the emission of the volcanic gas also perturbs the atmosphere. This process is simulated by setting a nonzero boundary condition for $w(z)$ at the level $z = 0$: $w(0, t) = w_0$, where w_0 is the parameter characterizing the intensity of gas emission from the crater.

2. Statement of the problem

In calculations we varied the following input parameters: (1) characteristics of the medium γ_1 and γ_2; (2) parameters of perturbation ΔT and w_0; (3) radius R of the cylindrical zone within which the perturbation evolves.

The change of the profile of vertical component of the medium velocity $w(z, t)$ was considered, and the following parameters calculated: (1) maximum value of the upward flow rate profile in the jet $W(t)$, (2) the vertical component of the convective flow rate averaged over the atmospheric column: $\bar{w}(t) = \frac{1}{H}\int_0^H w(z)\,\mathrm{d}z$ ($H = 8$ km), (3) the level of convection $h(t)$ (h is the maximum altitude at which w exceeds 0.5 m/s).

According to the conditions of the problem, ΔT and w_0 are independent of time. As the calculations showed, at time independent parameters of perturbation the stationary mode of convection is established in a time interval τ about 10–15 min. In this mode, the dynamic characteristics of the VP vary only slightly (the equilibrium between forces accelerating and slowing-down the jet motion is established), and at $t > \tau$ the parameters $\bar{w}(t)$, $W(t)$, and $h(t)$ reach their stationary values. In the stationary mode, $W(t)$, $\bar{w}(t)$, and $h(t)$ experience fluctuations in the vicinity of some asymptotic values W_s, $\bar{w}_s$, and h_s, respectively;

$$\bar{w}_s = \lim_{t\to\infty} \bar{w}(t), \quad W_s = \lim_{t\to\infty} W(t), \quad h_s = \lim_{t\to\infty} h(t).$$

The amplitude of fluctuations is about 1 to 10% for h_s and $\bar{w}_s$ and about 0.01–0.1% for W_s.

The task is to study the change of the profile $w(z)$ in time, as well as the dependence of W_s, $\bar{w}_s$, and h_s (1) on γ_1 at fixed γ_2, ΔT, w_0, and R; (2) on γ_2 at fixed γ_1, ΔT, w_0, and R; (3) on ΔT at fixed γ_1, γ_2, w_0, and R; (4) on w_0 at fixed ΔT, γ_1, γ_2, and R; (5) on R at fixed ΔT, γ_1, γ_2, and w_0.

3. Calculated results

Figure 1*a* shows vertical profiles $w(z)$ for the given set of input parameters at different moments in time (the time t is measured from the onset of perturbation). Convection appears due to the emission of heated gas from the crater into the atmosphere, what leads to air overheat above the crater compared to the ambient medium. Thus, the convective flow rate depends on buoyancy, which, in turn, depends on the inflow rate of the volcanic gas determined by w_0 and on the temperature stratification of the medium. In the considered case, the atmospheric stratification is stable; therefore, as time $\tau \simeq 10$ min passes, convection develops into the stationary process because the forces acting on the medium achieve equilibrium. The dependence of the profile $w(z)$ on w_0 at $t = 9$ min is illustrated in Fig. 1*b*.

The rate of the convective flow significantly depends on the temperature stratification of the atmosphere both near the perturbation level ($\partial T/\partial z = \gamma_1$) and in the upper layers ($\partial T/\partial z = \gamma_2$). The intensity of convection must increase with the decreasing vertical lapse rate of temperature.

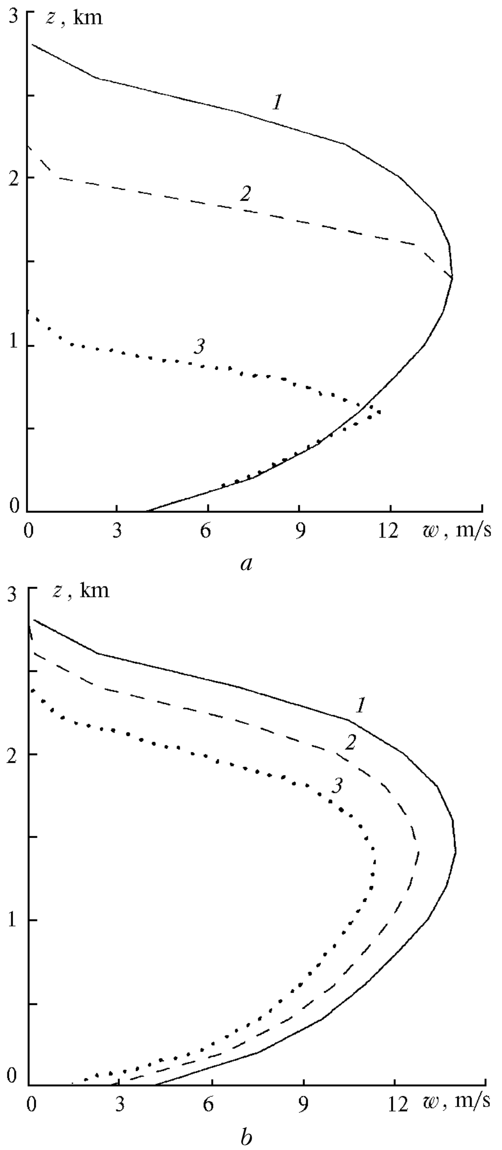

Fig. 1. Altitude profiles of the vertical component of medium velocity $w(z)$ at $\Delta T = 10°C$, $\gamma_1 = -9.35°C/km$, $\gamma_2 = -5.4°C/km$, $R = 1000$ m: upper panel (*a*): $w_0 = 4$ m/s, $t = 9$ (curve *1*), 6 (*2*), and 3 min (*3*); lower panel (*b*): $w_0 = 4$ (*1*), 2.5 (*2*), and 1 m/s (*3*).

Figure 2 shows the dependence of W_s, $\bar{w}_s$, and h_s on γ_1. It is seen that these parameters grow smoothly with decreasing γ_1; sharp change is not observed even at $\gamma_1 < -\gamma_a$, i.e., when the layer $z < z_1$ turns out to be unstable. This is explained by the fact that the convective jet experiencing acceleration in the surface layer due to the energy of medium instability slows down in the upper troposphere.

The vertical lapse rate of temperature in the layer $z > z_1$ has a significant effect on the VP height and, consequently, on $\bar{w}_s$; at $\gamma_2 \to -\gamma_a$ the intensity of convection starts to increase sharply and at $\gamma_2 = -\gamma_a$ the avalanche acceleration of the jet is observed. However, under actual conditions the temperature lapse rate $|\partial T/\partial z|$ in the upper troposphere rarely exceeds 5–6°C/km. If a realistic variability range of γ_2 (roughly from −6 to 0°C) is considered, then the growth of $\bar{w}_s$ and h_s is relatively smooth. The parameter W_s is little sensitive to γ_2; the growth of W_s becomes noticeable only at $\gamma_2 \approx -\gamma_a$, i.e., the degree of stability of the atmosphere largely affects only the VP depth (Fig. 3).

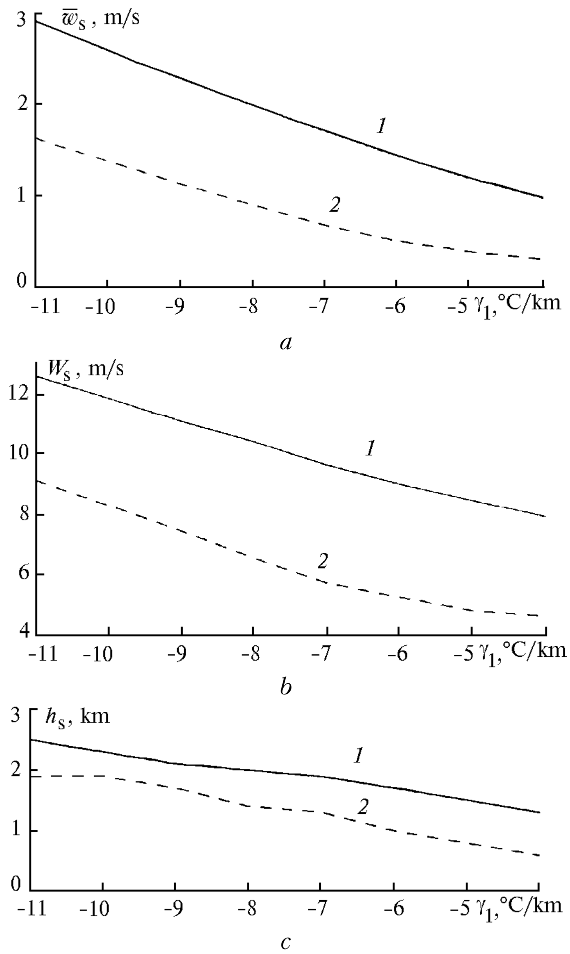

Fig. 2. Dependences $\bar{w}_s(\gamma_1)$, $W_s(\gamma_1)$, and $h_s(\gamma_1)$ at $R = 1$ km, $\gamma_2 = -5.4°C/km$, $w_0 = 4$ m/s: $\Delta T = 10°C$ (curves *1*) and 5°C (curves *2*).

If the medium is perturbed continuously, the dynamic characteristics of the jet depend not only on the state of the atmosphere, but on the parameters of perturbation as well.

Figure 4 shows the dependence of W_s, $\bar{w}_s$, and h_s on the value of constant overheat at the surface level ΔT at the fixed w_0. At $\Delta T \to 0$ $W_s \to w_0$, because the buoyancy is zero in the absence of overheat and the perturbation due to the emission of gases is damped fast in the stable atmosphere; $w(z)$ nowhere exceeds w_0, and the convection level is within the lower, most unstable, layer of the troposphere with $\partial T/\partial z = \gamma_1 = -9.35°C/km$. As ΔT increases, $\bar{w}_s$, W_s, and h_s grow due to the buoyancy effect. As the overheat increases, the growth of $\bar{w}_s$, W_s, and h_s slows down, since the jet penetrates deeper into the more stable atmospheric layer $z > 1$ km. The position of the curves $\bar{w}_s(\Delta T)$, $W_s(\Delta T)$, and $h_s(\Delta T)$ significantly depends on w_0 (Fig. 4).

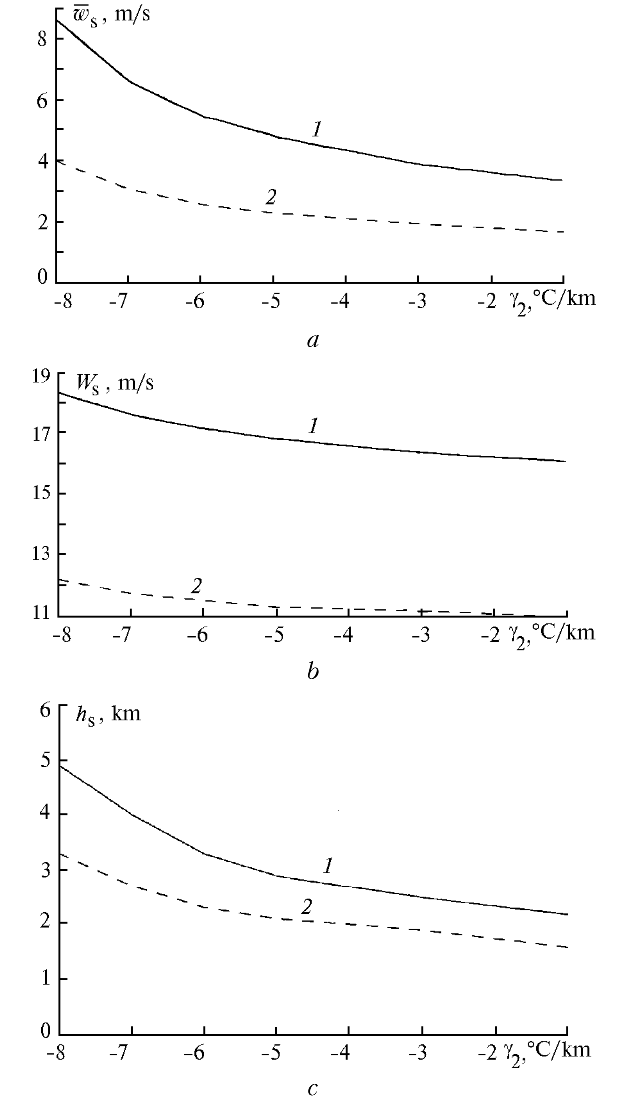

Fig. 3. Dependences $\bar{w}_s(\gamma_2)$, $W_s(\gamma_2)$, and $h_s(\gamma_2)$ at $R = 1$ km, $\gamma_1 = -9.35$°C/km, $w_0 = 4$ m/s: $\Delta T = 20$°C (curves *1*) and 10°C (curves *2*).

The dependence of the VP characteristics on w_0 in the stationary mode at different fixed values of ΔT is plotted in Fig. 5. The parameter h_s relatively weakly depends on w_0 (as w_0 increases four times, h_s increases only by 5–10%, whereas the fluctuations of h_s in the stationary mode are about 10–15% of the mean value). The dependence of $\bar{w}_s$ and W_s on w_0 is roughly linear.

The heat and momentum exchange between the convective flow and the ambient medium plays a significant part in the development of convection due to the ordered horizontal movement of air through the lateral boundary of the jet, as well as due to turbulent entrainment[1,2] (in Eqs. (1) and (3) these processes are described by the second and third terms, respectively). The contribution of these terms depends significantly on the jet radius R. Figure 6 illustrates the dependence of W_s, $\bar{w}_s$, and h_s on R. With the growth of R, the intensity of convection increases (the growth of the horizontal dimensions of the jet leads to a less significant role of the processes at its boundary, and the energy outflow into the atmosphere decreases). However, $\bar{w}_s$, W_s, and h_s tend to asymptotically approach some fixed values at $R \to \infty$. Physically, this means that the intensity of exchange with the ambient medium decreases with the increasing R, and starting from some R value, it becomes negligibly low as compared to the intensity of the vertical transfer of heat and momentum.

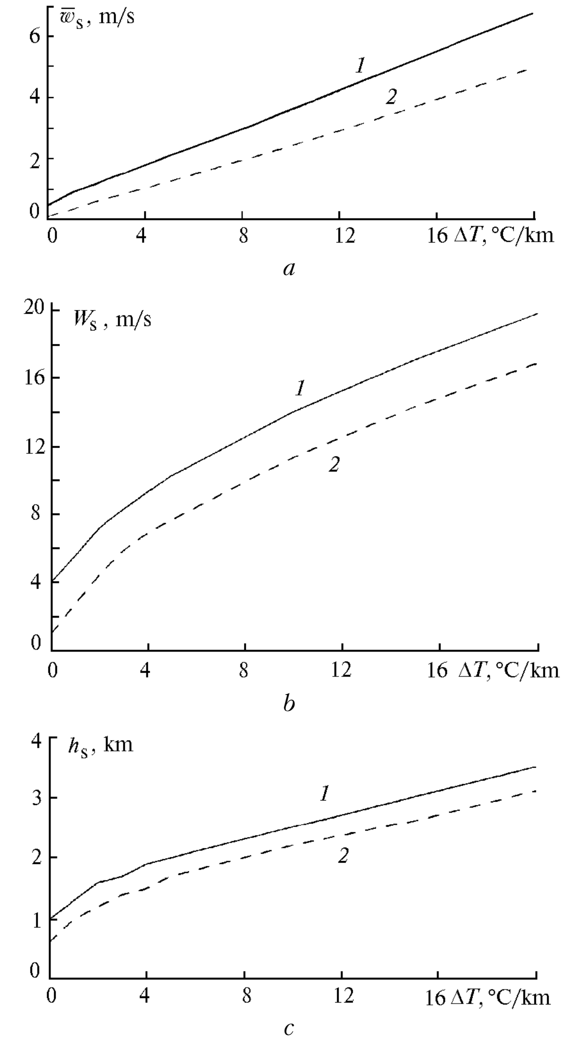

Fig. 4. Dependences $\bar{w}_s(\Delta T)$, $W_s(\Delta T)$, and $h_s(\Delta T)$ at $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $R = 1000$ m: $w_0 = 4$ (curves *1*) and 1 m/s (curves *2*).

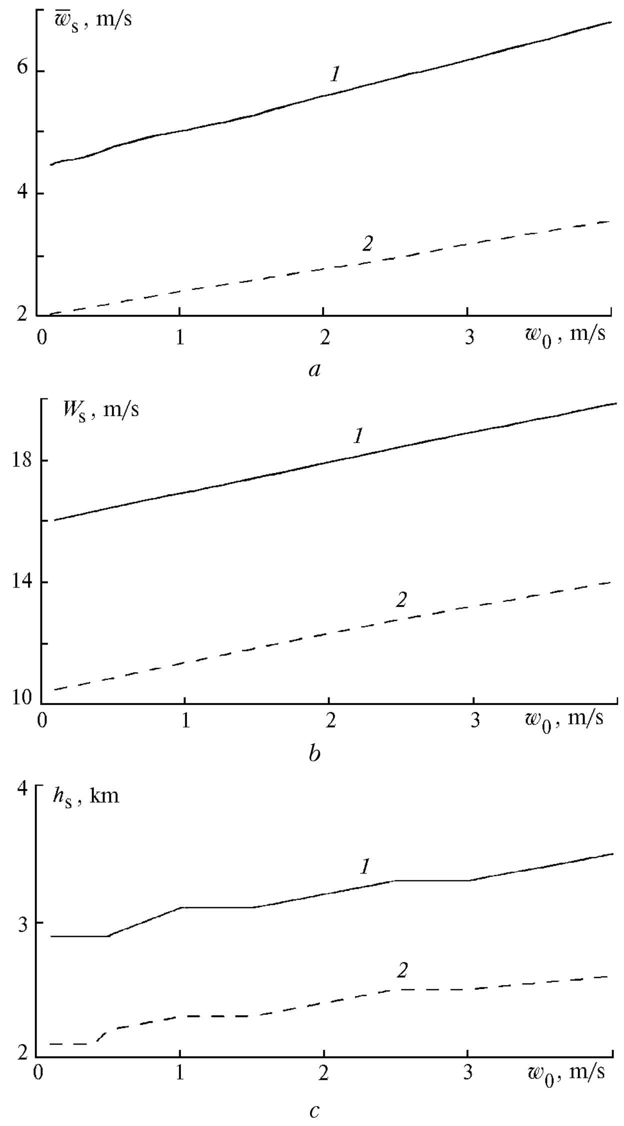

Fig. 5. Dependences $\bar{w}_s(w_0)$, $W_s(w_0)$, and $h_s(w_0)$ at $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $R = 1000$ m: $\Delta T = 10$°C (curves *1*) and 5°C (curves *2*).

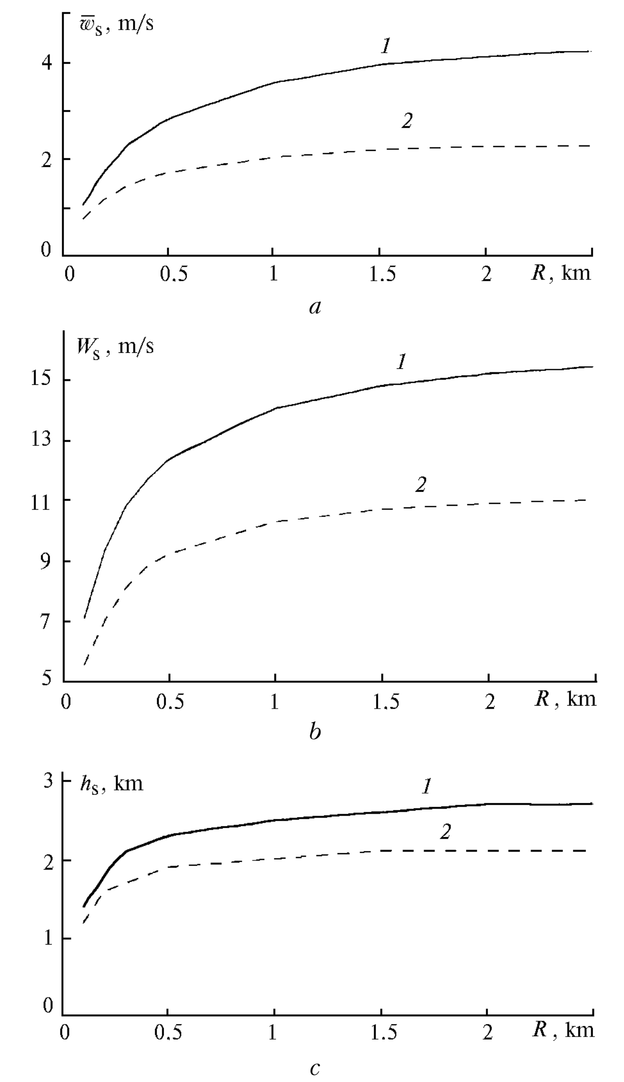

Fig. 6. Dependences $\bar{w}_s(R)$, $W_s(R)$, and $h_s(R)$ at $\gamma_1 = -9.35$°C/km, $\gamma_2 = -5.4$°C/km, $w_0 = 4$ m/s: $\Delta T = 10$°C (curves *1*) and 5°C (curves *2*).

Conclusion

The evolution of a volcanic plume being the vertical cylindrical convective jet in the atmosphere at the given vertical profiles of temperature and pressure has been simulated within the framework of the numerical model of a nonstationary convective jet ignoring condensation of water vapor. The results of numerical simulation allow the following conclusions to be drawn.

1. At the time-independent parameters of perturbation and of the unperturbed atmosphere, as some time (about 10–15 min) passes, the vertical profile of the upward flow rate becomes almost constant in time, and the stationary mode of convection is established. The fluctuations of the stationary upward flow rate $w(z)$ are no more than 5–10%.

2. The temperature stratification of the atmosphere significantly influence the dynamic characteristics of the VP, and the maximum value of the upward flow rate is most sensitive to the temperature lapse rate in the surface layer, whereas the medium stratification in the upper layers influences largely the spread of the jet. The decrease of $\partial T/\partial z$ in the upper troposphere ($z > 1$ km) by 1°C/km can result in an elevation of the level of convection by 200–1000 m, depending on the specific conditions.

3. The intensity of convection determined by the upward flow rate and the altitude of the jet spread increases significantly with the growth of the air overheat above the crater (ΔT). Thus, the increase of ΔT from 1 to 10°C leads to the increase by several times of the upward flow rate (in the stationary mode).

4. The dependence of the maximum and column mean values of $w(z)$ in the stationary mode on the

upward flow rate at the surface level, which determines the intensity of emission of the volcanic gas, is close to a linear one.

5. The decrease of the horizontal dimensions of the jet leads to a certain decay of the convective flow intensity, since in this case the heat and momentum outflow through the lateral boundary of the jet into the ambient medium starts to play a significant role. The dependence of W_s and $\bar{w}_s$ on R is most pronounced at $R < 300$–500 m. As R increases, the contribution of the terms describing the interaction of the VP with the ambient medium decreases, and at $R > 1$ km the jet radius practically does not influence the intensity of convection.

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