Laboratory Simulation of the Gyre in the Alboran Sea

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A laboratory experiment is described which appears to exhibit flows which are similar to the flow-counterflow in the Strait of Gibraltar and, for certain values of the parameters involved, to the gyre and front in the western Alboran Sea. The experiment is transient in nature and is made with two connecting basins on a rotating turntable. A sliding door is fitted into the channel connecting the two basins. Each basin is filled with water, the door is closed, and salt is added to one side so that the two waters have different densities. After the waters have spun up to rest in the rotating frame, the door is opened. A flow, driven by the density imbalance, is observed shortly thereafter, the lighter fluid rising up over the heavier fluid and pushing into the basin containing the heavy fluid. Likewise the heavy fluid pushes into the basin containing lighter fluid. For very rapid rotation these flows are violently unstable. For less rapid counterclockwise rotation both currents stay confined to a narrow jet which clings to the right-hand wall of the basins which they are entering. At some lower rate of rotation the jet cannot hold to a sufficiently curved wall, and the jet separates from the wall—a gyre is observed between the jet and the wall. The gyre and the jet initially are both a Rossby radius in size, but gradually the gyre grows larger. Growth of the gyre seems to result from an accumulation of fluid from the jet as it returns to the wall. Scaling arguments and estimates of buoyancy, Coriolis, and wind forces are advanced in support of the concept that this laboratory-produced gyre and the gyre in the Alboran Sea share the same dynamics.

INTRODUCTION

It is well known that the water in the Mediterranean Sea is saltier than the water in the Atlantic Ocean and that the resulting density imbalance at the Strait of Gibraltar creates a distinct density-driven flow. Mediterranean water flows out of the Mediterranean near the bottom of the connecting passage, while Atlantic water flows near the surface into the westernmost basin of the Mediterranean Sea—the Alboran Sea. The water of Atlantic origin is easily identified as having a salinity lower than 37.5%. A curious feature of the water in the Alboran Sea (at least the western portion) is that the Atlantic water covers much of the Alboran Sea. If the gyre were not there and the jet of Atlantic water were to veer southward along the coast of Africa, for instance, the salinity structure of the western Alboran Sea would be very different from the present structure to a depth of 200 m. Since there is presently little overlap between our understanding of ocean dynamics and our present knowledge of water mass characteristics, it is hoped that our small study can slightly bridge this gap, at least for this very specific problem.

One might not predict the existence of such a gyre from dynamical principles because mechanics of rotating fluids would lead one to believe that the Atlantic water would veer to the right as it entered the Alboran Sea and would hug the coast of Africa as a jet with a width of approximately a Rossby radius, which is about 20-40 km. The jet would be able to curve around the African shoreline with approximately the same length scale. Indeed, a jet of Atlantic water does exist, with a size of approximately 35 km, according to Cheney [1978a, b]. However, it appears that the gyre is more or less a permanent feature of the western Alboran Sea.

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these numbers are close to the ones appropriate for the Alboran Sea, the laboratory jet is approximately the same size (suitably scaled) as the real cold jet in the Alboran Sea and the laboratory gyre is the same scaled size as the gyre in the Alboran Sea. Finally, some comparison is made between the present ideas and various features of the currents in the Alboran Sea.

THE EXPERIMENT

The 2-m diameter turntable at Woods Hole Oceanographic Institution was fitted with a watertight dividing wall along its central chord so that the basin was separated into two equal semicircular basins. The bottom of the tank was flat and level to 1 mm. At the center of this dividing wall a vertically sliding watertight door was fitted so that when the door was opened, water could pass from one basin to the other. When the door was closed, the two basins were essentially isolated. Artificial walls were also placed in both basins. Three artificial wall geometries were used, as sketched in Figure 3. The first had walls which were quarter-circle arcs of radius \( r \) connected to the edge of the sliding gate at one end and connected to a straight artificial wall at the other, as shown in Figure 3a. The second had a straight channel 30 cm long which then joined quarter-circle arcs which joined a straight wall, as shown in Figure 3b. In both of the above geometries the opening was 10.2 cm wide. The third had styrofoam walls which were carved to give a rough approximation of the Alboran Sea–Strait of Gibraltar, reduced so that 1 cm in the laboratory equaled about 6 km in the Alboran Sea, as sketched in Figure 3c. The opening was 3 cm wide, which is slightly wider than the (scaled) width of the narrowest opening of the Strait of Gibraltar.

All experiments with the geometries shown in Figures 3a

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Fig. 1. North-south section of salinity at 4\(^\circ\)00'W (data taken from Lanoix [1974], Figure 11).

Fig. 2. Dynamic height in centimeters in relation to 200 dB for the Alboran Sea (data taken from Lanoix [1974], Figure 25).

Fig. 3. Sketch of the three basin geometries which were used in the experiment.
Fig. 4. Surface currents, as marked by streak photographs of floating pellets, which demonstrate the four principal ways
the flow was observed to evolve. Width of the channel is 10.2 cm. Salty water, representing the Mediterranean water and
dyed black, lies at the top of the picture. The first column shows very rapid rotation where there is violent instability. $R = 2.9$ cm. The second column shows rapid rotation where the flow went unstable and generated small gyres which were
propelled downstream. $R = 5.8$ cm. The third column shows intermediate rotation, where no gyre was observed. $R = 7.3$
cm, and the radius of the wall is 7.6 cm. The fourth column shows slow rotation, where one distinct gyre was observed to
build up. $R = 14.5$ cm, and the radius of wall is 15.2 cm.

Fig. 5. Summary of results for runs with geometries 3a and 3b. G indicates that a gyre was observed, J indicates that a jet was observed, i indicates that weak instability was observed, so the jet retained its integrity, and I indicates that strong instability was observed.

Table showing results for geometries 3a and 3b (hereafter referred to as geometries 3a and 3b) were
conducted as follows: the sliding door was opened, and the
entire tank was filled with water at rest to a depth of 5 cm. The
artificial walls were not sealed watertight on the bottom and
sides, so the area behind the artificial walls was also filled. The
watertight sliding door was closed, and 150 g of salt (sodium
chloride) and 50 cc of saturated potassium permanganate solu-
tion were added to one side. This was thoroughly mixed into
the water. Special care was taken to insure that water behind
the artificial walls was completely mixed with the water in the
main basin. Hydrometer and refractometer readings were
taken routinely to check the resulting properties of the water.
In experiments with geometry 3c the water was also 5 cm deep,
and 47 g of salt and 50 cc of saturated potassium permanganate were added in the 26-l Mediterranean basin. The
resulting solution is 0.195% solute by weight and has a density
difference of 0.0014 ± 0.0001 from the fresh water in the
adjoining basin.

Next, the turntable was brought to the desired rate of rota-
tion and was left for at least 25 min. This is many times longer
than the spin-up time of 167 s, which corresponds to the
slowest-used rotation rate. In order to aid the spin-up process,
the water was stirred for a few moments before the turntable was started. In this way the interior fluid possesses some initial vorticity so that the rotating spin-up mechanism, as discussed, for instance, by Greenspan [1968], will immediately operate, and the usual problems of spin-up from rest, where the fluid initially has no vorticity, will not be encountered. Before removing the barrier a small amount of dye was injected into each side in order to double check whether there was any remnant motion. None was found for any experiment. Next, small paper pellets were scattered over the surfaces of both basins. The experiment began when the door was drawn up and completely removed from the tank. Immediately thereafter a 6-s time exposure photograph was taken by a camera that was rotating synchronously with the table by means of a servo system. Subsequent photographs were taken at fixed intervals. Experiments for geometries 3a and 3b were conducted for each of the following parameters: rotation periods of 14, 28, 35, 70, and 140 s; artificial barrier radii $r$ of 7.6, 15.2, and 30.4 cm. Experiments for geometry 3c were conducted at rotation periods of 10, 14, 17, 20, 28, 35, 56, 110, and 220 s and also at zero rotation.

**Results**

**Scaling**

First, the experimental observations on geometries 3a and 3b will be reported. In order to more easily visualize the various dynamics involved, all results will be scaled as follows: the natural length scale associated with the density-driven current is the Rossby radius, $R = (g \Delta \rho h / \rho f^2)^{1/2}$, where $g$ is force of gravity, $\Delta \rho$ is the density difference between the salty and fresh water, $h$ is a suitably chosen depth of the water, and $f$ is 2 times the angular rotation rate of the fluid. This not only comes out of scaling arguments but arises from density-driven flow-counterflow through the Strait [Whitehead et al., 1974, equation 6.6]. In the experiments, $\Delta \rho$, $g$, and $f$ were fixed and $h$ was varied. The value of $h$ was not so easily picked, since depth actually varied with radius owing to centrifugal force. The values of $R$ shown here are presented using a value for $h$ of 5 cm. Fluid depth actually gets as small as 4.0 cm at the center and 6.0 cm near the outer wall for the fastest rotation rate, and one might prefer to use a value of $R$ based on the true depth at the center (or some other depth). If one uses a value of $h$ at the center, values of $R$ should be reduced by 11, 5, 3.5, and 2.5% for rotation periods of 10, 14, 17, and 20s, respectively. Longer periods have corrections less than 2.5%. These corrections are
all small enough for us to feel they are unwarranted in the present work, where \( R \) spans a range of 10. There are three lengths in the experimental geometry: width of the opening, radius of the artificial wall, and outer radius of the tank. Experimental parameters were selected so that the first two geometric lengths were sometimes greater and sometimes less than the Rossby radius. The outer radius of the tank was always greater than the Rossby radius (except for the one run at zero rotation).

**Results for Geometries 3a and 3b**

The observed flows were easily divided into three categories. If rotation was sufficiently rapid so that \( R \) was less than the width of the connecting channel, a sharp shear zone would form within the channel, which would go violently unstable and develop small turbulent eddies (of both rotational sign and of Rossby radius size), as shown in Figure 4, first column. There would be little transport from one basin to another, and the radius of the artificial wall would not affect these results. If rotation was less rapid so that the Rossby radius was greater than the width of the opening, light fresh water would flow into the salty basin as a narrow jet propagating along the right-hand wall, as shown in Figure 4, third column. The heavy dyed, salty water would behave like this too and would wedge along the right-hand bottom of the freshwater tank. The wedges would be very close to a Rossby radius in width. The dividing line between a jet flow and a turbulent breakdown was rather indistinct in these experiments. The second column in Figure 4 shows a weak instability in which one eddy formed but was transported downstream. If the Rossby radius was equal to or less than curvature of the wall, the jet would have no trouble staying next to the wall. However, in other cases, usually when the Rossby radius was greater than wall curvature, the jet would separate from the curving artificial wall, as shown in Figure 4, fourth column. In this case a steadily growing gyre was observed in the separation region, the gyre initially being a Rossby radius in size and larger thereafter. The growth of the gyre appeared to be produced by gradual accumulation of water, caused by splitting of the separated jet as it impinged on the wall. The right-hand branch (looking downstream) would flow back toward the opening, where it would be deflected to its right and curl around again and again to form a gyre which lies between the wall and the jet. The left-hand branch would continue to flow along the artificial wall and go left and flow along the outer wall around the whole tank until it finally returned to the opening, where it would flow alongside the jet of clear water coming in from the opening. At this point the experiment was terminated, although the subsequent evolution of the currents could have readily been observed.

Figure 5 shows a summary of the results of the runs. In points labeled G a steadily growing gyre was clearly observed to form as in Figure 4, fourth column. J denotes that a jet, as in the third column of Figure 4, was observed. I denotes an instability so violent that the original jet was hardly discerned, as in the first column of Figure 4. The letter i denotes an instability less violent, so the jet retained its integrity, as in the second column of Figure 4. There was at least one eddy that was swept downstream. The exact values of \( R \) and radius of the wall which denote the transition from G to J are beyond the scope of these exploratory experiments and may be functions of the width of the opening, Ekman number, detailed roughness of the walls, and perhaps even details of the way the gate is opened. In these experiments the results were clearly reproducible, and most were run more than once, but all one can say at present is that the transition from G to J occurs approximately when the wall radius is less than \( R \).

To determine whether the width of the jet was scaled to the Rossby radius, measurements were made of the width. The data are shown in Figure 6. To get these data, the width of the jet as determined by the streak photographs was measured with an optical micrometer in two or three places that were considered typical.

The measurements are not extremely precise owing to a number of factors and should only be believed to \( \pm 30\% \). as given by the sample error bars in Figure 6. The principal factor causing imprecision is the decision as to exactly which streak line constitutes the edge of the jet. Also, in cases where the jet separated from the wall it was difficult to determine which was jet and which was gyre. Furthermore, the experiment was transient, and the front or nose of the jet was consistently observed to be greater than the fully developed jet. In spite of these problems the data in Figure 6 exhibit a consistent tendency for the jet to become Rossby radius in width. The data for the largest Rossby radius could only be taken after a substantial gyre had formed, and it may not be correct to compare them too closely with the other data, which were taken before a substantial gyre had formed.

Measurements were taken of the length of five clear particle trajectories in all experiments with a clear jet. There was no systematic change of the velocity in the jet with rotation rate of the turntable, and the velocity averaged 1.9 cm/s with a standard deviation of 0.8 cm/s. Inertial-rotational theory such as that of Whitehead et al. [1974] predicts that velocity is of a magnitude \((gA\Delta \rho \phi)^{1/2}\), which for this problem has a magnitude of 2.6 and is consistent with the measurements. Since the jet is observed to scale as Rossby radius, the Rossby number of the jet based upon jet width is close to 1, a result consistent with Rossby adjustment ideas.

It is clear from the sequence of photographs in the fourth column of Figure 4 and other flows where a gyre was generated that the gyre was initiated by separation of the jet from the wall but that once the gyre was initiated it continued to grow. Figure 7 shows measured length (right to left) and breadth (top to bottom in photos) of the gyre as a function of time for three cases in which a gyre was clearly identifiable. Measurements were made from contact prints of the streak photographs with an optical micrometer. The gyres looked in all cases like the one in Figure 4, fourth column. The size of the gyre starts out greater than a Rossby radius in extent and increases as the square root of time, which implies that the volume of the gyre is growing at a constant rate.

Examination of the float streak lines in the photographs revealed that the jet split into a right- and left-hand branch as it impinged on the artificial wall. It is possible that the stagnation point dynamics have quite a lot to do with the evolution of the gyre. A clue to this effect comes from the sequence shown in Figure 8, in which the gyre got so big that it began to graze the outer radius of the tank. As soon as this happened, the jet developed a new stagnation point on the outer wall, which dramatically rebranched the flows.

These experiments therefore have produced a plausible description of the initiation and growth of a gyre next to a strait which connects water masses of differing density. They suggest that if Atlantic water were to veer southward as it passed Point Almina, the jet would separate from the coast of Africa and would subsequently impinge upon the coast of Morocco and branch into an eastward and westward flowing current. The
eastward flowing branch would continue into the Mediterra-
nean, but the westward flowing branch would begin to fill the
region between the jet and the coast of Africa with water of
Atlantic origin and initiate a gradually growing gyre.

Results for Geometry 3c

In the previous experiments the gyre continually grows until
it fills a substantial portion of the basin. Because of this, one
might expect that a large portion of the western Mediterranean
would be substantially covered by Atlantic water. This is not
the case, however; the gyre seems to remain confined to that
portion of the Alboran Sea west of Alboran Island. The fol-
lowing set of experiments indicates that the growth of the gyre
stops when the eastern portion of the Alboran Basin is filled. It
suggests one mechanism by which the continued growth of the
gyre can be curtailed. In these experiments the coastal geo-
mtry of the Atlantic and eastern Mediterranean was modeled by
styrofoam land areas. It was necessary to smooth the Cape
Tres Forcas which projects up from the south to avoid separa-
tion of the nose of the jet of Atlantic water in early stages of
the experiment. The resulting coastline more nearly resembles
the 100-m bathymetric contour. The growth and evolution of a
gyre in one experiment is shown in the sequence of photo-
graphs in Figure 9. It is evident in the photographs that the jet
begins to follow a sequence of gradual gyre growth similar to
that shown in Figure 4, fourth column. That is, the jet initially
veers southward but separates from the African coast east of
the strait. As it reimpinges on the African coast, the jet bifur-
cates so that water begins to accumulate in an anticyclonic
gyre that forces the jet northward. This continues until the jet
impinges east of a topographic feature that corresponds to
Cape Tres Forcas in Morocco, at which point the cape appears
to deflect the entire jet eastward so that the gyre-filling process
is terminated. One might envision that such a shoreline-in-
duced flow is even stabilizing, since if the gyre were to get
bigger and expand further to the east, the cape would scoop
out some of the fluid in the gyre and send it eastward, thus
reducing the size of the gyre.

As a caution, one should note that Alboran Island has a
long shallow shelf due north of Cape Tres Forcas. This shelf
does not come to the surface but only protrudes partially into
the bottom of the Atlantic gyre. The experiments here do not
incorporate that shelf and cannot provide any information
concerning the role of that shelf except to say that the gyre
apparently can form without its presence.

The parameters used in the run shown in Figure 9 were as
follows: density difference, 0.0014; rotation period, 28 s; water
depth, 5 cm. This yields a Rossby radius \((g\Delta \rho \kappa / \rho F)_{1/2}\) of 5.84
cm. Whitehead et al. [1974] found that this parametric group
specifies the width of a two-layer shear zone, and the data in
Figure 6 show that jet width follows this. At the scale of
1 cm = 6 km, 5.84 cm represents a 35-km shear zone. Since
Cheney [1978b, p. 4597] gives a typical width of the cold jet as
35 km, it is felt that this experiment has the parameters which
optimize the modeling of the Alboran Sea-Strait of Gibraltar
dynamics.

Figure 10 shows the flows in experiments with other rates of
rotation after having run for 10 min except for the run with a
scaled \(R\) of 12 km, which had small, tightly wound eddies
which are difficult to see in the picture. For \(R = 17\) km the gyre
Fig. 10. Streak photograph of flow in experiments with a modeled shoreline and with different rotation rates. Owing to camera jiggle in some pictures, the photographs were selected for quality (lack of jiggle) rather than selected at a consistent time, so times vary from 5 to 12 min after the start of the experimental run. Scaled Rossby radii are, from top to bottom on the left, 17, 22, 25, and 45 km; on the right they are 70, 138, and 276 km.
does not form; instead, the jet goes unstable to small turbulent eddies which are approximately a Rossby radius in size. For \( R = 21 \) and 25 km there was a gyre and, in addition, lots of smaller eddies in the Mediterranean. The photograph for \( R = 35 \) km was already shown in Figure 9 and has a gyre in the Alboran Sea and another further to the east. For \( R = 45 \) km there was a gyre in the Alboran Sea and another very weak one further to the east. For \( R = 70 \) km there was one gyre in the Alboran Sea with no gyres to the east. For \( R = 138 \) and 276 km there was a gyre which extended substantially further into the Mediterranean. One experiment was done at zero rotation. It differed little from the flow with a scaled shear zone of 276 km. The presence of one gyre in this case suggests that the obliquity of the axis of the strait plays some role in the weak rotation gyre.

Figure 11 shows the sizes, as defined below, of the gyres as a function of time for all the experimental runs, with the exception of the two runs in which Rossby radius was smaller than the width of the strait. These were omitted because small turbulence with gyres going in both directions was observed, almost exactly as shown in first column in Figure 4, and no gyre existed which was steady on a time scale long in comparison to the circulation time of the water going into the basin. Measurements were taken with an optical micrometer and were made of the distance between the place corresponding to Point Almina and the outer edge of the gyre. Figure 11 shows that initially the gyres grew quite rapidly, but when the gyres attained approximately 25 km and rotation period was less than 111 s, they essentially stopped growing; at least the rate was far less than a \( t^{1/2} \) power law. A line with slope \( \frac{1}{2} \) is shown for comparison. Only experiments with periods of 111 s or longer exhibited gyres which continued to grow. The most striking result is that the Alboran gyre grew until it attained approximately the same size for the rather wide range of rotation rates corresponding to Rossby radii of 21–70 km, while those with larger Rossby radii continued to grow. The reason for the gyre not exceeding this size is undoubtedly connected with the geometry of the basin in some way, but it is not entirely clear which feature of the geometry is most important. If our conjecture is correct that the position of the stagnation point with respect to coastline features is central to the growth mechanism of the gyre, then possibly the geometry of the African coast strongly influences the final size of the gyre; it is interesting that the gyre always grew until the southward flowing jet on the eastern side of the gyre impinged on a feature which corresponds to Cape Tres Forcas in Morocco.

**DISCUSSION**

Observational data which hint that there is indeed a stagnation point and a bifurcation of the flow in the region near Cape Tres Forcas do exist. A persistent westward current exists along the coast of Africa east of Cape Tres Forcas, according to the study of nearshore currents as deduced from photographic analyses by Stanley et al. [1975].

The trajectory of drifting buoy Marisond B03 of the Laboratoire d'Océanographie Physique, Paris, supplied by P. Tchernia (personal communication, 1978), is shown in Figure 12. This is also shown, in modified form, by Petit et al. [1978]. It shows a well-developed gyre in which the buoy made one complete cycle and then hovered near the proposed point of impingement north of Cape Tres Forcas for approximately 4 days.

Another observation that is consistent with a stagnation point lying north of the cape is the satellite infrared imagery in Figure 13, taken June 11, 1978. It shows an anomalous temperature distribution from the usual well-defined gyre observed from satellites. Here the jet of Atlantic water skews eastward and then bends to impinge and deflect left and right.

![Fig. 12. Trajectory of the drifting buoy Marisond B03, which indicates both the rapid speed of the gyre and the possibility of a stagnation point north of Cape Tres Forcas. Data courtesy of P. Tchernia.](image-url)
To see this, let us compare the total Coriolis force exerted upon a jet 35 km wide, 200 m deep, 100 km long, and flowing at 0.3 m/s, which is perhaps a slight overestimate based upon the data of Lanoix [1974]. This corresponds to new Atlantic water entering the Mediterranean and does not include water recycling in the gyre. For purposes of simplicity we take the Coriolis parameter to be $10^{-4}$ s$^{-1}$, and total force is easily calculated to be $2.1 \times 10^8$ N. What wind velocity would be needed to exert this amount of force? Using a drag coefficient of $2 \times 10^{-4}$, which appears to be a typical value for moderate wind conditions [Bunker, 1976, p. 1124], a surface area of the eastern Alboran Sea waters of $10^8$ m$^2$, and approximating density of air as 1 kg/m$^3$, we find that a wind speed of 45 m/s is necessary, which is absurd. The observed value of 8 m/s for wind speed is not only in the wrong direction but is more than 1 order of magnitude too weak to hold the jet along the coast of Spain against Coriolis force.

Nof [1978] has recently suggested a mechanism for the deflection of the Atlantic water to the left as it leaves the Strait of Gibraltar. This mechanism hinges upon a theoretical prediction of adjustment of a steady free jet in a rotating coordinate system. It is predicted that deflection to the left will occur if the entering current possesses a suitable shear across the stream. We cannot at this time determine how strongly the Nof theory bears upon our experiments, since they were transient and our control over the detailed velocity profile was nonexistent. We can say, however, that the internal Froude number in our experiments (and probably in the Strait of Gibraltar) attains a value of 1, whereas the analysis of Nof concerns small Froude numbers. Both studies emphasize the need for a clearer understanding of ageostrophic jets.

**CONCLUDING REMARKS**

The experiments clearly indicate that the initiation of a gyre results from separation of the southern edge of the jet of Atlantic water as it leaves the Strait of Gibraltar. The subsequent growth of the gyre to a size many times greater than a Rossby radius of approximately 35 km appears to be linked with a dynamical filling process which is not clearly understood, but it may be linked with the relative position of the stagnation point of the jet with respect to coastal features where it impinges on the coast of Africa. The obliquity of the strait axis with respect to the axis of the Alboran Sea may play a role in this process.

The notion that the properties of the stagnation point region of a jet control the filling behavior of that jet appears to be new in rotating fluid mechanics. We have been unable to locate the existence of any studies of the properties of stagnation point flows in baroclinic, rotationally influenced jets. The dynamics of flows in the vicinity of stagnation points is not new in nonrotating fluid mechanics, and interaction of stagnation points with the basin geometry lies at the heart of the design of fluidic amplifiers. The notion that these processes control the filling properties of large jets which are streaming into large seas or lakes and determine whether one or another water type

![Fig. 13. Infrared photograph showing the splitting of the jet at approximately 3°W. Photo courtesy of J. Gallagher.](Image)

![Fig. 14. Average annual surface wind distribution of waters about southwestern Europe, from Miller [1977].](Image)
will be found on the surface of that body may be worthy of more field observations and theoretical, laboratory, and numerical modeling. Such a study is beyond the scope of this laboratory study. Possibly some day, if these ideas are borne out by such investigations, surface water types in lakes and even seas can be controlled in a beneficial way by giant stagnation point deflectors.

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