

THE JOHNS HOPKINS UNIVERSITY  
Department of Civil Engineering  
BALTIMORE, MARYLAND  
December, 1953

**A DIFFUSION PHENOMENON IN ROTATING  
AND STRATIFIED FLUIDS**

By Robert R. Long

***Technical Report No. 2***



Sponsored by

THE OFFICE OF NAVAL RESEARCH

The research reported in this document was supported by The Office  
of Naval Research under Project NR 082-104, Contract N-onr-248(31).

## A DIFFUSION PHENOMENON IN ROTATING AND STRATIFIED FLUIDS

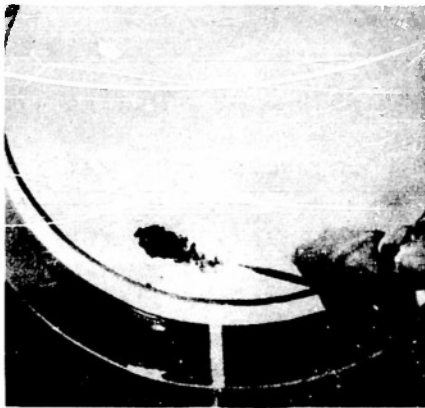
Sir Geoffrey Taylor, in one of his first papers on rotating fluids (1921), discovered the following remarkable phenomenon, apparently by accident: If a body of water in solid rotation is disturbed very slightly and a quantity of ink of the same density is dropped into it, the ink, instead of diffusing in a normal manner, gathers into vertical walls.<sup>1</sup> The walls become very thin and very elongated as time goes on, until they can hardly be seen when viewed with a line of sight perpendicular to the axis of rotation. Viewed from above, however, they have the appearance of very thin ink filaments of great total length.

The experiment is reproduced in fig. 1. Just before the ink was inserted, a weak relative motion was generated by a gentle stirring. The Rossby Number, using the radius of the pan, is about 0.03. The angular velocity is 10 rpm. For the purposes of comparison a similar experiment was performed in a non-rotating body of water. The ordinary diffusion process is shown in fig. 2.

Taylor's explanation of this phenomenon was incomplete, and the purpose of this note is to advance a qualitative explanation which seems to serve the purpose. Taylor noted that the relative velocities were so small, compared to the basic rotation, that steady motions had to be two-dimensional, i.e., no vertical motion and no vertical shear. This follows

---

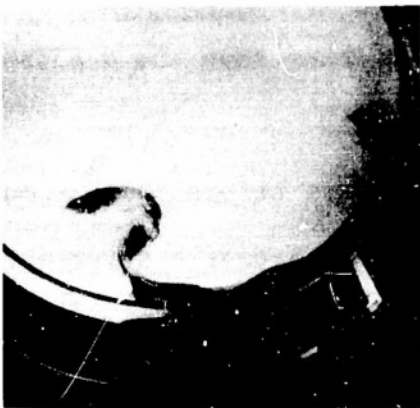
<sup>1</sup>It is not necessary to disturb the water before putting in the ink. The walls will form without the added disturbance, but they remain so close together that they are more difficult to see in a photograph.



(a) 0 sec.



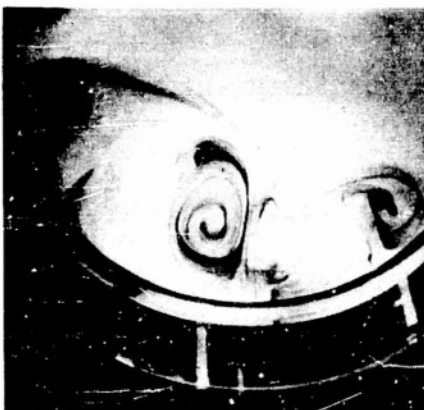
(b) 6 sec.



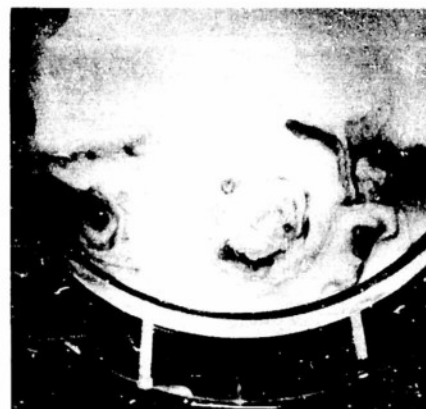
(c) 18 sec.



(d) 30 sec.

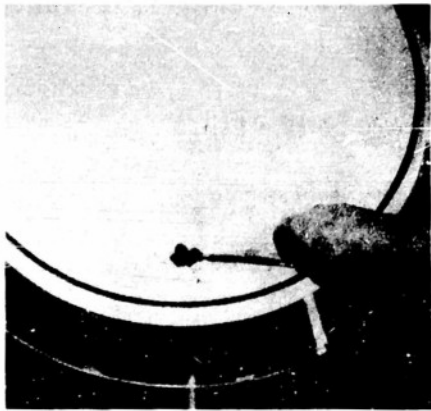


(e) 1 min. 12 sec.

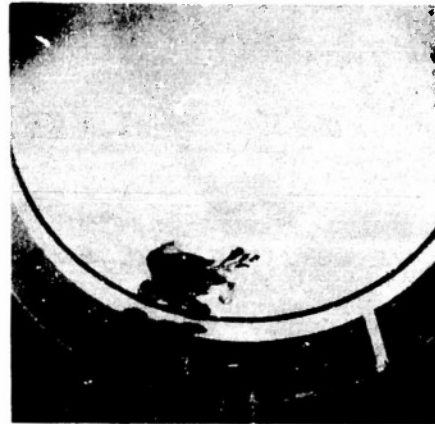


(f) 5 min.

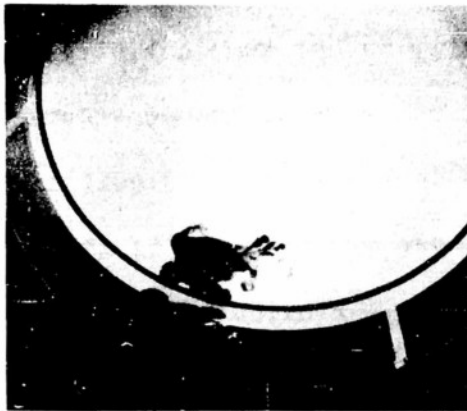
Figure 1. Taylor's ink walls.



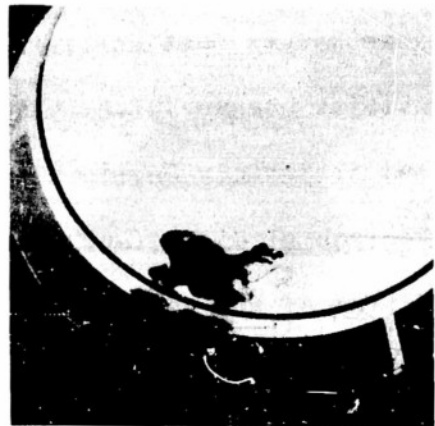
(a) 0 sec.



(b) 10 sec.



(c) 18 sec.



(d) 30 sec.



(e) 48 sec.



(f) 5 min.

Figure 2. Diffusion in a non-rotating liquid.

from the steady state vorticity equations of a homogeneous frictionless rotating fluid:

$$u\xi_x + v\xi_y + w\xi_z = \xi u_x + \eta u_y + (f + \zeta)u_z$$

$$u\eta_x + v\eta_y + w\eta_z = \xi v_x + \eta v_y + (f + \zeta)v_z$$

$$u\zeta_x + v\zeta_y + w\zeta_z = \xi w_x + \eta w_y + (f + \zeta)w_z$$

where the relative vorticity is  $(\xi, \eta, \zeta)$  and the axis of rotation is parallel to the z-axis. As the relative velocities become smaller and smaller all terms involve products of small quantities except  $fu_z$ ,  $fv_z$ ,  $fw_z$ . If we assume that derivatives of velocity do not remain finite as the velocities become infinitesimal,  $u_z$ ,  $v_z$ , and  $w_z$  must become second-order, and ultimately negligible compared to derivatives of velocities in the horizontal direction. Furthermore in our experiment  $w$  is zero at the bottom of the vessel. Since its vertical variation is negligible,  $w$  is zero everywhere.

The above argument shows that once a vertical wall of ink is formed it will remain as such, undeformed by subsequent motions. For the time intervals of the experiment, molecular diffusion is nearly negligible.

Taylor's explanation is quite correct, but does not explain why the ink gathers originally into walls, nor why the walls become so thin and elongated vertically and horizontally. A rotating fluid possesses vorticity and this is represented by vortex lines parallel to the axis of rotation if there is no relative motion. The number of lines per unit horizontal area is a measure of the intensity of rota-

tion. Neglecting friction, vortex lines are material lines; in all subsequent motions they are composed of the same fluid particles. If we suddenly plunge a foreign body of fluid into a system in solid cyclonic rotation, the vortex lines will be forced apart and as a result the relative circulation on horizontal rings of fluid surrounding the foreign fluid will become negative. Initially, the resulting anticyclonic vortex will not have a balance of pressure gradient and Coriolis force, and the rings will contract. This will force the injected fluid to spread vertically until it reaches the bottom of the vessel and the free surface. The relative motion will now be two-dimensional and the newly-formed ink wall will be stretched out horizontally by local shearing motion.

Such a remarkable type of diffusion process might seem at first glance to be a most unusual occurrence, or, indeed, peculiar to rotating fluids. This is not the case, however; in fact, the above explanation occurred to me while reflecting on the tendency for cigarette smoke in a quiet room to concentrate into sheets of smoke parallel to the floor. A similar phenomenon exists in the atmosphere when smoke is discharged into the air during stable conditions. Using the above approach, the injection of the smoke causes a local separation along the vertical of the surfaces of constant density. The action of gravity, in attempting to restore the horizontality of these surfaces, will compress the smoke vertically and spread it horizontally into sheets. The analogy to the rotating phenomenon is very close.

A more intuitive explanation of the formation of sheets of smoke in a stable atmosphere is that the smoke rises under the action of gravity until it reaches an inversion surface. This prevents any further vertical motion and the smoke spreads horizontally. In order to check the analogy to a rotating system, and to dismiss the necessity for a near-discontinuity in density gradient, implied by the last argument, an experiment was conducted with ink injected into a stable water and salt solution. By careful preparation a vessel was filled with a mixture having a smooth density-height curve (fig. 3). A quantity of ink, with a density equal to the mean density of the fluid in the vessel, was then injected. The subsequent developments are shown in fig. 4. The ink forms a fairly thin sheet within approximately 5 min. After a half-hour or so, the gravitational diffusion effect, tending to spread the ink horizontally and contract it vertically, is reduced to the level of importance of molecular diffusion. Before this occurs, the diffusion process, if it were Fickian, (Sutton, 1953), would involve large horizontal diffusion coefficients and a negative vertical coefficient.

It is of some interest to investigate the time interval required for the formation of the ink walls in a rotating fluid. This may be done crudely by a dimensional argument. Assuming that a spherical volume  $V$  of foreign material is injected into an unlimited rotating fluid of the same density, and denoting the decreasing horizontal dimension by  $d$ , we have simply

$$d = \sqrt[3]{V} \chi(\Omega t).$$

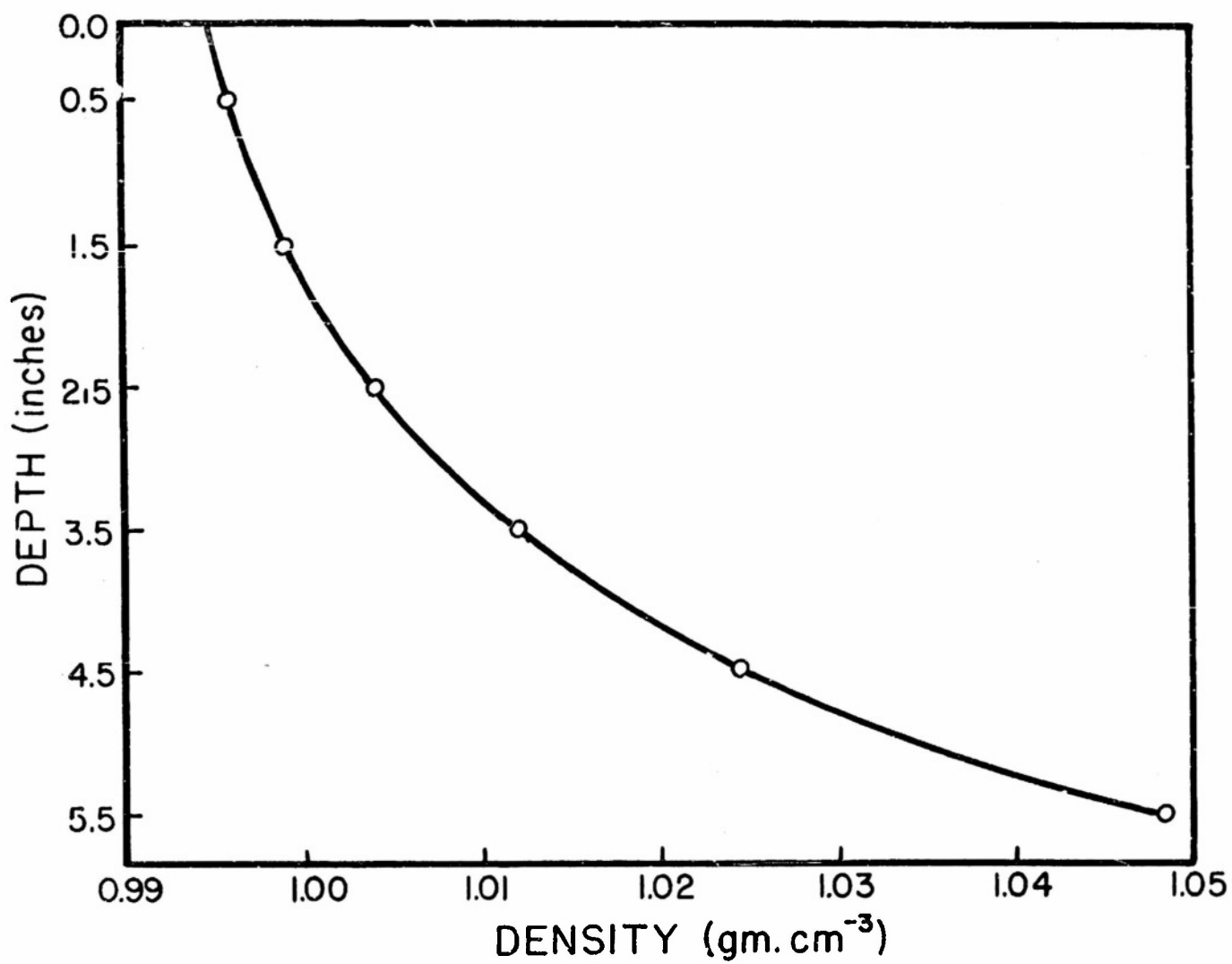
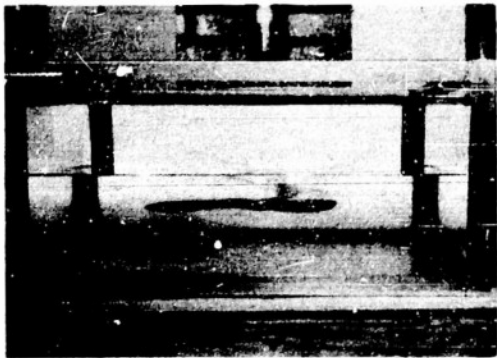
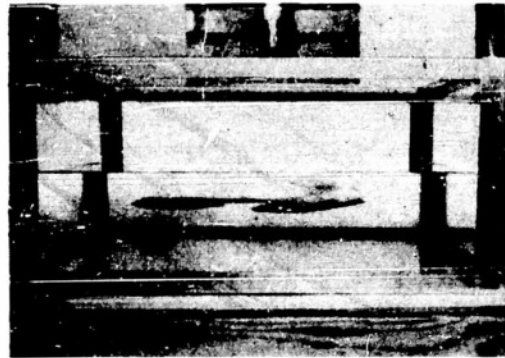


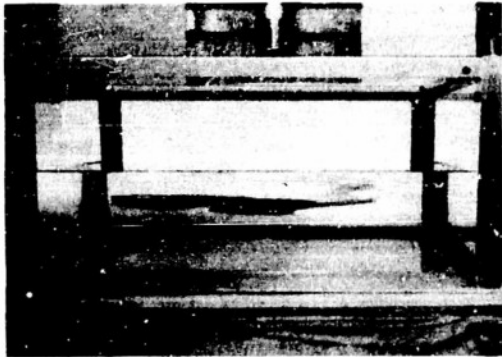
Figure 3. Density-height curve for experiments of fig. 4.



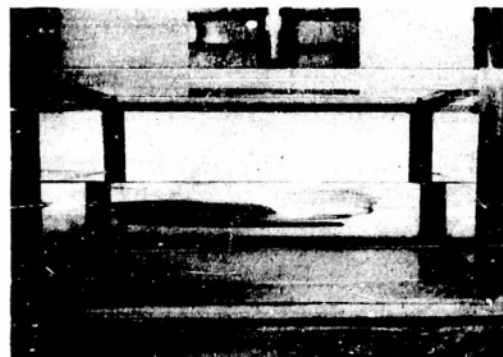
(a) 32 sec.



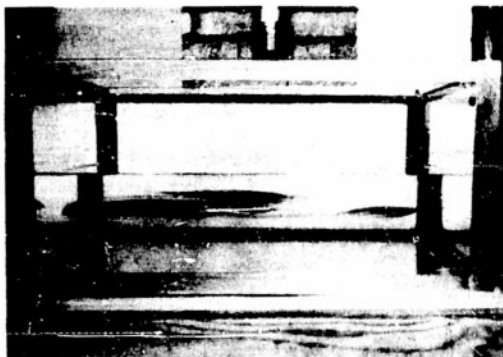
(b) 51 sec.



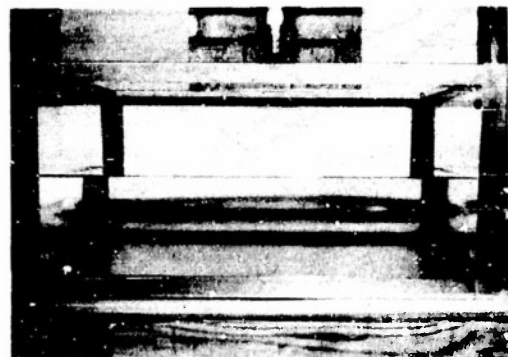
(c) 1 min. 18 sec.



(d) 4 min.



(e) 12 min.



(f) 42 min.

Figure 4. Formation of ink sheets in a stratified fluid.

This assumes, of course, that the volume retains its initial axial symmetry so that it spreads vertically and not horizontally. The experiments<sup>2</sup> indicate that  $d$  changes by a factor of 1/10 in perhaps 30 sec at an angular velocity,  $\Omega = 1 \text{ sec}^{-1}$ . Thus a change to  $d/V^{1/3}$  of 1/10 is associated with a value of 30 for  $\Omega t$ . In the atmosphere, where  $\Omega$  is about  $7 \times 10^{-5} \text{ sec}^{-1}$ , such a change would require  $t = 30/7 \times 10^{-5} \text{ sec}$  or about 5 days. For any conceivable atmospheric phenomenon of this kind, the effect of eddy diffusivity would be several orders of magnitude greater.

The analogous effect in a stratified fluid would seem to be of more practical importance. A dimensional analysis of this case leads to

$$d = V^{1/3} \phi \left( \frac{V^{1/3} \alpha}{\rho_0}, \frac{g t^2 \alpha}{\rho_0} \right),$$

where  $d$  is the diminishing vertical dimension,  $\rho_0$  is the uniform density of the foreign matter,  $\alpha$  is the density (potential temperature) gradient of the environment, and  $g$  is gravity. The first term in the argument of  $\phi$  is the non-dimensional density difference between the ink mass and its environment. If we regard this quantity as important only insofar as it is associated with the buoyancy effect (and therefore only when associated with  $g$ ), we may neglect this number. In the experiment  $\alpha/\rho_0$  was about  $3 \times 10^{-3} \text{ cm}^{-1}$ , and the

<sup>2</sup>The experiment is limited vertically by the bottom of the vessel and the free surface. A full analysis should include this dimension and gravity.

time  $t$  for a reduction of  $d$  to  $1/10$  of its original value was about 5 min. If we choose a mass in a stable environment with a potential temperature rise of  $5-10^\circ\text{C}$  in a hundred meters, the requirement that the second argument of  $\phi$  be equal in the laboratory and the atmosphere yields a value of 1-3 hours for the mass in the atmosphere to form a sheet. This assumes, of course, a complete absence of eddy diffusivity.

This time period seems too long if the above process is responsible for the frequent tendency for smoke to concentrate into sheets in a stable atmosphere. Reports of this phenomenon (Barad, 1951) indicate that it occurs in a matter of minutes. It is possible that the local stability at the height of the stack may be considerably greater than that assumed in the above calculation. It is more likely, however, that the above analysis is too crude. In any event, the vertical eddy diffusivity drops to exceedingly small values if the stability is high. It is, therefore, reasonable to assume that the gravitation effect, tending to condense vertically and spread horizontally, is frequently of the order of magnitude or greater than the vertical eddy diffusivity. This effect, may, moreover, help to explain the findings by Parr (1936) that stability increases horizontal diffusivity.

Acknowledgment

I would like to acknowledge the assistance of Messrs. James F. Haubert and Edwin C. Brockenbrough in conducting the experiments for this work.

REFERENCES

- Barad, M. L., 1951: Diffusion of stack gases in very stable atmospheres. Meteor. Monogr., Vol. 1, No. 4.
- Parr, A. E., 1936: On the probable relationship between vertical stability and lateral mixing processes. Conseil. Perm. Internat. p. l'Explor. de la Mer, Journal du Conseil, 11, 308-313.
- Sutton, O. G., 1953: Micrometeorology. New York, McGraw-Hill Book Co., 333 pp.
- Taylor, G. I., 1921: Experiments with rotating fluids. Proc. Roy. Soc. London, A 100, 114-121.

## APPENDIX

It seems desirable to present a theoretical development which helps to explain the analogy between rotating and stratified fluids with respect to the diffusion phenomenon described above. We divide the investigation into two parts:

### A. Stratified fluid.

According to the description of the experiments the introduction of ink serves initially to distort the density distribution in one case, and the pattern of vortex lines in the other. In this portion of the investigation we will assume a disturbance,  $\rho'$ , of the density field. The latter is given by  $\rho_0 e^{-\beta z}$ , when undisturbed. The coordinates are  $z$ , upward,  $x$ , horizontal. For simplicity we assume that the disturbance is independent of the  $y$ -direction. This does not conform to the situation in the experiment or in the atmosphere but will serve sufficiently well for the present purpose. The exponential density distribution was chosen for simplicity. If we take the origin of the  $z$ -axis near the disturbance,  $\beta z$  will be very small in the vicinity of the disturbance and the density gradient will be nearly linear in this region. In fact, we will assign a length  $L$  for the characteristic vertical dimension of the disturbance and assume  $\beta L \ll 1$ . Then, if  $z_0$  is the undisturbed height of a given density surface,  $\rho' = \rho_0 (e^{-\beta z_0} - e^{-\beta z}) \cong \rho_0 \beta (z - z_0) = o(\rho_0 \beta L)$ . From this we infer that  $\rho'/\rho_0 \ll 1$ , an entirely reasonable result of the assumption,  $\beta L \ll 1$ .

The vorticity equation is

$$\frac{d\zeta}{dt} + \frac{1}{\rho} \rho_x \frac{dw}{dt} - \frac{1}{\rho} \rho_z \frac{du}{dt} + \frac{1}{\rho} \rho_x g = 0, \quad (1)$$

$$\zeta = w_x - u_z, \quad (2)$$

where partial derivatives are denoted by subscripts as before. Since the pressure distribution is very closely hydrostatic we may neglect the second term, compared to the last term in equation (1). We assume now that the motion is very slow and neglect the non-linear terms in the velocity and density perturbation. Equation (1) becomes

$$\frac{\partial \zeta}{\partial t} - \frac{\rho_z}{\rho} u_t + \frac{\rho_x}{\rho} g = 0. \quad (3)$$

By the same assumptions the requirement of incompressibility leads to

$$\rho_t = w \rho_0 \beta. \quad (4)$$

Introducing the stream function by the expressions

$$u = -\psi_z, \quad w = \psi_x, \quad (5)$$

the vorticity equation becomes

$$\nabla^2 \psi_{tt} - \beta \psi_{ztt} + g \beta \psi_{xx} = 0, \quad \nabla^2 \psi = \psi_{xx} + \psi_{zz}. \quad (6)$$

The ratio of the second term to the first term is of the order of  $\beta L$ , so that we have, approximately,

$$\nabla^2 \psi_{tt} + g \beta \psi_{xx} = 0. \quad (7)$$

Since initial conditions are given in terms of the disturbed positions of the density surfaces, we may introduce the quantity  $\delta = z - z_0$ . We obtain finally

$$\nabla^2 \delta_{ttt} + g\beta \delta_{xxt} = 0. \quad (8)$$

#### B. Rotating fluid.

Assuming axial symmetry of the disturbance about the x-axis (axis of rotation), the equations of motion are

$$\frac{dv}{dt} - \frac{w^2}{r} - 2\Omega w = -\frac{\partial X}{\partial r}, \quad (9)$$

$$\frac{du}{dt} = -\frac{\partial X}{\partial x}, \quad (10)$$

$$\frac{d}{dt}(\Omega r^2 + wr) = 0, \quad (11)$$

where  $X = p/\rho$  plus centrifugal and external forces,  $v$  is the radial velocity,  $u$  is the velocity along the x-axis,  $w$  is the velocity tangent to circles about the x-axis, and  $r$  is radial distance.

The vorticity equation is

$$r \frac{d}{dt} \left( \frac{\xi}{r} \right) - \frac{2ww_x}{r} - 2\Omega w_x = 0, \quad (12)$$

$$\xi = v_x - u_r. \quad (13)$$

Neglecting second-order terms in the velocities, this becomes

$$\xi_t - 2\Omega w_x = 0, \quad (14)$$

and, to the same order of approximation, (11) reduces to

$$w_t + 2\Omega v = 0. \quad (15)$$

Introducing the stream function by the expressions

$$u = -\frac{1}{r} \psi_r, \quad v = \frac{1}{r} \psi_x \quad (16)$$

and eliminating  $w$ , the vorticity equation is

$$\nabla^2 \psi_{tt} + 4\Omega^2 \psi_{xx} = 0, \quad \nabla^2 \psi = \psi_{xx} + \psi_{rr} - \frac{\psi_r}{r}. \quad (17)$$

We now introduce  $\delta' = r^2 - r_0^2$ , where  $r_0$  is the Lagrangian distance of a vortex line from the  $x$ -axis. This expression occurs in the integral of (11):

$$\Omega r^2 + w r = \Omega r_0^2. \quad (18)$$

In terms of  $\delta'$ , (17) becomes

$$\nabla^2 \delta'_{ttt} + 4\Omega^2 \delta'_{xxt} = 0 \quad (19)$$

It is remarkable that equations (8) and (19), governing the development of an initial disturbance in a stratified and rotating fluid, respectively, are almost identical except for the fact that the Laplacean opera-

tor is in cartesian coordinates in one case and in cylindrical coordinates in the other. The parameters  $g\beta$  and  $4\Omega^2$  show that the time scales of the two phenomena are in the ratio

$$\tau_s/\tau_r = 2\Omega/(g\beta)^{\frac{1}{2}} \quad (20)$$

so that geometrically similar initial disturbances should develop in time periods having this ratio, provided the fluids are effectively infinite or the boundary conditions are geometrically similar. For the experimental conditions of this paper this ratio is about one, whereas the experimental results indicate roughly that the ratio is about 10 (300 sec/30 sec). Possibly this results from the fact that the ink was injected along a line perpendicular to the density surfaces in one case and parallel to the vortex lines in the other.<sup>1</sup> It is physically clear that this would make a considerable difference in the experimental results. The theoretical indication that the time period in the stratified case may be as little as 1/10 of the 1-3 hr period computed from dimensional considerations of the experimental results, is interesting with regard to smoke diffusion in the atmosphere. If smoke issues from a stack at a temperature close to that of the air, the injection would be more or less along a line parallel to the density surface and the vertical flattening may occur in a matter of minutes instead of the 1-3 hr period suggested by the experimental evidence.

---

<sup>1</sup>We assume here that the different meanings of  $\delta$  and  $\delta'$  ( $z - z_0$ ,  $r^2 - r_0^2$ ), and the two-dimensionality of the stratified portion of the theory are insufficient to explain the order-of-magnitude difference of the time-scale ratios in experiment and theory. A more involved theoretical investigation would be needed to decide this.

# DISTRIBUTION LIST FOR UNCLASSIFIED TECHNICAL REPORTS

| <u>Addressee</u>                                                                                                                                                 | <u>No. of Copies</u> |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Geophysics Branch, Code 416<br>Office of Naval Research<br>Washington 25, D. C.                                                                                  | 2                    |
| Director, Naval Research Laboratory<br>Attention: Technical Information Officer<br>Washington 25, D. C.                                                          | 6                    |
| Officer-in-Charge, Office of Naval Research<br>London Branch Office, Navy No. 100<br>Fleet Post Office, New York, New York                                       | 2                    |
| Office of Naval Research, Branch Office<br>346 Broadway<br>New York 13, New York                                                                                 | 1                    |
| Office of Naval Research Branch Office,<br>10th Floor, The John Crerar Library Bldg.,<br>86 East Randolph Street<br>Chicago, Illinois                            | 1                    |
| Office of Naval Research Contract Administrator<br>Southeastern Area, c/o George Washington University<br>2110 G Street, N.W.<br>Washington 7, D. C.             | 1                    |
| Office of Naval Research Branch Office<br>1030 East Green Street<br>Pasadena 1, California                                                                       | 1                    |
| Office of Naval Research Branch Office<br>1000 Geary Street<br>San Francisco, California                                                                         | 1                    |
| Office of Technical Services<br>Department of Commerce<br>Washington 25, D. C.                                                                                   | 1                    |
| Armed Services Technical Information Center<br>Documents Service Center, Knott Building<br>Dayton 2, Ohio                                                        | 5                    |
| Assistant Secretary of Defense for Research and<br>Development, Attention: Committee on Geophysics<br>and Geography<br>Pentagon Building<br>Washington 25, D. C. | 1                    |

| <u>Addressee</u>                                                                                                                 | <u>No. of Copies</u> |
|----------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Office of Naval Research Resident Representative                                                                                 | 1                    |
| Department of Aerology<br>U. S. Naval Post Graduate School<br>Monterey, California                                               | 1                    |
| Aerology Branch, Bureau of Aeronautics (Ma-5)<br>Navy Department<br>Washington 25, D. C.                                         | 1                    |
| Mechanics Division, Naval Research Laboratory<br>Anacostia Station<br>Washington 20, D. C.<br>Attention: J. E. Dinger, Code 3820 | 1                    |
| Radio Division I, Code 3420<br>Naval Research Laboratory<br>Anacostia Station<br>Washington 20, D. C.                            | 1                    |
| Meteorology Section, Navy Electronics Laboratory<br>San Diego 52, California<br>Attention: L. J. Anderson                        | 1                    |
| Library, Naval Ordnance Laboratory, White Oak<br>Silver Spring 19, Maryland                                                      | 1                    |
| Bureau of Ships, Navy Department<br>Washington 25, D. C.<br>Attention: Code 851, (Special Devices Center)                        | 1                    |
| Bureau of Ships, Navy Department<br>Washington 25, D. C.<br>Attention: Code 327, (Technical Library)                             | 2                    |
| Chief of Naval Operations, Navy Department<br>Washington 25, D. C.<br>Attention: Op-533D                                         | 2                    |
| Oceanographic Division,<br>U. S. Navy Hydrographic Office<br>Suitland, Maryland                                                  | 1                    |
| Library, Naval Ordnance Test Station<br>Inyokern, China Lake<br>California                                                       | 1                    |

| <u>Addressee</u>                                                                                                                | <u>No. of Copies</u> |
|---------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Project Arowa, U. S. Naval Air Station<br>Building R-48<br>Norfolk, Virginia                                                    | 2                    |
| The Chief, Armed Forces Special Weapons Project<br>P. O. Box 2610<br>Washington, D. C.                                          | 1                    |
| Office of the Chief Signal Office<br>Engineering and Technical Service<br>Washington 25, D. C.<br>Attention: SIGGCM             | 1                    |
| Meteorological Branch<br>Evans Signal Laboratory<br>Belmar, New Jersey                                                          | 1                    |
| Office of the Quartermaster General<br>2nd and T Streets<br>Washington 25, D. C.<br>Attention: Environmental Protection Section | 1                    |
| Office of the Chief, Chemical Corps<br>Research and Engineering Division, Research Branch<br>Army Chemical Center, Maryland     | 2                    |
| Commanding Office<br>Air Force Cambridge Research Center<br>230 Albany Street<br>Cambridge, Massachusetts<br>Attention: ERHS-1  | 1                    |
| Headquarters, Air Weather Service<br>Andrews Air Force Base<br>Washington 20, D. C.<br>Attention: Director Scientific Services  | 2                    |
| Commanding General<br>Air Material Command, Wright Field<br>Dayton, Ohio<br>Attention: NCREEO                                   | 1                    |
| Commanding General<br>Air Force Cambridge Research Center<br>230 Albany Street<br>Cambridge, Massachusetts<br>Attention: CRHSL  | 1                    |

| <u>Addressee</u>                                                                                                               | <u>No. of Copies</u> |
|--------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Commanding General<br>Air Research and Development Command<br>P. O. Box 1395<br>Baltimore 3, Maryland<br>Attention: RDDG       | 1                    |
| Department of Meteorology<br>Massachusetts Institute of Technology<br>Cambridge, Massachusetts<br>Attention: H. G. Houghton    | 1                    |
| Department of Meteorology<br>University of Chicago<br>Chicago 37, Illinois<br>Attention: H. R. Byers                           | 1                    |
| Institute for Advanced Study<br>Princeton, New Jersey<br>Attention: J. von Neumann                                             | 1                    |
| Scripps Institution of Oceanography<br>La Jolla, California<br>Attention: R. Revelle                                           | 1                    |
| General Electric Research Laboratory<br>Schenectady, New York<br>Attention: I. Langmuir                                        | 1                    |
| St. Louis University<br>3621 Olive Street<br>St. Louis 8, Missouri<br>Attention: J. B. Macelwane, S. J.                        | 1                    |
| Department of Meteorology<br>University of California at Los Angeles<br>Los Angeles, California<br>Attention: M. Neiburger     | 1                    |
| Department of Engineering<br>University of California at Los Angeles<br>Los Angeles, California<br>Attention: L. M. K. Boelter | 1                    |
| Department of Meteorology<br>Florida State University<br>Tallahassee, Florida<br>Attention: W. A. Baum                         | 1                    |

| <u>Addressee</u>                                                                                                                   | <u>No. of Copies</u> |
|------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Woods Hole Oceanographic Institution<br>Woods Hole, Massachusetts<br>Attention: C. Iselin                                          | 1                    |
| The Johns Hopkins University<br>Department of Civil Engineering<br>Baltimore 18, Maryland<br>Attention: R. Long                    | 1                    |
| The Johns Hopkins University<br>Department of Physics, Homewood Campus<br>Baltimore, Maryland<br>Attention: G. Flass               | 1                    |
| New Mexico Institute of Mining and Technology<br>Research and Development Division<br>Socorro, New Mexico<br>Attention: E. Workman | 1                    |
| University of Chicago<br>Department of Meteorology<br>Chicago 37, Illinois<br>Attention: H. Riehl                                  | 1                    |
| Woods Hole Oceanographic Institution<br>Woods Hole, Massachusetts<br>Attention: A. Woodcock                                        | 1                    |
| General Electric Research Laboratory<br>Schenectady, New York<br>Attention: V. Schaefer                                            | 1                    |
| Geophysical Institute<br>University of Alaska<br>College, Alaska<br>Attention: C. T. Elvey                                         | 1                    |
| Blue Hill Meteorological Observatory<br>Harvard University<br>Milton 86, Massachusetts<br>Attention: C. Brooks                     | 1                    |
| Laboratory of Climatology<br>The Johns Hopkins University<br>Seabrook, New Jersey                                                  | 1                    |

| <u>Addressee</u>                                                                                                                                          | <u>No. of Copies</u> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Department of Meteorology<br>New York University<br>New York 53, New York<br>Attention: B. Haurwitz                                                       | 1                    |
| Texas A & M, Dept. of Oceanography<br>College Station, Texas<br>Attention: J. Freeman, Jr.                                                                | 1                    |
| Massachusetts Institute of Technology<br>Department of Meteorology<br>77 Massachusetts Avenue<br>Cambridge 39, Massachusetts<br>Attention: T. F. Malone   | 1                    |
| Rutgers University, College of Agriculture<br>Department of Meteorology<br>New Brunswick, New Jersey                                                      | 1                    |
| National Advisory Committee of Aeronautics<br>1724 F Street, N. W.<br>Washington 25, D. C.<br>Attention: Mr. Eugene B. Jackson                            | 2                    |
| U. S. Weather Bureau<br>24th and M Streets, N. W.<br>Washington 25, D. C.<br>Attention: Scientific Services Division                                      | 2                    |
| Air Coordinating Committee<br>Subcommittee on Aviation Meteorology<br>Room 2D889-A, The Pentagon<br>Washington, D. C.                                     | 1                    |
| American Meteorological Society<br>3 Joy Street<br>Boston 8, Massachusetts<br>Attention: The Executive Secretary                                          | 1                    |
| Research Professor of Aerological Engineering<br>College of Engineering, Dept. of Electrical Engineering<br>University of Florida<br>Gainesville, Florida | 1                    |
| Division of Oceanography<br>U. S. Navy Hydrographic Office<br>Washington 25, D. C.                                                                        | 2                    |