A DEMONSTRATION OF FRONTS AND FRONTAL WAVES IN ATMOSPHERIC MODELS

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ABSTRACT

The remarkable similarity between the motions in a heated rotating tank of water (dishpan experiments) and the large-scale motions of the atmosphere has raised the question of the similarity of the details of the motion. It has been found possible to demonstrate visually the existence of frontal systems and associated wave cyclones. Analyses and photographs showing the relationships of these systems to the large-scale circulations are presented. It is concluded that similarity in laboratory models is not confined to that scale of motion commonly referred to as the general circulation.

1. Introduction

Considerable progress has been made in recent years in the development of models of the large-scale atmospheric motions (see Fultz, 1951b). The present article describes some new developments which seem to extend the usefulness of such experimental models.

Some preliminary work by the writer with a 2-ft (diameter) rotating tank suggested that a still larger apparatus would be desireable so that the frontal structures noted by the writer in smaller models and by Fultz (1952) could be studied in greater detail. The effects of scale upon the general characteristics of the motion and the experimental practicability of larger models were also to be investigated.

2. Experimental apparatus

The model outlined in fig. 1 was provided a stable variable-speed drive by setting it upon the rotating paraboloid used by Von Arx (1952) for oceanographic model experiments. The cylinder consisted of a brass rim, 4 in. high, fastened around a plywood base. A central cooling system was provided by circulating cold water through a stationary piping system to the underside of a copper plate set in the center of the base. Heat was applied near the rim by means of twelve 250-watt heat lamps fixed 1 ft above the tank. For these experiments, the angular rotation rate was 0.140 sec^{-1}, and the depth was 3 cm.

One of the important and difficult problems in such experiments is that of tracing the motion of the fluid. The following methods were found useful in this case:

1. The motion at the top surface of the water was determined by photographing the displacements of floating particles in a measured interval of time. Small discs of waterproof paper were found to be most practical as floating particles.
2. Crystals of potassium-permanganate dye were scattered uniformly over the tank. These fell to rest on the bottom and dissolved slowly, so that the plumes from the diffusing dye indicated the direction of the flow at the bottom.
3. Several revolutions after the introduction of the dye, regions of convergence were indicated by concentrations of dye at the bottom of the fluid. This seemed to be a consequence of the fact that the dye was heavier than the water and tended to concentrate in regions of low-level convergence and upward motion. Fronts and associated wave cyclones were clearly seen. After the initial effects of the convergence, however, it was somewhat fortuitous whether dye was available to indicate any newly developing regions of convergence.

3. Results

Fig. 2 illustrates the circulations at the bottom and at the free surface at a particular time. The left-hand portion shows the bottom circulation as

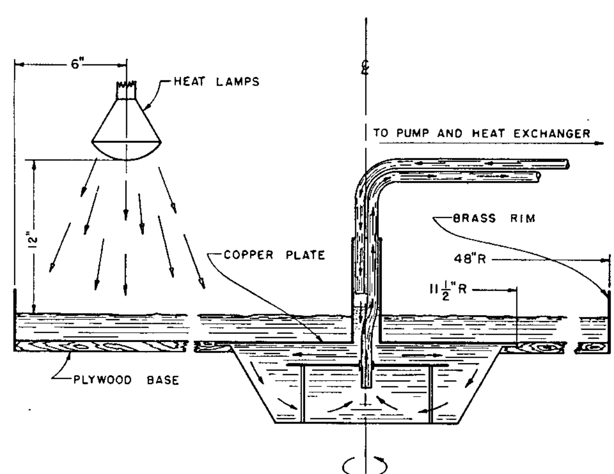

FIG. 1. Schematic diagram of rotating apparatus.

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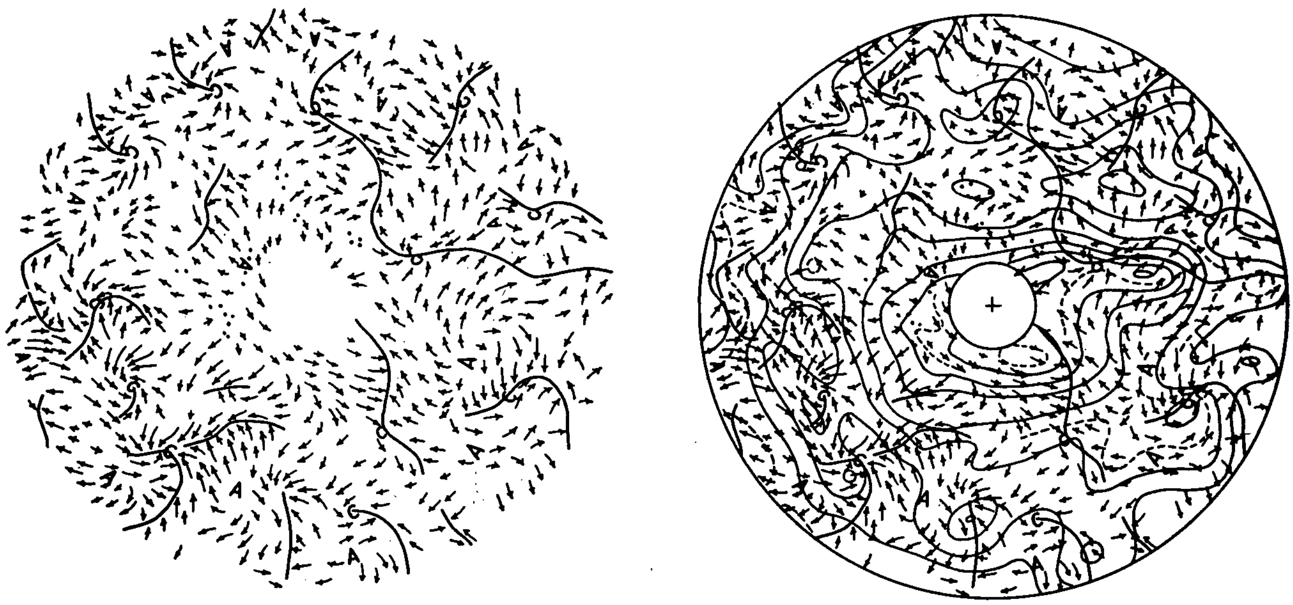

FIG. 2. Analysis of bottom circulation (left) and free-surface circulation superimposed upon bottom circulation (right).

indicated by the plumes of dissolving dye. Distinct lines of convergence and cyclonic shear, apparently fronts, are denoted by solid lines. Regions of clearly cyclonic or anticyclonic motion are labeled *C* or *A* respectively. Some attempt was made to indicate speeds by the lengths of the arrows, even though no accurate measurements could be made. The right-hand diagram illustrates the free-surface circulation superimposed upon the bottom circulation. To obtain the representation used here, velocity vectors were derived from the displacements of the paper discs in a 10-sec interval, and the velocity field was converted to an equivalent isobaric chart by constructing approximate streamlines with a spacing inversely proportional to the speeds. Due to observational difficulties close to the rim of the tank, the limit of the diagrams is taken a short distance from the rim. The tilt of cyclones with height, and the relationships of fronts to the upper-level pattern, are very similar to those in the atmosphere.

Fig. 3 shows a representation of the circulation seven revolutions after that shown in fig. 2. The frontal systems are made clear by the bands of dye and, again, the close connection with the free-surface circulation is evident.

An example of the development of wave cyclones is shown in fig. 4. The time interval between photographs is one revolution, and the sequence proceeds

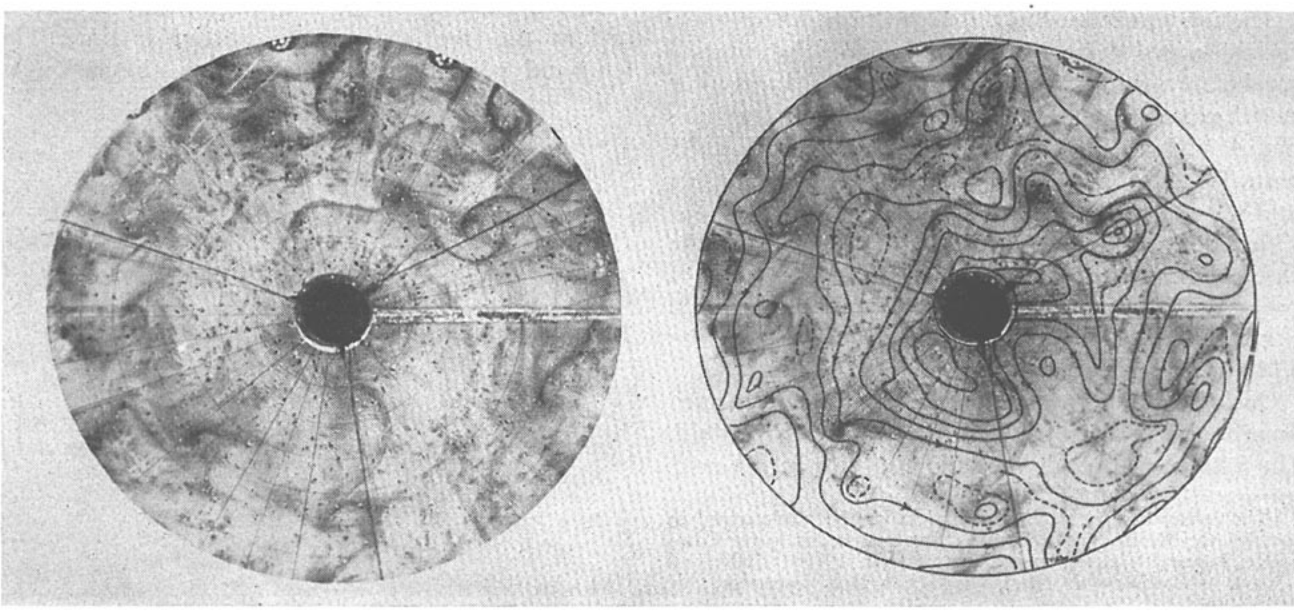

FIG. 3. Bottom circulation seven revolutions after fig. 2 as indicated by dye fronts (left), and corresponding free-surface circulation (right).

from left to right and from top to bottom. The development of two waves may be seen on the principal front. The one in the centers of the frames reached occlusion rapidly, while the cyclone near the bottoms developed more slowly. Moving cold fronts, other than those in the principal frontal system, may be

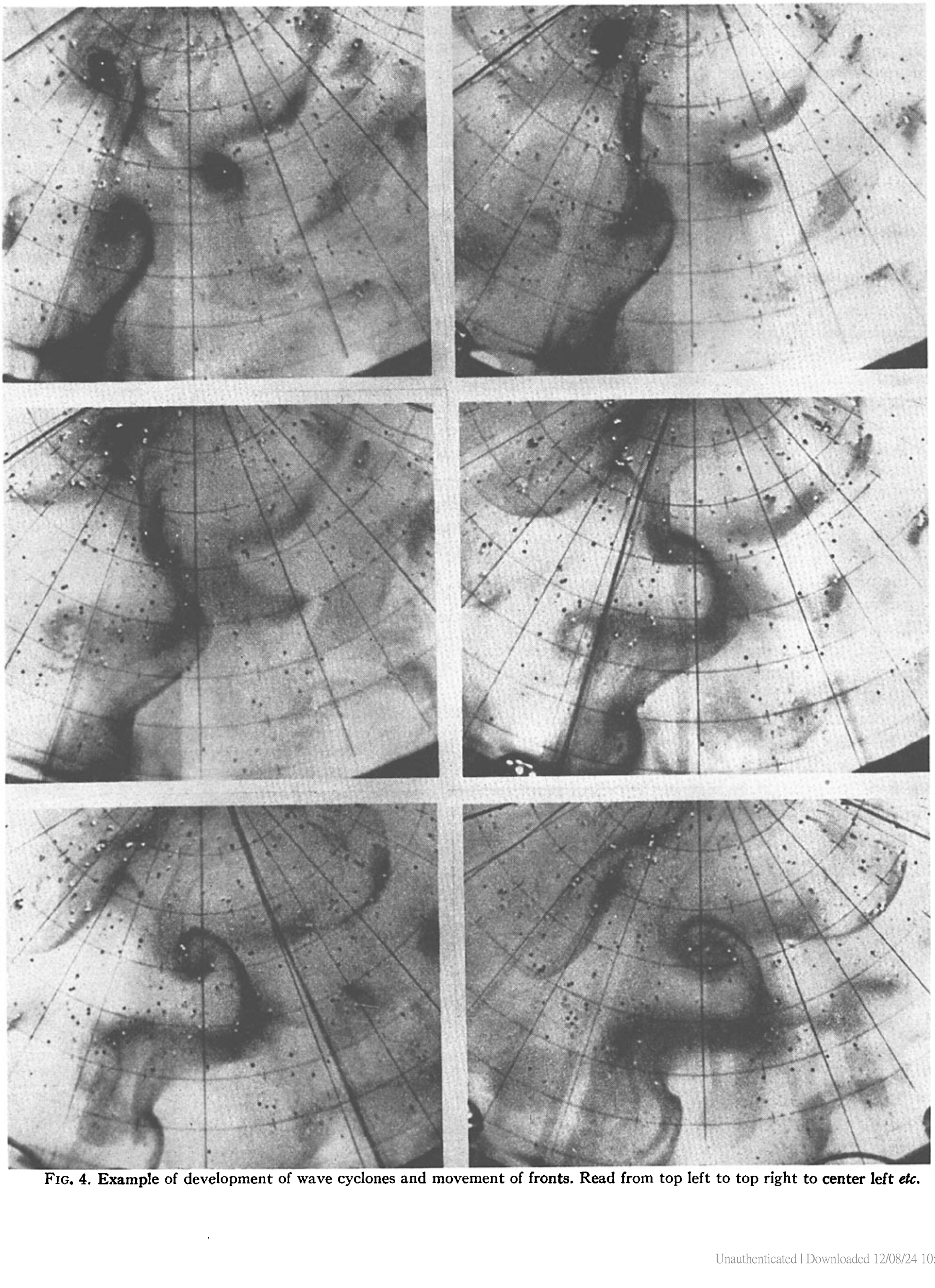

FIG. 4. Example of development of wave cyclones and movement of fronts. Read from top left to top right to center left *etc.*

detected in the upper left and upper right of each photograph.

To establish the presence of thermal contrast at the fronts indicated by the dye, a line of stationary thermocouples was immersed $\frac{1}{2}$ cm beneath the free surface from the center to the rim of the cylinder. In one revolution, each thermocouple, therefore, described a complete circle at its particular radius, and the overall thermal pattern was revealed. Despite the time lag inherent in the thermocouples and recording system, and the rapid movement of the thermocouples through the water, very sharp temperature changes associated with the dye fronts were evident.

4. Conclusions

One may note certain dissimilarities between the configurations of fronts as indicated in the model and those found on weather charts. In view of the simplicity of the apparatus, these discrepancies are not surprising; rather, the similarity is considered to be remarkable. A sufficient condition for the generation of fronts which bear marked resemblences to those envisioned in the atmosphere seems to be a proper combination of the rotation rate and the meridional temperature gradient. Since the meridional temperature gradient is related to the velocities, this condition of similarity may be attained by requiring equality in the model and in the prototype of the non-dimensional ratio v/rf = Ro (the Rossby number, see Fultz, 1951a), where v is a representative velocity, r a representative length, and f is the Coriolis parameter. For the model, using values of $v = 1$ cm/sec, $f = 2 \times 0.140$ sec^{-1}, and $r = 122$ cm (the radius of the model), one obtains Ro = 0.003. For the atmosphere, using $f = 10^{-4}$ sec^{-1} ($2\omega \sin \varphi$ at $\varphi = 45°$), $r = 6400$ km (the radius of the earth), and a velocity of 50 m/sec, one finds Ro° = 0.008. In view of the lack of geometric similarity and the indefinite specification of a representative velocity, the similarity in this respect is satisfactory.

The exact manner of production of the meridional temperature gradient does not appear to affect the qualitative results appreciably. Although in the apparatus a large fraction of the applied radiant energy was absorbed in the top layers of the water (50 per cent in the top 2 mm, 27 per cent in the remainder of the 3 cm, and 23 per cent transmitted to the bottom), similar circulation was obtained in other apparatus when heated from below. In addition, substantially the same results were obtained by using either the heat source near the rim or the cooling mechanism near the pole alone, except that in those cases a steady-state mean temperature distribution could not easily be obtained.

It is evident, however, that to attempt a model more similar in detail it would be necessary to pay strict attention to the distribution of heating, and disturbing influences such as evaporation from the free surface would have to be eliminated or kept under control.

A more complete analysis of the results of these experiments is not warranted at the present time. However, the results demonstrate that complete frontal systems may be produced in models and suggest that much may be learned from experiments concerning their atmospheric counterparts. Indeed, they suggest that the similarity of laboratory models is not confined to the larger-scale circulation.

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