Excitation of cyclonic vortex or laboratory model of tropical cyclone

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A phenomenon analogous to a tropical cyclone has been observed experimentally. When a plane rotating liquid layer is locally heated from below, an intense cyclonic vortex forms in the central zone. The conditions for the occurrence of this vortex in terms of dimensionless numbers are found.

Tropical cyclones have been the subject of recorded observations for more than 200 years, and a large number of mathematical models has been constructed on the basis of these observations.[1] Despite this abundance of models, the physical mechanism for the nucleation of tropical cyclones remains unexplained.[2] The experimental results which we are reporting here open up some new opportunities for analytic and numerical studies of this problem.

A distinctive feature of a tropical cyclone is the interaction of a large-scale advective flow with Coriolis forces with zones of rising air in a central region. To study this interaction, we used a plane rotating liquid layer heated from below in its central zone.

The diameter of the working vessel, which was made of polymethyl methacrylate, was 300 mm, and the thickness of the liquid layer, h, was 30 mm. The vessel was rotated by a dc motor acting through a reducing gear. The rotation velocity Ω was varied from 0.002 s^{-1} to 0.4 s^{-1}. The angular velocity ω of the liquid in the central zone was determined with a floating pickup consisting of three cylindrical polymethyl methacrylate cups 10 mm in diameter spaced at angles of 120° and positioned 15 mm from the center. The gap between the bottom of the vessel and the pickup was about 0.5 mm.

The liquid was heated with a brass heat exchanger at the center of the vessel, flush with its bottom. The diameter of this heat exchanger was 105 mm. The experiments were carried out under steady-state conditions; the heat exchanger was heated by an electric heater at a constant power. The temperature drop ΔT between the heater and the liquid surface was measured with a thermocouple device. In the experiments, ΔT ranged from 2 °C to 35 °C.

In the case $\Omega = 0$, three types of convection structures can be distinguished when the heater is turned on. Because of the radial temperature drop, a large-scale advective motion arises: There is an average rise of the liquid above the heater, there is a divergent flow with natural heat removal, the liquid near the vertical wall of the vessel descends, and a convergent flow occurs toward the center of the cavity in the lower layers. A structure consisting of "thermals," floating up in a random pattern, is established above the heater. Convection rollers form away from the heating zone; their axes tend to assume a radial orientation.

As the vessel is rotated, Coriolis forces act along with convection forces on the liquid. In the lower layers, where the radial component of the velocity is directed toward the center, the liquid twists up in the vessel rotation direction. The flow away from the center toward the periphery, in contrast, undergoes an anticyclonic twisting. If the Grashof number $G = g\beta\Delta Th^3/\nu^2$ (g is the acceleration due to gravity, β and ν are the thermal expansion coefficient and kinematic viscosity of the liquid) is below a certain critical G^*, the cyclonic twisting is balanced by the anticyclonic twisting. In this case the angular velocities Ω and ω are the same. If $G > G^*$, a spiral cyclonic vortex is nucleated at the center of the cavity, and the relative angular rotation velocity of the floating pickup, $\delta = (\omega - \Omega)/\Omega$, becomes nonzero in the rotating coordinate system. Figure 1 shows the behavior of δ as a function of the Grashof number for two Reynolds numbers, $\mathrm{Re} = 2\Omega h^2/\nu$.

The spiral vortex is a formation which is independent of the advection cell. On the side of the outer boundary of the heating region, the liquid flows from the lower layers to the upper layers in a conical spiral. The liquid reaches the surface in the central zone of the vortex. Without a change in its cyclonic rotation, the liquid flows in the opposite direction along an untwisting spiral, with a gradual descent. Near the boundary of the heat exchanger, the liquid turns and flows back into the central zone. This description of the vortex should be regarded as a generalized flow against the background of a random small-scale motion. The photograph in Fig. 2 is a top view of a spiral vortex; here $G = 9.5\times10^5$ and $\mathrm{Re} = 12$. (The motion was visualized by adding powdered aluminum to the liquid; the dark lines and spots correspond to descending liquid.)

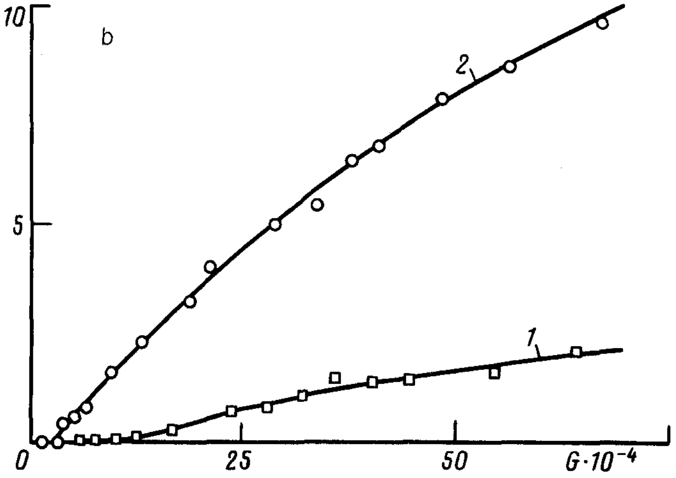

FIG. 1. Increase in the vortex intensity with increasing Grashof number *1*—Re = 105; *2*—Re = 7.

FIG. 2.

According to visual observations of the motion of small polystyrene balls suspended in the liquid, the boundary between the convergent and divergent flows is also the boundary between the cyclonic and anticyclonic motions up to the critical point for the interface. Consequently, as the anticyclone is weakened by the thermals which are floating up (they carry angular momentum out of the lower layers), the interface arises. This rise causes a decrease in the convergent component of the velocity, while the divergent component increases, restoring the system of its original state. If $G < G^*$, the system is thus at dynamic equilibrium.

Experiments with a small floating pickup revealed that the local vorticity of the liquid was cyclonic above the heat exchanger under the condition $\mathrm{Re} \neq 0$. Under the condition $G < G^*$ the convection thermals are slowly rotated around the vertical by this vorticity. During a local heating of the layer, the number of ascending thermals above the heater is greater than the number of descending thermals, so the average value of the cyclonic helicity of the convective motions is nonzero. It may be that the small-scale helicity of the ascending thermals is the reason why a large-scale perturbation with the structure of a spiral cyclonic vortex begins to develop in a critical fashion.[3]

We used two liquids in the experiments, with Prandtl numbers differing by a factor of more than two. The experiments revealed that G^* is independent of the Prandtl number but does vary (Fig. 3) with the Reynolds number.

The shape of the curve in Fig. 3 agrees qualitatively with the conditions under which tropical cyclones appear in nature. They nucleate in the latitude band 5°–30°,

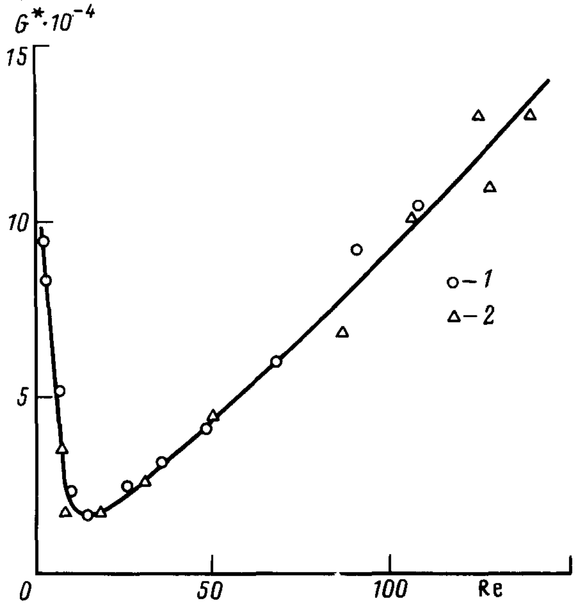

FIG. 3. The critical Grashof number G^{*} versus the Reynolds number Re. *1*—Transformer oil; *2*—2:1 mixture of transformer oil and kerosene.

most frequently at latitudes between 10° and 15° (Ref. 1), i.e., at a certain optimum Reynolds number, for which the vertical temperature drop is minimized.

[1] A. P. Khain, *Mathematical Modeling of Tropical Cyclones*, Gidrometeoizdat, Leningrad, 1984.
[2] V. G. Fedoreĭ, *Evolution of Typhoons*, Gidrometeoizdat, Leningrad, 1987, No. 138.
[3] S. S. Moiseev *et al.*, Akad. Nauk SSSR **273**, 549 (1983) [Sov. Phys. Dokl. **28**, 926 (1983)].

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