Laboratory Vortices in Rotating, Sheared Flow

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ABSTRACT

By placing a small convective source (electrical heater) in a rotating, vertically sheared, stratified flow in a rotating annulus, a well-organized vortex flow is generated. A qualitative description of the flow is given. The flow is always cyclonic below the heater and anticyclonic above, and is quite persistent in the sheared flow.

1. Introduction

Cumulonimbi exist as convective entities in strongly sheared environments. In fact, the ambient wind field and the cloud can interact strongly, and thus produce significant alterations of either system (Newton, 1967). Such a situation was simulated in the laboratory by placing a small electrical heater in a horizontally and vertically sheared flow. The flow was generated in a rotating annulus of water by imposing a temperature difference ΔT between the outer and inner cylinders of the annulus.

This note describes qualitatively the interaction between the zonal and convective flows which in many cases take the form of a vortex. This vortex is always cyclonic (counterclockwise as seen from above) under the heater, and the flow above the heater, though turbulent, is always definitely anticyclonic. The vertical flow shows great persistence in the vertical in the presence of the shear. The effect on the vortex of changes in shear and rotation rate are also examined.

2. Basic flow and techniques

The basic flow is generated in an annulus of water rotating about its vertical axis. The outer radius of the

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fluid is 4.90 cm, the inner radius 2.46 cm, and the depth 13.00 cm. Additional details concerning the apparatus are given in Kaiser (1969). The rotation rate Ω used for the measurements was 0.5 rad sec^{-1} unless otherwise stated.

For the majority of the observations the temperature difference ΔT imposed horizontally across the annulus (the outer cylinder being warmer) was 4C; this produced a total density difference of 8.70×10^{-4} gm cm^{-3}. This combination of ΔT and Ω produces a flow which is symmetric about the rotation axis. In addition to thermal boundary layers on the side walls of the annulus and an Ekman layer on the bottom, a quasi-geostrophic zonal current exists in the "interior" of the fluid. A cross section of the measured zonal velocity field for 4C and 0.5 rad sec^{-1} is shown in Fig. 1a. The inner cylinder is on the left of each field of Fig. 1 and the outer cylinder on the right. The upper 60% of the fluid exhibits a westerly flow (counterclockwise as seen from above) which reaches a maximum velocity of 0.8 cm sec^{-1} just below the upper nonrigid surface. Below the westerlies the flow is easterly, attaining a minimum velocity (maximum easterly) of -0.31 cm sec^{-1} just above the lower Ekman layer.

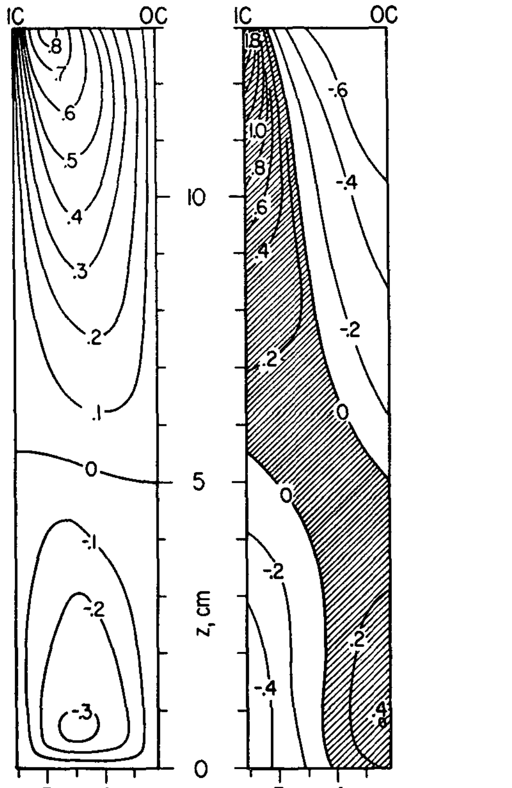

FIG. 1. Cross sections of (a) the zonal velocity field (cm sec^{-1}) and (b) the relative vorticity field (sec^{-1}) of the basic flow. In both fields the inner cylinder is on the left and the outer on the right.

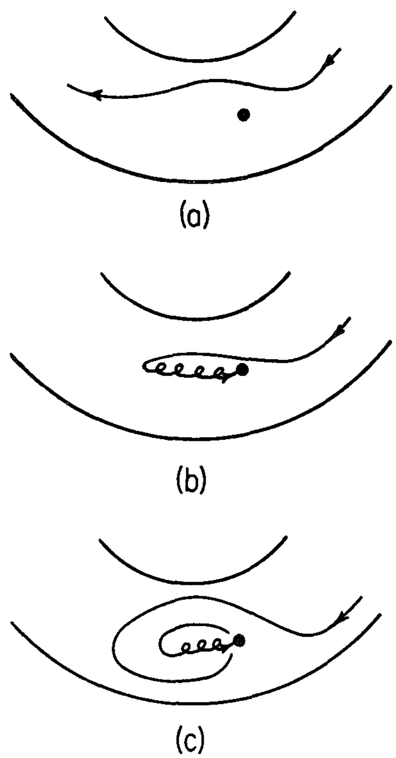

FIG. 2. Top views of ink streamers below the heater: (a) outside of capture region; (b) and (c), in capture region. The arrowheads indicate flow direction.

The field of relative vorticity $\zeta_r[=r^{-1}\partial(rv_\theta)/\partial r]$, where v_θ is the zonal velocity and r the radial distance from the rotation axis, is given in Fig. 1b. The shaded zone is cyclonic ($\zeta_r>0$) while the other areas are anticyclonic. For comparison, the vorticity of the rotation, 2Ω, is 1.0 sec^{-1}.

Temperature or density profiles similar to those which occurred can be inferred from Kaiser (1969; in particular, his Fig. 4). In the interior of the fluid as determined from the relations given in Kaiser, the average vertical temperature gradient was 0.31C cm^{-1} and the average horizontal gradient 0.35C cm^{-1}. Away from the boundary layers, the gradients of the thermal fields vary at most by a factor of 2.

The heater used for the observations was a constantan coil 0.3 cm in diameter and 0.8 cm high. Up to 50 W of power could be delivered safely by the heater; this heating rate increased the stratification of the fluid by a factor of about 3 and also raised the zero-velocity surface in the fluid considerably, thus increasing the extent of the easterlies.

Below the heater, which was placed at various heights in the fluid, the flow pattern was rendered visible by a fine stream of a methylene blue dye mixture whose density was made equal to that of water at 20C. The dye stream came from a fine hypodermic which was located 70° counterclockwise from the heater. The "inker" was remotely positionable in the axial plane.

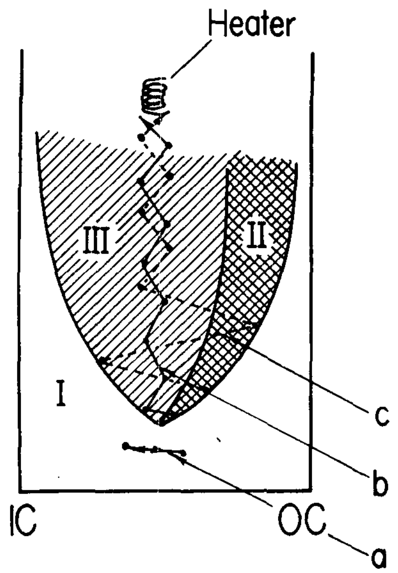

FIG. 3. Cross section of the caputre regions: I. no vortex; II, inker capture region; II and III, heater capture region. Curves a, b and c are the respective side views of the trajectories of Fig. 2.

The flow immediately above the heater was turbulent whenever the heating rate exceeded 5 W. However, fine aluminum powder indicated the general features of the flow at the free surface.

3. Description of the flow

The ink-stream pattern observed below the heater depended strongly on the position of the ink release relative to that of the heater. Nevertheless, the patterns in all cases fit into one of three classes which are sketched in Fig. 2. Ink released much below the heater (in the easterly flow) near the inner cylinder did not enter the vortex flow region but merely underwent an anticyclonic deflection (which occurred initially in all cases), then a weak cyclonic deflection, and finally continued around the annulus. The top view of this trajectory is shown in Fig. 2a. The heater position is indicated by the small solid circle.

If the tip of the inker was moved outward radially and upward, the ink stream, after the initial anticyclonic deflection, would go into a closed cyclonic flow which ascended to the heater. The ink bands observed by looking into the annulus from above for two such flows are sketched in Figs. 2b and 2c. The arrowheads show the direction of flow. In both cases the ink release was in the easterlies and hence the ink was carried past the heater by the zonal flow, but then on its ascension flowed back to the heater.

Fig. 3 is a cross section of the lower portion of one side of the annulus and shows the source regions in both the axial planes of the inker and heater for the vortex flow. Consider the axial plane in which the *inker* is located. Ink released anywhere in regions I and III in that plane will not enter a vortex flow, but merely undergo the deflected flow sketched in Fig. 2a. Ink released from the tip of the inker at any coordinate in region II or the "inker capture region" (icr) will always enter into a vortex flow. If, however, attention is now focused on the axial plane in which the *heater* is located, any ink stream which *enters* the heater plane in the region which is the union of II and III will always undergo a vortex flow. Thus, regions II and III together constitute the heater capture region (hcr) which is that region in the plane of the heater in which all flow will spiral upward in a vortex.

The tightness of the vortex flow depended almost exclusively on the position of the ink release. An ink release near the bottom of either capture region (cr) would produce the tight vortex illustrated in Fig. 2b. This trajectory is also shown in cross section in Fig. 3 and labelled b. The open-bottom vortex of Fig. 2c occurs when ink is released further up in the cr such as trajectory c of Fig. 3. Even in this latter case the ink enters into a central core after one or two circulations and continues upward to the heater remaining in essentially the same core as for the tight vortex.

Once the fluid rose to the height of the heater, the flow above the heater became very turbulent, typical of a thermal plume. Even when the heater was 0.5 cm above the bottom of the annulus its effect was very prominent at the free surface for heating rates $\geqslant 10$ W. Fig. 4 shows the top surface flow at 10 W (a) and 25 W (b). A few degrees counterclockwise from the heater the flow was always markedly anticyclonic. The anticyclonic flow at 10 W was persistent but unsteady with a generally stagnant region upstream from it. Sometimes closed streamlines could be discerned. The top-surface westerly flow was "crowded" into the inner cylinder wall by the circulations. At a 25 W heating rate the anticyclonic circulation enlarged, mostly in the longitudinal direction, with a somewhat irregular

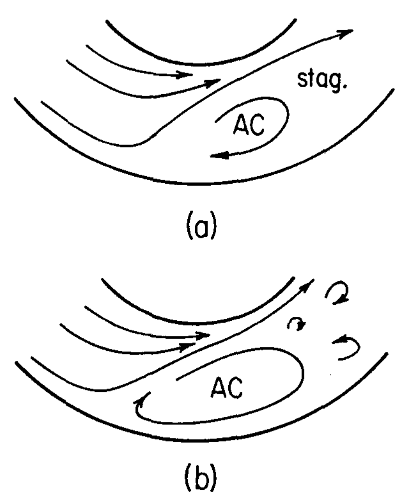

FIG. 4. Top surface flow patterns for (a) 10 W and (b) 25 W.

shedding of small vortices on the downstream side. No closed streamlines were observed. A 40 W heating rate caused the top-surface flow adjacent to the outer wall to become easterly everywhere around the annulus while retaining the westerlies next to the inner cylinder.

The above flows, which are typical of most conditions, were observed when 20–40 W of power was delivered to the heater. Also, the bottom of the heater was 5 cm above the bottom of the annulus and was at mid-gap. A steady closed anticyclonic circulation was obtained when the heater was 3 cm below the top surface and when the heating rate was 20 W. A greater heating rate increased the intensity of the turbulence and did not allow a steady flow while a lesser heating rate did not advect fluid upward fast enough to produce a closed circulation.

The reversal in the circulation in a convective vortex has been observed in some calculations of Lugt and Schwiderski (1966). In their work the circulation reversed at nearly the height where the radial velocity changed sign. In these experiments this occurred at the heater. The great degree of verticality of the vortex flow in the presence of the zonal wind was noteworthy. Throughout the interior of the fluid the vertical shear was 0.05 sec^{-1}, while the estimated vertical velocity in the vortex core was on the order of 10^{-1} cm sec^{-1}. This strong persistence in the vertical is also typical of large cumulonimbi (Newton, 1967).

4. Effects of varying ΔT and Ω

Increasing Ω definitely increases the vertical extent of the vortex flow. If the bottom of the heater is 6 cm from the bottom of the annulus and $\Omega=0.5$ rad sec^{-1}, the lower extent of the cr (the bottom of region II of Fig. 3) is at 1.5 cm. Increasing Ω to 1.0 rad sec^{-1} drops the lower end of the cr to below 0.5 cm. However, no estimate was made of the speed of the circulation as Ω was changed.

At $\Omega=0.5$ rad sec^{-1}, an increase of ΔT from 4 to 8C tended to weaken the vortex intensity. This could be due to the fact that the vertical shear in the fluid is doubled by such an increase.

When ΔT is reduced to 0.25C the vortex is still present but much slower. Even causing ΔT to become negative retains a cyclonic vortex below the heater. The flow in the bottom of the annulus is now counterclockwise and a streamer of ink flows around most of the annulus before arriving in the axial plane of the heater. Referring to Fig. 2c, the ink streamer would now enter the vortex from the left, be deflected outward toward the outer cylinder, then curve cyclonically as in Fig. 2c, and finally rise up toward the heater. For $\Delta T<0$, the ζ_r field of Fig. 1b would apply if the ζ_r values were multiplied by about -0.3. In this case $\Delta T=-1.25$C and in the lower portion of the fluid $|\zeta_r|<0.2$ sec^{-1}. So, in all cases which have been observed at $\Delta T<0$ or >0, $\zeta_r+2\Omega>0$ and the flow is always cyclonic below the heater.

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