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Abstract

Full Text

Geophysics

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THE EFFECT OF AIR HUMIDITY ON THE DEVELOPMENT OF CONVECTIVE MOTIONS IN A CLOUDLESS ATMOSPHERE

(Presented by Academician E. K. Fedorov, 15 III 1963)

1. It is known that density inhomogeneities in a fluid, which lead to the occurrence of convective motions in it, need not necessarily be caused by temperature inhomogeneities; gravitational convection may also arise as a result of different concentrations of admixtures whose density differs from that of the fluid. Under atmospheric conditions, for example, such an admixture leading to the formation of air-density inhomogeneities is water vapor. Therefore, under some conditions of the development of convection in the atmosphere, the role of air humidity may prove to be substantially greater than that of its temperature.

2. The phenomenon of a stationary, axisymmetric jet of warm moist air propagating in a quiescent atmosphere, after the usual simplifications of the theory of convection and boundary-layer theory ([1,2]), can be described (in cylindrical coordinates) by the equations of motion, heat influx, water-vapor influx, and continuity in the form

$$u\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z} = g\beta\theta' + g\beta_1 q' + \frac{1}{r}\frac{\partial}{\partial r}\left(Kr\frac{\partial w}{\partial r}\right); \tag{1}$$

$$u\frac{\partial \theta'}{\partial r} + w\frac{\partial \theta'}{\partial z} = -\frac{d\theta}{dz}w + \frac{1}{r}\frac{\partial}{\partial r}\left(K_1 r\frac{\partial \theta'}{\partial r}\right); \tag{2}$$

$$u\frac{\partial q'}{\partial r} + w\frac{\partial q'}{\partial z} = -\frac{dq}{dz}w + \frac{1}{r}\frac{\partial}{\partial r}\left(K_2 r\frac{\partial q'}{\partial r}\right); \tag{3}$$

$$\frac{\partial}{\partial r}(ur) + \frac{\partial}{\partial z}(wr) = 0 \tag{4}$$

with boundary conditions

$$\text{at } r = 0 \qquad u = \frac{\partial w}{\partial r} = \frac{\partial \theta'}{\partial r} = \frac{\partial q'}{\partial r} = 0, \tag{5}$$

$$\text{at } r = R \qquad w = \theta' = q' = Kr\frac{\partial w}{\partial r} = K_1 r\frac{\partial \theta'}{\partial r} = K_2 r\frac{\partial q'}{\partial r} = 0, \quad ur \text{ is bounded.}$$

Here u and w are the radial and vertical components of velocity; θ' and q' are the differences of temperature and specific humidity in the jet $(\theta_1;\ q_1)$ and in the surrounding air $(\theta;\ q)$; g is the acceleration of gravity; β and β_1 are the temperature and concentration coefficients of density $(\beta = 1/\theta,\ \beta_1 = (1-\delta)/\delta$, where δ is the ratio of the density of water vapor to the density of air ρ); K, K_1, and K_2 are the coefficients of turbulent friction and turbulent exchange of heat and moisture; R is the distance from the jet axis at which conditions (5) are satisfied with sufficient accuracy and which may be interpreted as the nominal radius of the jet.

Let us first consider a convective jet caused only by air humidity, i.e., we shall consider a thermally neutral atmosphere without sources of heat $(d\theta/dz = 0,\ \theta' = 0)$*.

* Approximately such conditions should exist in summer during the greater part of the day over seas and oceans, i.e., over approximately 1/4 of the entire surface of the globe.

We shall seek an approximate solution of the system satisfying the general energy relations*. To this end we transform equations (1) and (3), with the aid of (4), to the form

$$\frac{\partial}{\partial r}(u\omega r) + \frac{\partial}{\partial z}(\omega^2 r) = g\beta_1 q' r + \frac{\partial}{\partial r}\left(Kr\frac{\partial \omega}{\partial r}\right),$$

$$\frac{\partial}{\partial r}(uq'r) + \frac{\partial}{\partial z}(\omega q' r) = -\frac{dq}{dz}\,\omega r + \frac{\partial}{\partial r}\left(K_2 r\frac{\partial q'}{\partial r}\right) \tag{6}$$

and integrate them with respect to r from zero to R, assuming at the same time that

$$\omega = \omega_0(z) f_1(r/R), \qquad q' = q_0'(z) f_2(r/R), \tag{7}$$

where f_1 and f_2 are the profiles of vertical velocity and humidity in the jet**, satisfying the condition $f_1(0) = f_2(0) = 1$, while ω_0 and q_0' are the distributions, to be determined, of the velocity and the excess specific humidity along the axis of the jet.

Then (6) takes the form

$$\frac{d}{dz}(\omega_0 R)^2 = a_1 g\beta_1 q_0' R^2, \qquad \frac{d}{dz}(\omega_0 q_0' R^2) = -a_2\frac{dq}{dz}\,\omega_0 R^2, \tag{8}$$

where a_1 and a_2 are constants depending on the profiles f_1 and f_2.

We shall further assume that the radius of the jet is a power function of height***

$$R = bz^n. \tag{9}$$

In the case of unstable stratification of the atmosphere $(dq/dz < 0)$ and the condition of constancy of the moisture flux F with height, dimensional considerations imply that the specific humidity q varies with height according to the same law as potential temperature in the case of thermal instability (^{5}), namely

$$q(z) = q_\infty + c' \left(\frac{F}{\rho}\right)^{2/3} \left(\frac{1-\delta}{\delta} gz\right)^{-1/3} \tag{10}$$

(c' is a dimensionless constant, q_∞ is a constant having the dimension of specific humidity), whence

$$dq/dz = -c_1 z^{-4/3}. \tag{11}$$

It is not difficult to see that system (8), taking account of (9) and (11), has the particular solution

$$q_0' = \frac{a_2}{2n} c_1 z^{-1/3}, \tag{12}$$

$$\omega_0 = \left[\frac{3}{4} \frac{a_1 a_2}{n(3n+1)} g \beta_1 c_1\right]^{1/2} z^{1/3}, \tag{13}$$

which describes the case of the so-called spontaneous jets, i.e., jets forming without sources of moisture; for any $n > 0$ the moisture flux $F \sim q_0' \omega_0 R^2$ at $z = 0$ is always equal to zero.

Thus, from the theoretical consideration it follows that if, over water surfaces (or moist areas of land), evaporation produces an unstable layer, then stationary moist jets can arise in this layer, and their formation occurs without sources

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* Thus, in particular, convective jets caused by thermal instability of the atmosphere were considered (^{2,3}).

** For example, of the form $(1 - r^2/R^2)^m$, according to measurements of the temperature profile of convective streams in the atmosphere (^{4}); if the center of the jet is taken to be not the geometric center, but the point corresponding to the maximum temperature of the jet, then m is somewhat greater than 1.

Oscillogram sample

Figure 1: Oscillogram sample

*** According to measurements of the sizes of convective streams in a thermally unstable atmosphere, $n = 1/3$ (^{4}).

moisture, as a result of some random disturbances in the fields of motion or humidity.

3. To verify the results obtained, special measurements were carried out over the Black Sea (in the region of Sukhumi) at the end of August 1962. The measurements were made from an aircraft using an installation for studying convective motions in the free atmosphere (^{4}), which, in addition to a low-inertia thermometer, included a sensitive automatic

Fig. 1. Sample oscillogram recorded over the sea: dew-point temperature (1), aircraft overload (2), air temperature (3), deviation from the prescribed altitude (4), and flight speed (5). The dew-point temperature increases upward, the air temperature downward. Vertical time marks are at 1-sec intervals. The flight took place on 25 VIII 1962 at approximately 13:00 Moscow time, at an altitude of 50 m, at a distance of about 30 km from the shore

condensation hygrometer (^{6}) (somewhat improved) and an accelerometer (^{7}). Flights were carried out in the daytime in cloudless and almost windless weather (0–1 points of sea roughness) at various distances from the shore (up to 40–50 km).

During these flights, at altitudes of 25 and 50 m it was possible to detect inhomogeneities (pulses) of humidity (with a relatively thin boundary layer), differing substantially (by up to 2–2.5 mb) from the comparatively homogeneous background of air humidity (Fig. 1,1). At the same time, weak aircraft bumpiness was observed (Fig. 1,2), which diminished somewhat in zones with comparatively small humidity pulses and ceased entirely at altitudes where humidity pulses were not recorded. The more humid volumes of air are very weakly expressed in the temperature field (as a rule, by no more than 0.1°)* or are not expressed at all (Fig. 1,3). This indicates that the stratification of the lower air layers during the flight was close to neutral. It should also be noted that the humidity pulses on the oscillograms have dimensions, shape, and structure close to the temperature pulses over level areas of land, which are recorded when relatively warm rising convective currents are crossed (^{4}).

On the basis of the theoretical considerations set forth above, the humidity pulses presented may be interpreted as ascending moist jets, and the result obtained may be regarded as experimental ev—

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* The temperature record from a sensor with a sensitivity of 0.1° (cut off in Fig.

1 together with the upper part of the oscillogram because of lack of space) is a smooth line (without any spikes), indicating only a weak change in the general temperature background.

proof of the possibility of the formation in the atmosphere of convective motions solely on account of the humidity of the air.

4. The phenomenon of convection in the humidity field apparently plays an essential role in a number of problems of atmospheric physics. The data obtained indicate, in particular, that water vapor evaporating from the surface of seas and oceans is transported upward mainly by convective motions arising as a result of instability of the lower layers of air. In winter and at night in summer, when the water is warmer than the adjacent layers of air, the transport is effected by thermal convection; in summer during the day, with thermally neutral or even weakly stable stratification, by convection caused by the humidity field. This may explain the specific features of evaporation processes and of the diurnal variation of humidity over seas, as compared with those observed over relatively small bodies of water ([8]).
5. In the problem considered in Section 2 it is not difficult to take into account simultaneously also thermal instability, for which ([5],[9])

$$d\theta/dz = -cz^{-4/3} \tag{14}$$

and law (11) is preserved. In this case, by completely analogous methods, a particular solution is obtained according to which the humidity along the jet axis is still described by relation (12), the temperature by the analogous relation

$$\theta'_0 = \frac{a_3}{2n} cz^{-1/3}, \tag{15}$$

and the velocity by the relation

$$w_0 = \left[\frac{3}{4}\frac{g}{n(3n+1)}(a_3a_4\beta c + a_1a_2\beta_1c_1)\right]^{1/2} z^{1/3}, \tag{16}$$

where a_3 and a_4 are constants depending on the temperature and velocity profiles in the jet $f_3(r/R)$ and $f_1(r/R)$.

According to estimates made from the mean values of simultaneously measured excesses of temperature and humidity in convective flows ([4]), it turned out that for $f_2 = f_3$ the second term in (16), due to air humidity, is approximately an order of magnitude smaller than the first, due to temperature. However, if one takes into account that the maximum measured excesses of humidity are 3-4 times greater than the mean values, and that the moistest convective flows are often not the warmest,* then in individual jets, even over land, the values of these terms may be closer to each other. This probably explains why aircraft bumpiness in flights near the earth’ s surface is perceptible also over comparatively moist areas of land.

Over the sea, for the most humid jets the magnitude of the second term in (16), on the contrary, is approximately 3 times greater than the first. Thus, the simultaneous accounting for temperature and humidity of the convective flows observed over the sea does not contradict the fact that these flows are caused mainly by the humidity of the air.

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* The warmest areas of land, as a rule, are not the most humid.

Note: Figure translations are in progress. See original paper for figures.

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