A Laboratory Study of the Wind-driven Ocean Circulation.[1]

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Abstract

Experiments with rotating oceanographic models are being attempted in the laboratory at Woods Hole in the hope that some information may be gained which will help to close the gap between recent theories of ocean circulation and the observed nature of the circulation. Recent theoretical descriptions by STOMMEL (1948) and MUNK (1950) indicate the broad features of the climatological mean circulation pattern. In contrast, observations usually allow description of possibly transient situations in only relatively small regions. The major observational problem at the moment, short of synoptic measurements over large areas, is to learn how the observations made from moving ships fit into the pattern of very large scale fluid processes.

Some insight has already been gained through the search for atmospheric counterparts initiated by Dr C.-G. Rossby, and it is hoped that a wind-driven model of the oceans may offer additional clues. It is recognized that ocean models cannot be scaled in every particular and that the scales taken into account may lead to error since processes of verification, ordinarily used to test the suitability of hydraulic models, cannot be applied. Thus the behavior of a rotating model can bear a limited resemblance only to contemporary ideas of what the primary ocean circulation may be like.

In terms of these ideas, however, it has been possible to reproduce westward intensification of the primary circulations in compartments shaped like the North Atlantic and North Pacific basins. Sargasso Sea-like features and several details have also appeared which are qualitatively like contemporary views of the major motions of the sea. These major, and some minor features of the circulation develop rapidly under wind-stress applied to homogeneous water.

1. Description of the apparatus

A basin having the internal form of a paraboloid of revolution was chosen because it provides a Coriolis parameter which varies with latitude, and a free liquid surface which is accessible for the application of wind stress, heat, light, and tracer materials. In a paraboloid of reasonable depth, however, the Coriolis parameter does not ordinarily approach zero at the rim. Therefore, experiments are generally limited to extratropical regions unless geometrical and dynamical distortions of various sorts are allowed. Figure 1 shows the arrangement of parts.

a) The mechanical system

The paraboloidal basin now in use is 2 meters in diameter and has a focal length of 0.5 meter. The paraboloid rises from the vertex to the latus rectum, then enters a toroidal section and is terminated in a cylindrical

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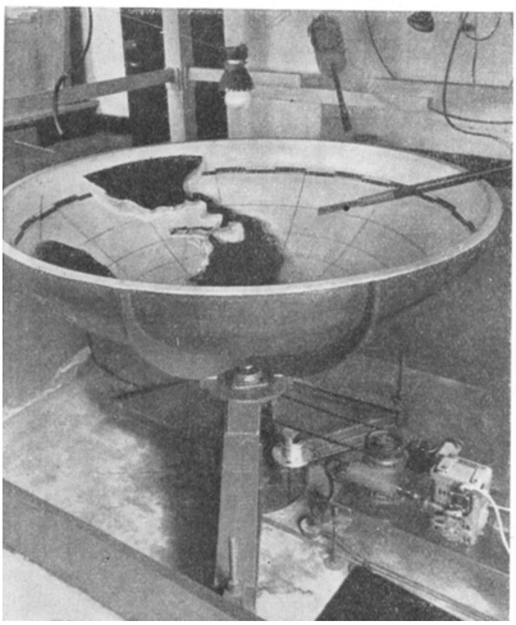


Fig. 1. General arrangement of the rotating basin apparatus. The control panel at the extreme right is accessible from the observers desk at the eye end of the optical train. The basin itself is mounted in a concrete sump below the observation platform. The drive machinery can be seen at the lower right. The main light at the effective center of curvature of the basin and the blowers around the basin are suspended from the platform. The continental modeling is 6 cm high and cemented in place.

section extended high enough to prevent a layer of water 10 cm deep from overflowing at the equilibrium rate of rotation. The basin is made of fiberglass bonded with a plastic. Eight ribs are bonded to the basin and to a stainless hub at the vertex. The basin weighs about 80 kilograms and will support a 500 kilograms load of water.

The basin is mounted on the end of a vertical shaft 10 cm diameter by 0.6 meter high, fitted snugly into two self-aligning radial-thrust bearings in a heavy, welded steel tripod which is secured to a concrete slab by nuts on three leveling screws embedded in the slab. The drive for the basin consists of a 1 H.P. capacitor-starting synchronous motor which drives the basin through a variable-ratio V-belt speed controller and a worm gear speed reducer. The basin shaft is coupled to the drive by a V-belt which has proven satisfactory when run with considerable slack. Once the basin has been accelerated to speed, it runs nearly free of the drive machinery except for the small amounts of power required to overcome friction and air resistance. The equilibrium rate of rotation of the basin is 3.13 radians per second, hence the tangential velocity of the rim is over 3 meters per second. Even so, the water in the basin remains quiet and the free surface is smooth except for the wind ripples which become noticeable in the zone within 20 to 35 cm of the rim. These ripples can be damped out by means of a detergent on the free surface. To avoid seiches the vertical shaft carrying the basin must be quite plumb.

b) The optical system

The optical system for observing the circulation in the basin and illuminating it requires consideration. In the Woods Hole installation, where there is only limited head-room, the entrance pupil of the optical system was, o necessity, placed 2.5 meters above the vertex of the paraboloid, hence a true field of 60° was required. This was accomplished by viewing the basin through the "wrong end" of a surplus M71H tank telescope having a 65° apparent field, focused so as to produce a beam of parallel rays emerging from the objective end. This places the image of the basin at infinity. Derotation of the image is accomplished with a Dove prism. This component, mounted in precision ball bearings, was placed in emergent beam and rotated by means of a selsyn repeater motor driven by a similar selsyn motor linked to the basin shaft by a rubber belt. The sheave ratio at the basin shaft was made 1/3 and the sheave ratio at the Dove prism 6/1, so that the Dove prism revolves at one-half of the basin rate regardless of the angular velocity of the basin, while the selsyns themselves turn over at a more efficient rate. It was found expedient to provide the Dove prism sheave with a cylindrical face and the repeater selsyn sheave with a 90° groove so that small changes required to adjust the ratio of these two sheaves could be effected by changing the tension of the round rubber belt connecting them.

A Dove prism must be placed in a beam of parallel light, so that the aberrations introduced at the first refracting face are exactly cancelled by the second. A Schmidt prism, or an equivalent system of plane mirrors, may be used if parallel light cannot be managed. Both prisms offer an odd number of internal reflections (one in the Dove prism and five in the Schmidt prism) so that an additional reflection is required to revert the image. This added reflection was obtained from a plane first-surface mirror ahead of the entrance pupil. This proved to be a convenient way to change the axis of the optical system from vertical to horizontal under low head-room conditions.

The parallel beam emerging from the Dove prism provides a stationary, real image at infinity which has only a small angular size due to the negative magnification of the reversed telescope. This image can be examined comfortably through a second telescope or photographed directly if lenses of suitably long focal length are used to cause the image to fill the frame. Exposures longer than one second have been possible. The light losses in the optical train amount to about 60 per cent.

Time lapse motion pictures have been made through this optical system which are synchronized with the rotation of the basin. A microswitch trips the camera electrically as it is engaged by combinations of 16 pins of different lengths concentrically arranged on a disc turning with the basin shaft. Of the 16 pins, one is longest, one is located at 180° from the first and is made a little shorter, two at 90° to the first pair are equal in length but shorter than the second mentioned, four still shorter pins are located at the 45° positions, and the eight shortest pins are located at the 22.5° positions. Thus by simply raising and lowering the micro-switch the camera can be tripped 1, 2, 4, 8, and 16 times per basin revolution regardless of the angular velocity of the basin. A small light mounted at rest in the field of view appears as a streak in each exposure indicating the angular motion during and between exposures. The duration of exposures and time elapsed between them can be measured in this way.

The main source of illumination is a 2000 watt lamp. The lamp is placed at the effective radius of curvature of the paraboloid so that the illumination is quite uniform and reflections from the free surface are returned to the light source.

The optical system is supported independently so that the vibrations of machinery do not disturb it, and the activities of the observer do not change its alignment with the axis of rotation of the basin.

c) The pneumatic system

The air streams over the model which are used to simulate atmospheric circulations are produced by three tank-type vacuum cleaners operating wrong-end-to as blowers, and spaced 120° apart around the basin. When equipped with nozzles these blowers can be aimed at limited zones of the paraboloid to increase or decrease the local relative motion of air beyond that due to the rotation of the basin. A variac controls the speed of all three blowers simultaneously. Suitable wind torques can be achieved either by directing the blowers so as to produce westerlies in temperate latitudes or easterlies in the trade wind zone. The latter requires smaller discharge velocities from the blowers and is more generally used.

d) Tracers

The matter of tracers for the detection and measurement of water motion is unsettled. Neutrally buoyant ink, potassium permanganate, aluminum tristearate, n-butyl phthalate and xylene, aluminum foil and several other substances (including cranberries) have been used at different times. The ink-potassium permanganate combination is useful since the ink stays near the surface and the permanganate crystals sink to the bottom to produce trails of color. In regions of upwelling the permanganate solution oxidizes the ink and changes the color of the mixture. The latter three tracers are essentially particulate but none has a high enough albedo to permit satisfactory streak photographs to be made with the present apparatus. An interesting alternative to streak photographs has been proposed; namely, if the two instantaneous photographs taken at slightly different times, the stereoscopic relief of displaced particles or dye fronts would be proportional to the velocity. In this manner a velocity solid might be visualized or constructed.

e) Comments on design

The design of the mechanical and optical systems for this rotating basin apparatus was exploratory, and can be improved in many ways. For example: ultra-wide field astronomical optical systems exist which, with a Schmidt prism for derotation, would be an improvement over the rather crude optical system now in use. Similarly, the frequency controlled synchronous telescope drives already in use in some observatories could be adapted to the basin drive to afford not only a steadier motion but better control and measurement of the angular velocity. Wind stresses should be applied in a more elegant manner than at present, and should be subject to better quantitative control. The matter of suitable tracers for the detection and measurement of circulation at all levels requires more study.

2. **Scaling and modeling**

An oceanographic model requires that certain elementary properties of the lithosphere, hydrosphere, and atmosphere be represented together. Since the hydrosphere is the principal object of study, the functions of the lithosphere and atmosphere are of consequence only where they touch the hydrosphere. Thus it is sufficient to model in the coastlines and ocean bed, and to reproduce the surface winds over the ocean areas.

The original choice of the diameter and focal length of the paraboloid imposes limits on the scale and degree of similarity attainable. If the diameter of the basin is equal to four times the focal length, the rim makes an angle of 45° with the axis of rotation and limits the variation of the Coriolis parameter from 0.707 f at the rim to f at the vertex, or pole.

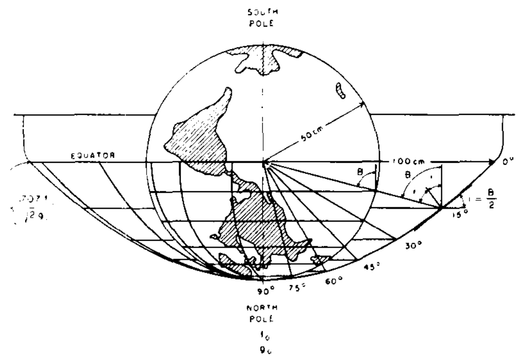


Fig. 2. Gnomic projection of the landmasses of the northern hemisphere on the interior of the paraboloidal basin. The variation of the Coriolis parameter at the equilibrium speed of rotation and the change of the combined gravitational and centrifugal accelerations are indicated.

The absolute magnitude of the Coriolis parameter is determined by the rate of rotation of the basin, which cannot (for practical reasons) depart from the equilibrium rate by more than a few per cent. This rate, in effect, also fixes the time scale of the model. For the Woods Hole basin, T_r is approximately 2.3×10^{-5}.

Despite the limitation that the Coriolis parameter cannot approach zero at the rim, the topography of the entire northern hemisphere has been projected on the interior of the paraboloid as an experiment, by the method shown in Figure 2. The projection was made gnomonically from the center of a sphere having a radius equal to the focal length of the paraboloid, placed so as to be tangent to the paraboloid at the vertex. The north pole of the sphere and the vertex of the paraboloid coincide. The resulting scale of the projection on the basin is the same as that of the sphere at the pole but increases toward the equator at the rim to $2\sqrt{2}$ times the north-south dimensions and 2 times the east-west dimensions of the sphere. This distortion is not objectionable to the eye.

Assuming that the length of a quadrant on the paraboloid is a characteristic length, the ratio L_r becomes 0.8×10^{-7} approximately, with respect to a quadrant on the earth. From this and the estimate of the time scale, T_r, the coefficient of lateral eddy diffusivity may be scaled by the ratio $(L_r)^2/T_r$, or 0.3×10^{-9}.

If a representative value for the lateral eddy diffusivity is in the order 10^8 cm²/sec. the scaled value for the basin becomes about 1 cm²/sec. which can be maintained experimentally.

The depth of water in the model may be exaggerated to allow for the nearly 100:1 inequality of the vertical and horizontal values of eddy diffusivity in the real ocean. If oceans are in the order of one thousand times wider than they are deep, an appropriate depth of water in the model is as much as one-tenth of the model ocean width. This can be accommodated, but departures from this ratio seem experimentally to produce very little effect.

Two other distortions exist in the paraboloid which are different from the situation on the earth; namely, the variation in the effective acceleration of gravity from g at the pole to $g\sqrt{2}$ at the rim, and the fact that at the equilibrium rate of rotation the depth of water measured normal to the free surface decreases as the cosine of the parabolic latitude. The increase of g and decrease of normal depth at the equilibrium rate of rotation cause the water to exert equal pressures on equal areas of the basin itself, but for the isobaric surfaces above the bottom to diverge poleward. This has an extraordinary effect which was explained by Dr C.-G. Rossby, that under these circumstances the cyclonic vorticity tendency associated with the horizontal convergence of the stretching water columns transferred from the rim to the pole is exactly equal and opposite to the anticyclonic vorticity tendency associated with the northward change in latitude. As a result, westward intensification of the circulation does not occur at the equilibrium rate of rotation. Having the effective planetary vorticity adjustment of the tendency under experimental control through meridional change in the depth of water in the model it becomes possible to study the changes in the broad pattern of the circulation under different combinations of the planetary, wind-stress and frictional vorticities. When the effective planetary vorticity tendency is increased by increasing the rate of rotation of the basin so that the normal depth at the rim is about 1.7 times that at the pole, the normal westward intensification of the circulation appears. If the rate of rotation is made correspondingly less than the equilibrium rate of rotation the sign of the planetary vorticity tendency is reversed, the circulation pattern is rotated 180°, so that the intensified circulation follows the eastern margins of the ocean basins. This occurs without any change in the intensity or distribution of wind torque. Theoretically the normal westward intensification should occur in the model when the depth normal to the free surface at the rim is $(1 + 1/\sqrt{2})$ times greater than that at the pole. The rate of rotation necessary to achieve the proper ratio of depths is, of course, a function of the average depth.

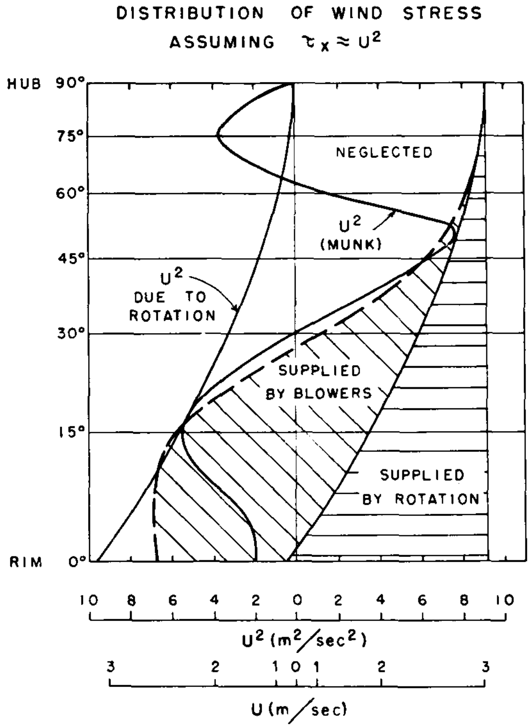


Fig. 3. Experimental distribution of zonal wind stress (dashed line) compared with that derived by MUNK (1950) (solid line) from records of the average zonal wind stress over the earth.

Figure 3 represents the experimental distribution of wind stress superimposed on that determined by Munk from average winds over the earth. The experimental curve approximates the natural one only in mid-latitudes. Experimentally the latitude of the inflection point seems to be more significant than the latitudes of the wind stress maxima, therefore attention has been concentrated on this adjustment for the time being. It is considered at the moment that a first approximation of the proper intensity of wind torque has been reached when the current velocities in the water approach the velocity scale L_r/T_r or 0.4×10^{-2}. The magnitude of the wind torque required to bring the velocity of the Gulf Stream nearly in scale is approximately 0.007 dyne/cm^2.

Because wavelets produce turbulent mixing at the coastlines, the wind stresses on the basin have been kept as small as possible. Wavelets, it is found, can be damped out to a great extent by covering the water surface with a film of Aerosol (a laboratory detergent). This film seems to have no important effect on the ratio of a given wind velocity to the water velocity produced. KEULEGAN (1951) reports similar results using Glim.

Modeling of the land masses has been done in commercial grade sponge rubber. This material permits the carving to be done originally on flat sheets which are easily bent to conform with the paraboloidal shape of the basin. The modeling was cemented in place. Besides being convenient to use, the sponge rubber modeling presents a rough surface along the margins of the ocean basins in contrast to the glassy smooth finish of the plastic of the basin which forms the bottom surface. The lateral roughness is of theoretical as well as experimental importance and can be changed through a wide range by either serrating the rubber, cutting it smoothly with sharp tools, or filling the pores with paint so as to be almost as smooth as the plastic surface of the basin. It is found that the roughness of the order of pore size in the rubber is of less consequence to the circulation than the large scale roughness of the geography of the continental masses themselves.

3. Some oceanographic results

The rotating basin experiments at Woods Hole have been in progress only a few months, so that this discussion is both qualitative and subject to change. It is regretted that no instantaneous photographs of the circulation, such as Figure 4 (opposite p. 318) can represent the changing occurrences that may be seen during an hour's operation of the basin. The description that follows has been written with the realization that others might have described or interpreted the same experimental results in other ways.

When the model is rotated at the optimum angular velocity for normal westward intensification, the circulation in both the North Atlantic and North Pacific compartments is dominated by a swift, narrow current flowing along the western margin of each compartment. The current in the North Atlantic compartment follows a course similar in many ways to present ideas of the course of the Gulf Stream. This current is composed of water from the south central North Atlantic area; from the slow drift of water upwelling in the lee of the West African bulge, and from the swift and relatively narrow Guiana current flowing northwestward along the northern coast of South America. Water from these sources flows through the Caribbean and through the Straits of Florida with very little transverse mixing. There is a pulsation of the flow through the Florida Straits which influences both the anticyclonic sweep of a small fraction of the flow into the eastern part of the Gulf of Mexico and the steadiness of the flow downstream as far as the Grand Banks. The similarity of this flow to the Gulf Stream extends to such details as the persistent anticyclonic bend over the Blake Plateau, and the oscillating cyclonic and anticyclonic curvature of flow east of Cape Henry. Meander structures of standing or slowly progressive (downstream) waves have occurred in the region between Cape Hatteras and the Grand Banks in recent experiments. These are similar to the actual meander structures that have been described by ISELIN and FUGLISTER (1948) and FUGLISTER and WORTHINGTON (1951) except that the wavelength is too long by a factor of about three.

FUGLISTER (1951) has also described some branches of the Gulf Stream system in the vicinity of the Grand Banks. Branching has been observed in the basin current in this region but the character of the circulation appears to be different. Multiple currents in the basin consist in stagnating streamers on the southeast side of the main current. A sudden discontinuity may occur in the flow which causes the active current to pass the older segment on the left. If the new thrust does not branch in the cyclonic circulation of the Labrador Sea it may penetrate northeastward as far as the coast of Norway before stagnating and being itself wedged aside by the next active thrust.

The circulations produced in the rotating basin resemble the ocean surface circulations best in the western regions of intense currents and sharply bounded water masses. In order to obtain a pattern of circulation along the eastern borders of the North Atlantic that resembles the patterns thought to exist, and for the North Atlantic Current to make its way toward the British Isles and to turn into the Arctic Ocean along the Norwegian coast, it is necessary in the model to vent the Arctic Ocean basin and return this discharge to the vicinity of the Gulf of Guinea. This artifice may be equivalent to the sinking of water in the northern North Atlantic, and the return, as either equivalent to upwelling off the coast of West Africa or possibly to the penetration of surface water northward across the equator from the South Atlantic Ocean.

The circulation of the North Pacific Ocean resembles some contemporary ideas of the actual circulation in several respects. In the model the Kuroshio is shorter than the Gulf Stream. It develops from the North Equatorial Current in the latitude of the Philippines north of Mindanao, accelerates steadily on its way past Formosa and the Ryikyu archipelago, is both swiftest and narrowest as it skirts the southern coast of Japan. During some experiments the Kuroshio stands off the southern coast of Japan, resembling to some extent the cyclonic bend described by UDA (1949), (1951). Beyond the 140° E meridian the Kuroshio decays rapidly, as does the Gulf Stream when it merges into the North Atlantic Current, and the circulation becomes quite sluggish. The equivalent of the Sargasso Sea in the Pacific is a very small patch of relatively motionless water directly south of the Kuroshio.

The prolongation of the Kuroshio Extension across the northern Pacific as the North Pacific Current is a slow, persistent movement which has no well defined boundaries but which accelerates slightly along the California coast and weakens again before joining the North Equatorial Current formed by the confluence of this water with the circulation northwestward along the west coast of Central America. The North Pacific Current crosses the mouth of the Gulf of Alaska and either contributes to, or sets up, a slow cyclonic circulation in the Gulf between Queen Charlotte Island and the beginning of the Aleutian archipelago. A similar cyclonic circulation appears east of the Kuril Islands, and a current flows southeastward along that chain which corresponds in a general way to the Oyashio. In certain experiments strong eddies develop in the region where the Kuroshio Extension and Oyashio meet off the coast of northern Japan, but in others the confluence is smooth or the Oyashio itself does not appear.

Within the main body of the North Pacific there is a slow general motion southward and southeastward from the paths of the strongest currents in the northwest which carries the complex filaments developed in the north toward the North Equatorial Current. The major contributions of water from the North Pacific to the North Equatorial Current appear to occur in the region between the coast of Central America and the 150° W meridian.

While the circulation within the North Pacific Ocean compartment is similar to that in the North Atlantic compartment, there are marked dissimilarities of detail. These may be due as much to the effects of northern seas on the Atlantic circulation as to the difference in shape and size of the two oceans in the temperate and equatorial latitudes.

4. In prospect

In none of the experiments with ocean compartments of realistic shape has it seemed desirable to include bottom topography other than that of the continental shelves to the level of the 200 meter isobath. Deeper topographic features such as major ridges and swells alter the circulation too much, and yet some modification of the otherwise featureless bottom seems to be needed. The surface circulation is thought to be represented in the basin and since, in nature, this is largely confined to the levels above the main thermocline, it may be that this interface is of importance to the wind-driven circulation. Experimentally a bottom surface having the topography of the main thermocline would influence the local changes in the planetary vorticity tendency and may alter the circulation pattern in instructive ways. In past experiments this has been considered as only a simple function of latitude.

Attempts to develop a density interface similar to that at the thermocline, through the solution of crystalline table salt dropped to the bottom of the basin, have failed. This failure is presumed to result from the halocline adjusting to an isobaric surface in which case the planetary vorticity tendency is canceled for motions in the upper less saline layer.

In homogeneous water, however, the Coriolis force is balanced only by the pressure gradient due to elevation of the free surface. Near the bottom, where velocities are small, the pressure gradient is greater than the Coriolis force. Therefore, there is marked anticyclonic motion in the bottom layer beneath the surface dome of the Sargasso Sea area. A line of weaker horizontal divergence extends northeastward from this point into the northern North Atlantic. There is a similar but weaker bottom circulation in the Pacific compartment. Presumably this mode of motion would not occur were it possible to establish a two layer system without losing experimental control of the planetary vorticity adjustment, except during periods of rapid acceleration due to increased wind torque. This problem and a study of the circulation resulting from equatorial heating and polar cooling in the absence of wind is of present interest, as are the circulation systems of the southern hemisphere.

REFERENCES

FUGLISTER, F. C., 1951: Multiple Currents in the Gulf Stream System. *Tellus* **4**, 230—233.

FUGLISTER, F. C., and WORTHINGTON, L. V., 1951: Some results of a multiple ship survey of the Gulf Stream. *Tellus* **3**, 1—14.

ISELIN, C. O'D., and FUGLISTER, F. C., 1948: Some recent developments in the study of the Gulf Stream. *Jour. Mar. Res.* **8**, 317—329.

KEULEGAN, G. H., 1951: Wind set-up in small closed channels. *Jour. Mar. Res. Natl. Bur. Stds.* **46** (5), 358—381.

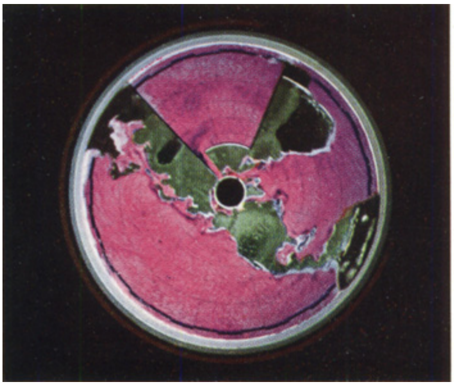
MUNK, W. H., 1950: On the wind-driven ocean circulation. *Jour. of Meteorology*, **7**, 79—93.

STOMMEL, HENRY, 1948: The westward intensification of wind-driven ocean currents. *Trans. Amer. Geophys. Union*, **29**, 202—206.

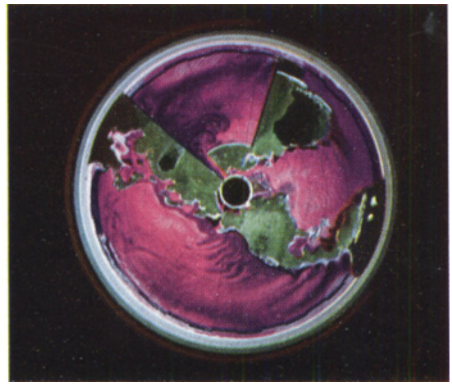
UDA, M., 1949: On the correlated fluctuation of the Kuroshio current and the cold water mass. *Oceanog. Mag.* (Tokyo) **1**, 1—12.

— 1951: On the fluctuations of the main stream axis and its boundary line of Kuroshio. *Jour. Oceanogr. Soc. Japan* **6**, 181—189.

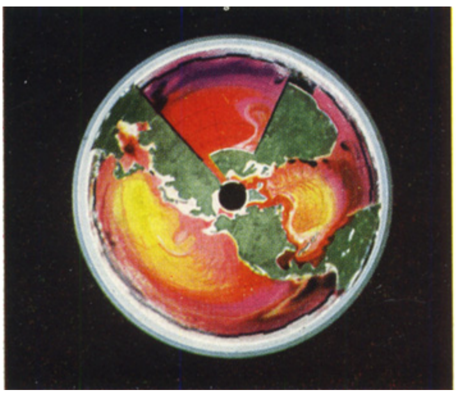
Fig. 4.



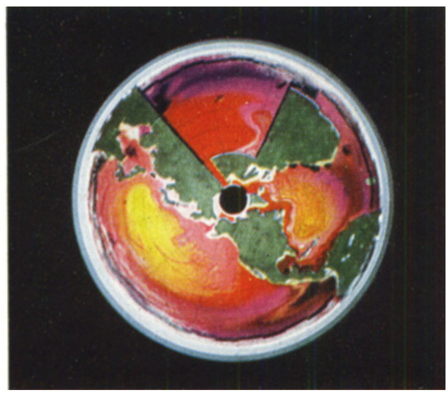
a) Color streamers from potassium permanganate crystals scattered on the bottom of the basin rotating at 3.18 radians/sec. Average depth of water 4 cm. Revolutions from start 24.



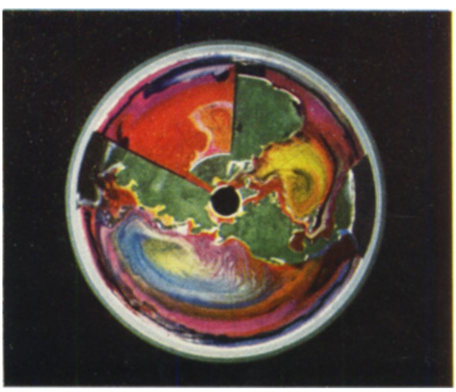
b) Same as (a) 150 revolutions from start. Color rises to the surface and occupies full depth of water in the regions of the coastal water masses.



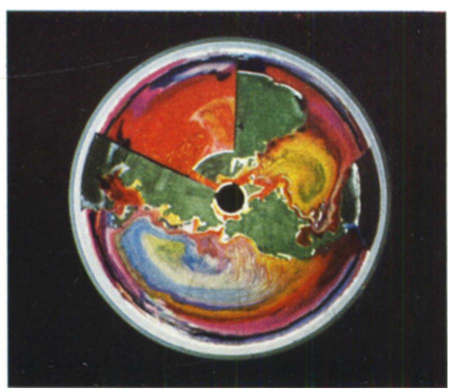
c) Occurence of patches of water on the right of the Gulf Stream system between Cape Hatteras and Grand Banks which may be similar to the patches of unusually warm water associated with the Gulf Stream.



d) An example of the type of multiple current in the Gulf Stream system in the vicinity of Grand Banks revealed in the basin. This differs from the description of the natural occurrence given by Fuglister (1951) and may not be the same phenomen.



e) Structure of the Gulf Stream and Kuroshio current systems 400 revolutions after the introduction of potassium permanganate crystals on the bottom and blue ink on the surface. The pulsating character of the flow of the Gulf Stream can be recognized, and the cyclonic bend of the Kuroshio described by Uda (1949), (1951) is suggested.



f) Further developments of the experiment shown in (e) at 450 revolutions. The small amount of lateral mixing along the course of the intensified western circulation is shown as well as the relative areas of the Sargasso Sea and its equivalent in the Pacific.

The quadrilateral compartment in the middle of Asia can be used as a control. The boundaries of this compartment are straight sided and uniformly smooth. In all of the photographs the Arctic ocean is permitted to drain through this compartment and reenter the North Atlantic circulation by way of the Gulf of Guinea.