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TRANSIENT PROCESSES IN A MODEL OF A CONVECTIVE SYSTEM

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Meteorological systems belong to the class of highly complex systems with an interweaving of "feedbacks." An example is the interaction of the temperature and velocity fields (taking into account latent heat above the condensation level) in phenomena of free convection.

However, as a rule, the connections in meteorological systems are artificially simplified; the component parts of one system or another are isolated from one another for separate study; some parameters are fixed so that the others change in a controlled manner. As a result, open systems are considered—one-sided, forced processes under rigidly specified external conditions. Thus calculations are usually made of changes in relative humidity and the condensational growth of droplets in an ascending air current with a prescribed velocity, or of the parameters of convective jets in a medium with a rigidly specified temperature stratification T_z.

At present a new approach is being applied to the study of complex meteorological systems, in particular convective systems. In many atmospheric phenomena the dominant role is played by buoyancy forces; examples of such phenomena on various scales are given in the article by Batchelor (^{1}). Meanwhile, many important features of the manifestation of buoyancy forces have not yet been identified (see (^{2})).

The use of electronic computers has made it possible to begin solving problems of free convection with allowance for the interaction of the temperature and velocity fields. Local and comparatively short-lived convection phenomena in a continuous medium have been considered. To take account of nonlinear effects over a large time interval, one has to pass to a system with lumped parameters (^{3}). In this case the starting point is a system of ordinary differential equations. The limitations standing in the way of numerical experiments have not made it possible to solve the problem of the interaction of convective elements and the

Fig. 1

Figure 1: Fig. 1

surrounding medium (the temperature stratification T_z). The pressing need to solve this problem was pointed out already by Bjerknes (^{4}).

Clarification of many questions in this field can be achieved sooner by laboratory experiment than by calculations. Bénard's experiments confirm this proposition. Laboratory studies of oscillations of a convective flow were carried out by N. L. Byzova (^{5}); oscillations that occur before the establishment of stationary convection in a one-dimensional model were recorded by Uillander (^{6}).

Laboratory manipulation of buoyancy forces can be carried out using a system of two liquid layers that differ only slightly in density and, as a result, are near the boundary of convective stability. This yields a model of a convective system that makes it possible to investigate some features of the mutual adaptation of convective motions and the temperature stratification of the medium T_z.

The experiment is performed in a sufficiently tall quartz vessel filled with water, onto the bottom of which a layer of aniline is poured (approximately 0.1 of the vessel volume). The liquids mix poorly. The coefficients of volume expansion for water and aniline are in the ratio $1 : 4$, and the density difference $\Delta\rho$ is small, as a result of which it can readily change sign.

By varying the heating regime of the system from below, it is possible to regulate the intensity of the convective processes in the system. The heating may be distributed uniformly over the bottom of the vessel or concentrated. Localization of the convective formations arising in the system can be enhanced by means of a metal cone on the bottom of the vessel. By changing the salt concentration, one can influence the distribution of the medium density with height. The vertical temperature gradient in the column of water was in some cases changed by cooling or heating the surface layer.

Fig. 1

Below are the results of experiments that made it possible to detect the appearance and development of various convective formations, and also to trace the transient processes in the system that characterize the interaction of the convective elements and the medium. The description of the processes is illustrated by situations of convective formations that were copied from the corresponding photographs.

The development of the convective system proceeds as follows. The heat arriving from the source begins to accumulate in the layer of aniline. Since intense convective mixing takes place in this layer, which almost does not extend beyond the layer, a large temperature difference is maintained between the aniline layer and the surface layers of water. Heating of the aniline leads to its floating up in the center of the vessel above the metal cone; then an aniline "tongue" is ejected

(Fig. 1A, 1, 2), which as if pierces the restraining warm layer of water adjacent to the aniline. The aniline "tongue" turns into a hybrid system consisting of an ellipsoidal head part (thermal) and a jet feeding it (stem), tied to the cone (Fig. 1A, 3, 4). Various dynamic regimes of development of such a hybrid system are possible.

As long as a large vertical temperature gradient is maintained in the water, violent convective "eruptions" of aniline occur. The head thermal formed in this process takes the shape of a mushroom cap and rises rapidly, since as it ascends it enters increasingly colder layers of water. At the same time the stem quickly becomes thinner and is destroyed; the cap reaches the surface of the water, cools, and collapses downward in parts (Fig. 1A, 4—6). Thus, the process ends with the destruction of the entire convective formation.

However, as a result of such successive convective "eruptions," and also of the appearance of convective jets in the medium after the destruction of the blocking layer of aniline, smoothing of the vertical-

temperature gradient in the water, and a reduction of the total temperature difference between the aniline layer and the upper layers of water. The development of each subsequent convective formation proceeds less and less violently. Thus conditions are gradually created for the emergence of more stable, quasi-stationary convective formations. Indeed, with a sufficiently smoothed gradient, the system consisting of a thermal and a jet passes into such a quasi-stationary oscillatory regime, in which a coordinated interaction of the two parts of the system takes place. In this case a feedback is established between the thermal and the jet, as a result of which the oscillatory motion of the thermal occurs without breaking away from the jet: the rise of the thermal leads to a thinning of the jet, the supply decreases and the thermal settles downward, which leads to a thickening of the jet and, consequently, to an increase in the feeding of the thermal, which again rushes upward, and so on (Fig. 1).

Thus we have the possibility of observing a convective self-oscillatory system, "for which a special connection between the system and the energy source is highly characteristic···The work performed by the source depends on the state of the system···" and the system "periodically draws definite portions of energy from a constant energy source, i.e., by means of a nonperiodic energy source creates a periodic process" (7).

In the process of self-oscillation, further smoothing of the temperature gradient in the water occurs, and the amplitude of the oscillations decreases; the degree of stability of the system increases (Fig. 1). The evolution of the system ends in a transition to a limiting state, in which the aniline drop, no longer attached by a stem to the heat source, performs an oscillatory motion along the vertical with a certain degree of damping (Fig. 1) (a metal cone is located below; the photographs were taken at intervals of 3-4 sec). It is precisely such a system that is usually presented as an illustration in considering the second law of thermodynamics.

The third variety of convective system is a mirror reflection of the hybrid system above the heat source, i.e., a thermal hanging downward on a stem with its base on the water surface (Fig. 1). The development of such an inverted system is determined not by a source, but by a sink of heat (evaporation and cooling of the aniline). The overturning of the system may occur already at the initial stage of its development, under a certain combination of the distribution of temperature and salt concentration in the water. This variety of convective system also may either be destroyed during violent development or pass into a regime of self-oscillation (Fig. 1). These self-oscillations die out; the system passes into a state of weak pulsations, and then may give an aniline drop performing a slow oscillatory motion along the vertical, i.e., the evolution of the system ends in the same way as in the case of convective motions caused by a heat source from below.

1. The results obtained have a qualitative, heuristic character. However, the entire course of investigations of convective processes in the atmosphere testifies to the fruitfulness of combining laboratory or field observations with calculations, which complement one another. Thus Bénard' s experiments gave the initial impetus to the development of the theory of cellular convection. The experiments of Scorer (3) and Woodward (8) made it possible to observe the internal motion in a thermal. On this basis Turner (9) and Levin (10), using expressions for the components of Hill' s vortex, constructed a system of equations for a thermal with internal circulation. Observation of the pattern of development of a smoke cloud above a patch of burning dry grass led Turner (11) to a mathematical model of an unsteady hybrid formation consisting of a thermal and a jet.

The results of the experiments described make it possible to note shortcomings of Turner' s model and suggest ways of improving it. In Turner' s model only the one-sided "supporting" influence of the jet on the

the head thermal, as a result of which the buoyancy force of the thermal increases with time. It is assumed that there is complete consistency in the motion of the two parts of the hybrid formation. The thermal moves in such a way that its velocity u at the level of merging with the jet is always a definite fraction of the jet velocity. Such an assumption is a severe restriction on the possible variety of motions in the system, excluding oscillatory motions. A mismatch, within certain limits, of the velocities v and u of the motion of the two parts of the corresponding model of a hybrid system can apparently be allowed by introducing into the equations describing the hybrid formation terms proportional to the difference of the velocities $(v-u)$ and to the cross-sectional area of the jet at its junction with the thermal.

2. An idea is taking shape concerning the preparatory role of transient processes, as a result of which a mutual adaptation occurs between convective motions and the medium in which they develop. The interaction of convective motions and the surrounding medium under a definite regime of heat inflow leads to a gradual smoothing of the gradient in the medium and cre-

ates conditions for the system to pass into a regime of self-oscillations. In other words, there may occur, as it were, a self-adjustment of the system to a definite quasi-stationary regime. The narrow interval of conditions necessary for the realization of more or less stable self-oscillations is found by the system itself, and it adjusts itself to them.

Possibly such a mechanism plays a role in the formation of cumulus clouds. According to the calculations of Mason and Emig (^{3}), a severe restriction is imposed on the coefficient of exchange of a protocloud with the environment. If the presence of the required coefficient of exchange were a matter of chance, the formation of cumulus clouds would be a rare phenomenon.

3. The modeling carried out provides grounds for the following hypothesis. Convective systems in the atmosphere pass, at certain stages of their development, through a sequence of quasi-stationary states. In this process self-oscillations with changing amplitude occur. A distinguishing feature of such states is the relative consistency of the various parameters of the system (for example, the velocities of its components); their mismatch is allowed only within definite limits, exceeding which signifies the destruction of the system. The data presented in Saunders' article (^{12}) on the mutual correspondence between the velocity of vertical motions in a cumulus cloud and its power may serve as an illustration of this proposition, as a necessary condition for development to the stage of shower precipitation.

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CITED LITERATURE

1. G. R. Batchelor, Quart. J. Roy. Meteorol. Soc., 80, No. 345 (1954).
2. R. S. Scorer, Natural Aerodynamics, London, 1958.
3. B. J. Mason, R. Emig, Quart. J. Roy. Meteorol. Soc., 87, No. 372 (1961).
4. J. Bjerknes, Quart. J. Roy. Meteorol. Soc., 64, No. 273 (1938).
5. N. L. Byzova, Izv. AN SSSR, ser. geofizich., No. 5 (1951).
6. J. B. Keller, J. Fl. Mech., 26, No. 3 (1966).
7. A. A. Andronov, A. A. Vitt, S. E. Khaikin, *Theory of Oscillations*, Moscow, 1959.
8. B. Woodward, Quart. J. Roy. Meteorol. Soc., 85, No. 364 (1959).
9. J. S. Turner, Proc. Roy. Soc. A, 239, 61 (1957).

10. J. Levine, J. Meteorol., 16, 653 (1959).
11. J. S. Turner, J. Fl. Mech., 13, No. 3 (1962).
12. P. M. Saunders, Meteorol. Mag., 88, No. 1046 (1959).

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