Laboratory Simulation of the Gyre in the Alboran Sea

JOHN A. WHITEHEAD, JR., AND A. R. MILLER

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

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 salinity lower than 37.5‰. A curious feature of the water in the Alboran Sea is that the Atlantic water covers much of the Alboran Sea (at least the western portion) to a depth of approximately 200 m. Figure 1, from *Lanoix* [1974], shows salinity in a north-south section at 4°00'W. The water of Atlantic origin lies in an anticyclonic gyre which has a clearly identifiable salinity and temperature front on its northern side. Figure 2, also from Lanoix, is perhaps the best known illustration of the gyre itself. It is over 100 km wide and roughly circular.

The gyre tends to move about, and there has been some debate about whether it occasionally vanishes or reverses. It is known, for instance, that the currents in the Strait [*Lacombe*, 1961; *Lacombe et al.*, 1964] and the Alboran gyre and frontal system are somewhat time dependent [*Donguy*, 1962; *Grousson and Faroux*, 1963; *Cano Lucaya and DeCastillego*, 1972; *Lanoix*, 1974; *Ovchinnikov et al.*, 1976; *Cheney*, 1978*a*, *b*]. However, it appears that the gyre is more or less a permanent feature of the western Alboran Sea.

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* [1978*b*], but it lies off the coast of Spain and borders the Alboran gyre on the northern and eastern sides, curving gradually to the right with a radius of the Alboran gyre, which is 2.5 times larger than the most liberally estimated Rossby radius.

The purpose of this paper is to describe some laboratory experiments which offer an explanation for the formation of the gyre, the reason why it is larger than a Rossby radius, and some observations of interaction of this gyre with the sharp, cold jet which borders it off the Spanish coast between the strait and Malaga.

There were many reasons for conducting this study. For one thing, the presence or absence of the gyre is strongly influential upon the water mass characteristics of the water in 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.

Another reason for studying this problem lies in the important influence which the gyre has upon nutrient upwelling, lateral advection, and frontal structure within the Alboran Sea. Not only are these features important for a variety of biological and environmental problems, but they might also strongly influence the dynamics of deeper currents, which may have some fundamental influence upon the deepwater characteristics of the western Mediterranean, as suggested, for instance, by *Stommel et al.* [1973].

The front is intense enough to be at the far limit of the quasi-geostrophic approximation, where nonlinear terms are important. Hence numerical or analytical approaches are particularly challenging. A quasi-steady experiment was found to be perfectly tractable and appeared to be a useful starting point for studies which may be planned in the future. The experiment is described in the next section. Further experiments with geometrically realistic basin shapes suggest that the interaction of the jet with the African coastline may produce a simple mechanism for stopping the growth of the gyre and ultimately may determine the final size of the gyre. It will be shown that two dimensionless numbers govern the flow and that when

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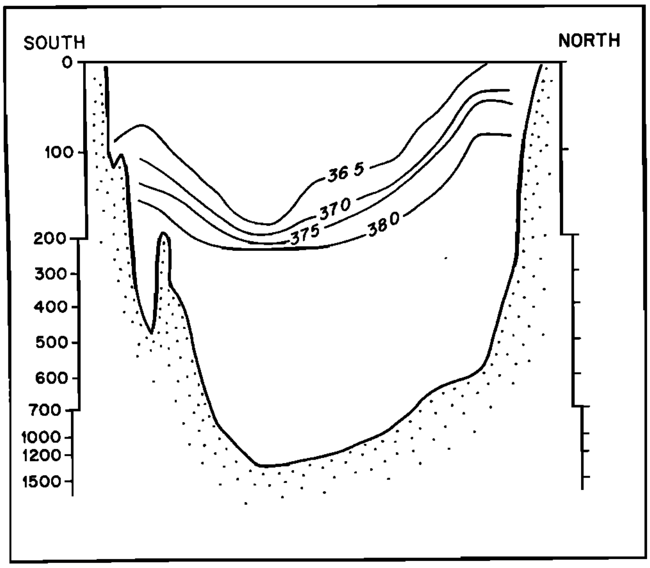

Fig. 1. North-south section of salinity at 4°00'W (data taken from *Lanoix* [1974], Figure 11).

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 3*a*. The second had a straight channel 30 cm long which then joined quarter-circle arcs which joined a straight wall, as shown in Figure 3*b*. 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-Straits-Bay of Cadiz shoreline, reduced so that 1 cm in the laboratory equaled about 6 km in the Alboran Sea, as sketched in Figure 3*c*. The opening was 3 cm wide, which is slightly wider than the (scaled) width of the narrowest opening of the Strait of Gibraltar.

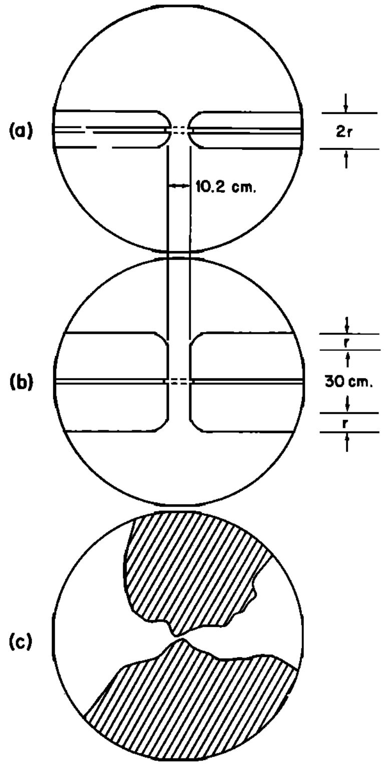

Fig. 3. Sketch of the three basin geometries which were used in the experiment.

All experiments with the geometries shown in Figures 3*a*

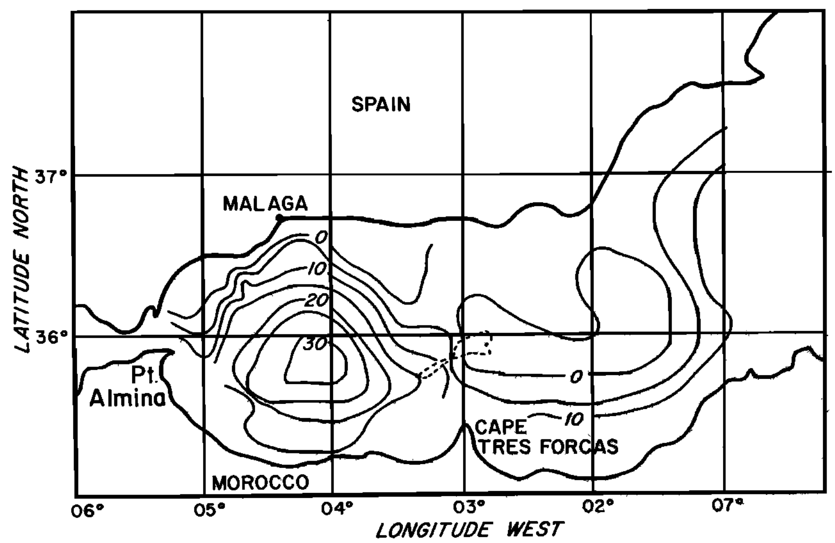

Fig. 2. Dynamic height in centimeters in relation to 200 dB for the Alboran Sea (data taken from *Lanoix* [1974], Figure 25).

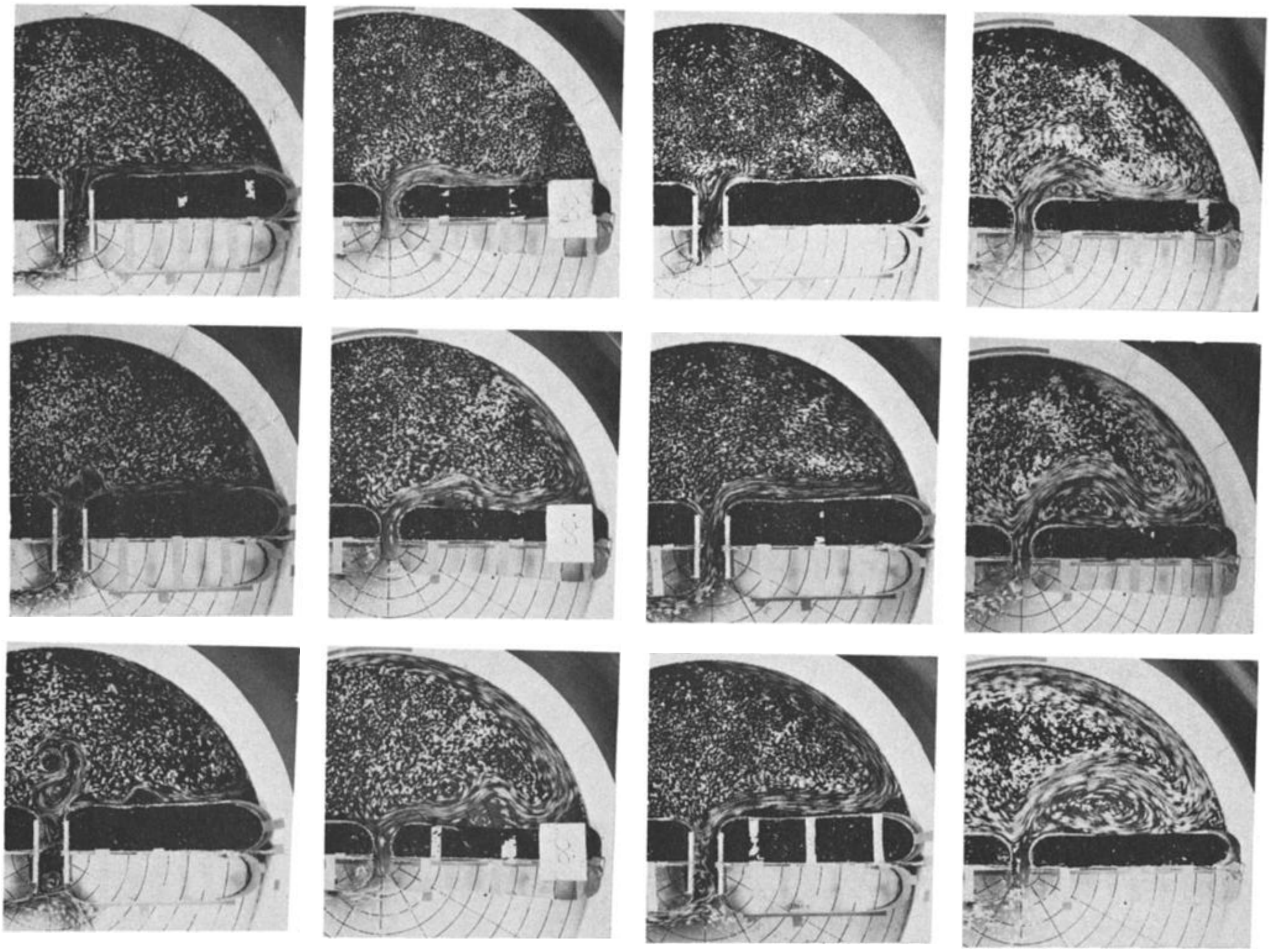

Fig. 4. Surface currents, as marked by streak photographs of floating pellets, which demonstrate the four principal ways the flow was observed to evolve. Width of the channel is 10.2 cm. Salty water, representing the Mediterranean water and dyed black, lies at the top of the picture. The first column 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.

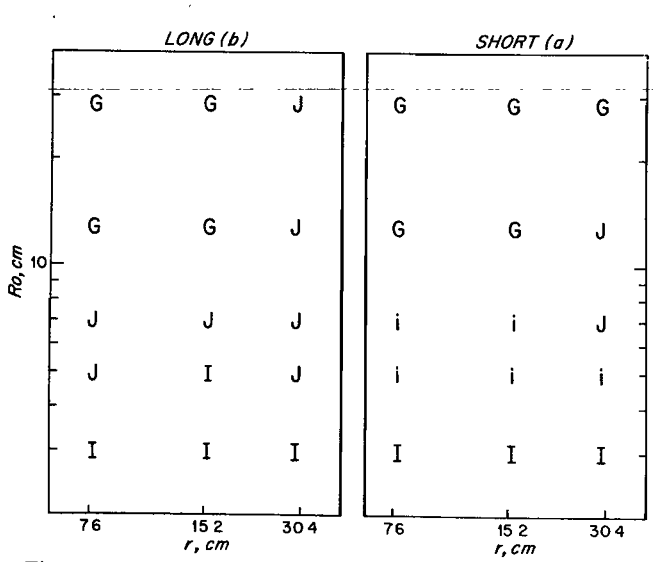

Fig. 5. Summary of results for runs with geometries 3a and 3b. G indicates that a gyre was observed, J indicates that a jet was observed, i indicates that weak instability was observed, so the jet retained its integrity, and I indicates that strong instability was observed.

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 solution 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 permanangante were added in the 26-l Mediterranean basin. The resulting solution is 0.195% sõlute 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 rotation 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,

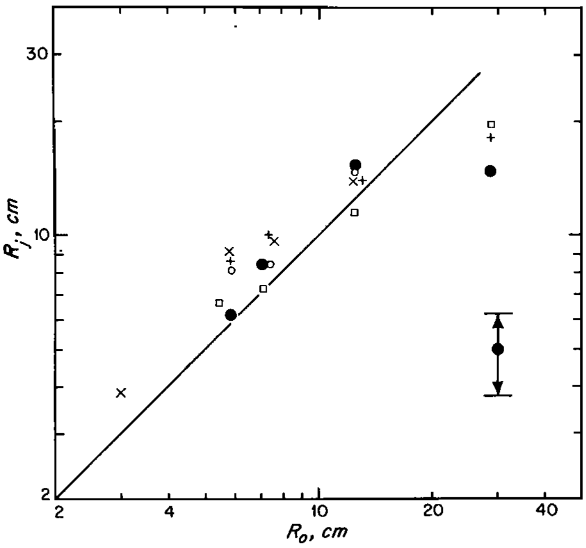

Fig. 6. Size of the jet R_j in centimeters as a function of Rossby radius $R_0 = (g\Delta\rho h/\rho f^2)^{1/2}$. Error is ±30% owing to causes mentioned in the text.

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 3*a* and 3*b* 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 3*c* were conducted at rotation periods of 10, 14, 17, 20, 28, 35, 56, 110, and 220 s and also at zero rotation.

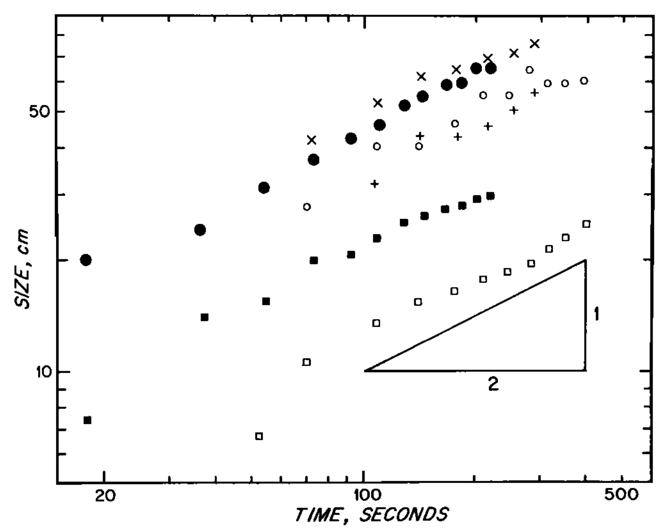

Fig. 7. Length (parallel to the artificial wall) and breadth of gyres as a function of time for three experiments. For a period of 143 s (R = 29 cm), crosses denote length and plusses denote breadth; for a period of 70 s (R = 14.4 cm), open circles denote length, and open squares denote breadth; for a period of 73 s (R = 14.5 cm), solid circles denote length and solid squares denote breadth.

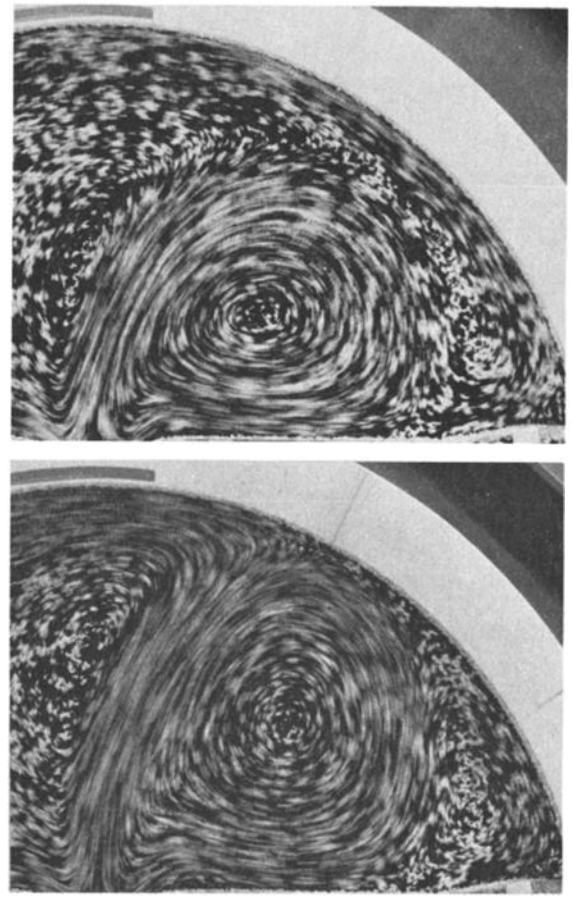

Fig. 8. Streak photographs showing the development of a new stagnation point and subsequent rebranching of the jet. Rotation period is 140 s; times after initiation are 215 and 322 s.

RESULTS

Scaling

First, the experimental observations on geometries 3*a* and 3*b* 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 ρ were fixed and f 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 ± 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 magnitude $(g\Delta\rho h\rho)^{1/2}$, 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

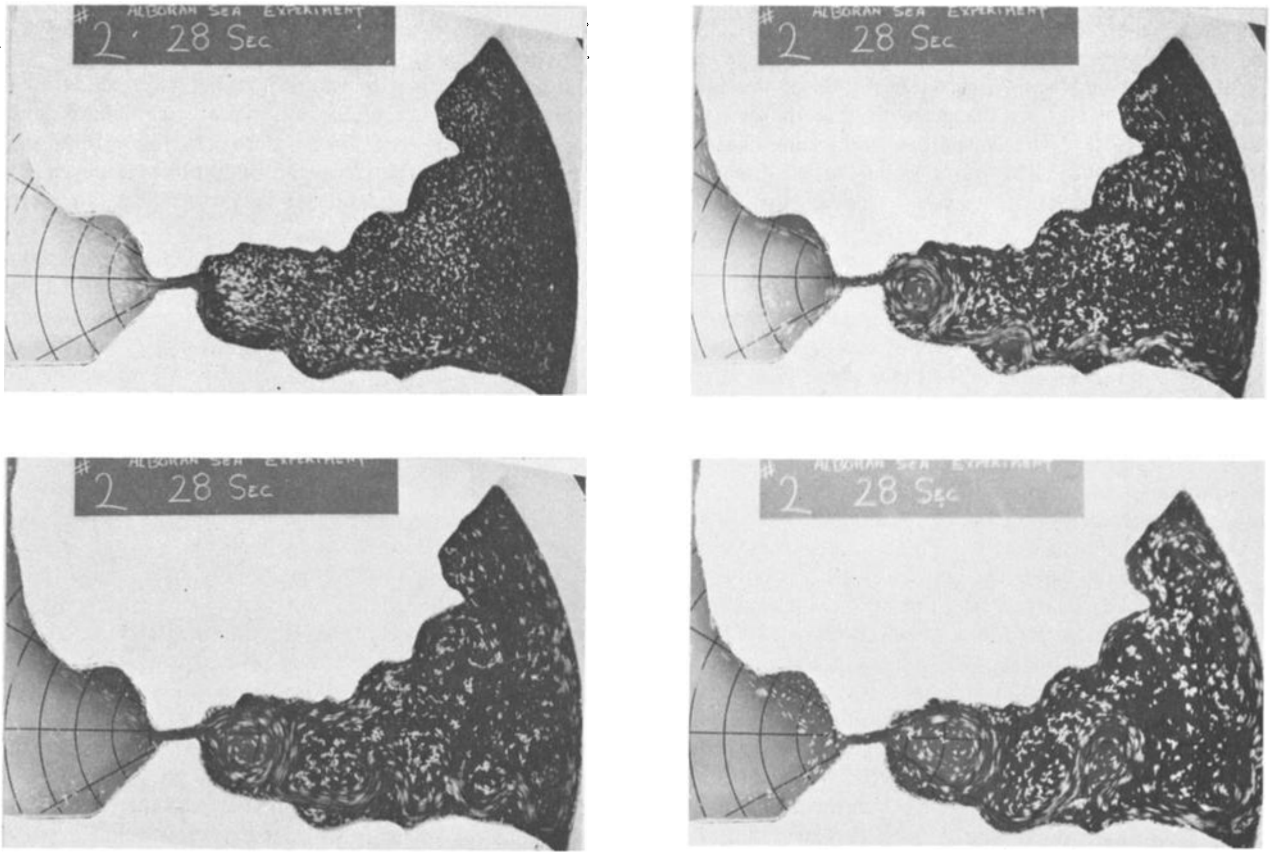

Fig. 9. Sequence of streak photographs of the formation of a gyre in an experiment with a shoreline modeled after the Bay of Cadiz–Strait of Gibraltar–Alboran Sea region. Scaled Rossby radius is 35 km. Times after start are, from left to right and top to bottom, 28, 196, 532, and 952 s.

eastward flowing branch would continue into the Mediterranean, 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 following 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 geometry 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 separation 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 photographs 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 bifurcates 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-induced 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 $(g\Delta\rho h/\rho f^2)^{1/2}$ 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* [1978*b*, 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

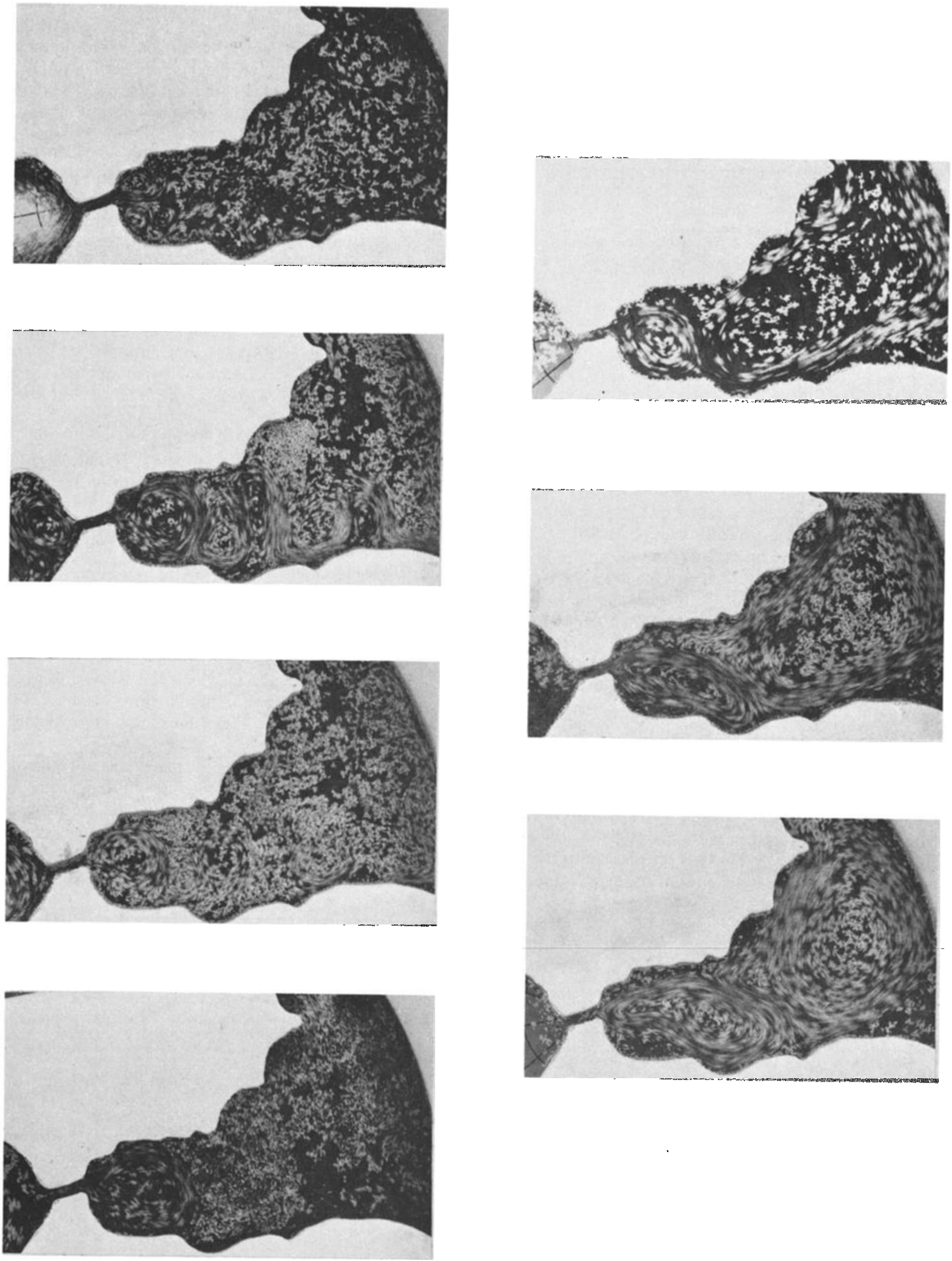

Fig. 10. Streak photograph of flow in experiments with a modeled shoreline and with different rotation rates. Owing to camera jiggle in some pictures, the photographs were selected for quality (lack of jiggle) rather than selected at a consistent time, so times vary from 5 to 12 min after the start of 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.

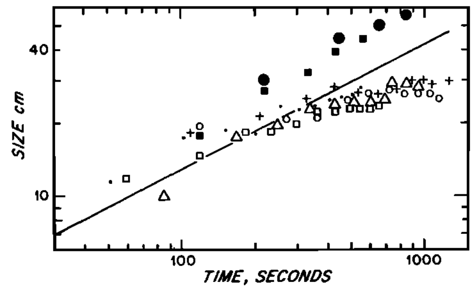

Fig. 11. Size of the gyres as a function of time for runs in the experimental geometry which duplicates the coastline. One cm in the laboratory scales to 6 km in the ocean. Scaled R in kilometers is: dots, 21; open squares, 25; triangles, 35; plusses, 45; open circles, 70; solid squares, 138; solid circles, 276.

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

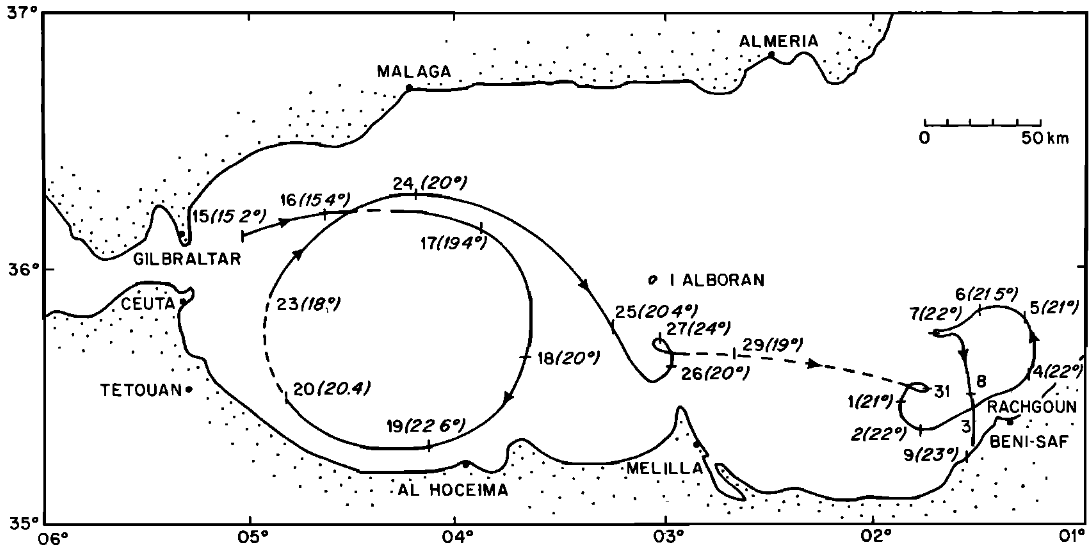

Fig. 12. Trajectory of the drifting buoy Marisonde B03, which indicates both the rapid speed of the gyre and the possibility of a stagnation point north of Cape Tres Forcas. Data courtesy of P. Tchernia.

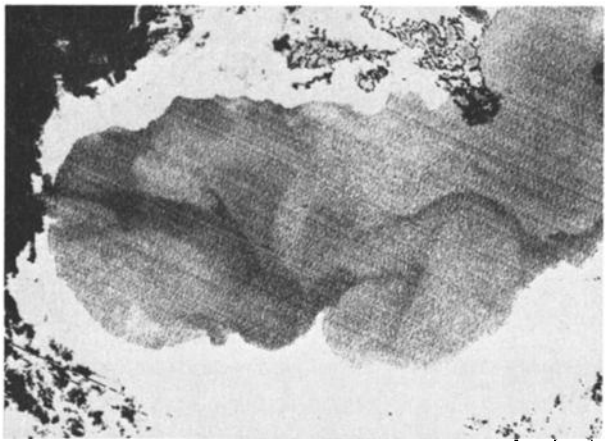

Fig. 13. Infrared photograph showing the splitting of the jet at approximately 3°W. Photo courtesy of J. Gallagher.

as it hits the African coast. A detailed though interpretive construction of surface circulation from *Huang and Stanley* [1971] also shows a well-developed gyre which splits at 3° west and indicates small transient eddies to the east of Ceuta.

Modification of the horizontal velocity profile of the jet as it rubs against the coast of Spain is another possible mechanism which could influence the ultimate size of the gyre. The effects of side friction upon a baroclinic jet, as in these experiments, is poorly understood. It has been known that the Spanish coast experiences strongly variable currents [*Stanley et al.*, 1975] and that the front lies tens of kilometers south of the coast [*Cheney*, 1978*b*], hinting that turbulence and/or local interaction with bottom topography may be important. The counterparts of local eddies near Spain, however, were not observed in this laboratory model.

The above experiments assume that the gyre is essentially produced by a buoyancy-driven process, while others have suggested its origin is in the wind field.

The thesis that wind conditions promote the formation of the Alboran gyre by forcing the jet northward to the coast of Spain is at odds with prevailing wind conditions as measured over the past 30 years. Mean winds by *Miller* [1977], as shown in Figure 14, illustrate that prevailing winds come from the northwest, consistent with the overall pattern of surface winds about the Iberian coast. This pattern changes little when broken down into monthly means. Mean wind force varies from 5 to 8 m/s, averaging about 6 m/s. Moreover, there is no indication of wind curl with inverse magnitudes of a few days, which would be necessary to drive a gyre directly by curl if it were to spin the buoys, as in Figure 12.

If anything, the mean winds probably promote a strong shear in the northern sector, along with some upwelling along the Spanish coast. In this area, actual wind conditions vary considerably both with location and season. The downpouring air flowing from the land to the south is probably influencing the Bay of Cadiz as well, since the mean pattern shows a divergence to the southwest west of Gibraltar and to the southeast east of Gibraltar.

It would appear that the winds have insufficient force to hold the jet away from the African coast east of Point Almina. 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 flowing into 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 2.1×10^{10} N. What wind velocity would be needed to exert this amount of force? Using a drag coefficient of 2×10^{-3}, 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^{10} 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

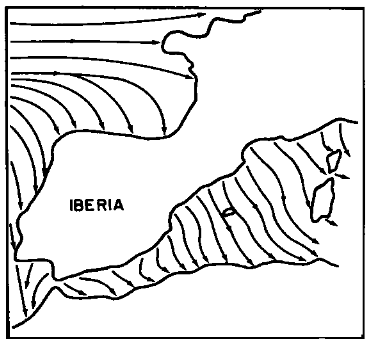

Fig. 14. Average annual surface wind distribution of waters about southwestern Europe, from *Miller* [1977].

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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