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A CONDITION FOR GYRE FORMATION BY THE SURFACE OUTFLOW FROM A STRAIT

Myriam BORMANS

Research School of Earth Sciences
Australian National University
G.P.O. Box 4, Canberra A.C.T. 2601
AUSTRALIA

ABSTRACT

A survey of relevant numerical, laboratory and observational studies, combined with my own laboratory experiments, suggest that the surface outflow from a strait generally forms a gyre in the adjacent sea if the right-hand exit corner is sharp (for the northern hemisphere in which the current will have a tendency to turn to the right). The gyre grows from an initial "separation bubble" of radius u/f, where u is the current speed and f the Coriolis frequency. The criterion for the maintenance of a coastal jet along a curved coast, instead of separation and gyre formation, seems to be that the Rossby number $u/(fR_w)<1$, with R_w the radius of curvature of the right-hand exit corner, so that the Coriolis force can hold the current to the coast. It is suggested that the relevant curvature is that where the interface between the two layers intersects the sea floor rather than where the sea surface meets the coast.

INTRODUCTION

The outflow from a sea-strait has been studied quite intensively. Observations in the Strait of Gibraltar (the Atlantic inflow) and in the Tsugaru Strait (the Japan Sea outflow) suggest that the surface outflow after exiting the strait tends to form an anticyclonic gyre to the right of the strait's exit.

A gyre has been successfully created in a number of laboratory and numerical experiments, which will be summarized later, but the precise criteria for its formation have remained rather obscure.

Interest in the problem has been heightened by reports that the gyral circulation is very variable and can occasionally disappear, possibly being replaced by a southward flow that follows the coast. It seems that the apparent bimodality of conditions in the neighbouring sea is related to the variability in the flow through the strait. I attempt to investigate this proposed connection and focus on the conditions for gyre formation but not concern myself with the factors that determine the size of the gyre. I will discuss the dimensionless parameters which are likely to be of significance and summarize previous studies. Then, I will report on my own laboratory experiments on the conditions for the outflow from a strait to form a gyre or a coastal jet and will finally discuss the results. Some of them have already been reported by Bormans and Garrett (1989).

RELEVANT DIMENSIONLESS PARAMETERS

I will consider a reduced-gravity surface current exiting from a strait of width W, flowing over a stagnant lower layer. The depth of the interface at the southern side of the strait is h. The right-hand exit (for the northern hemisphere in which the current will have a tendency to turn to the right) has a radius of curvature R_w and the sidewalls are vertical unless otherwise mentioned. The current has an average speed u, with variations across the strait which I ignore except insofar as they are related to a relative vorticity , which I also treat as a constant though it may vary across the flow. From these variables, the reduced gravity $g'=g\Delta\rho(\rho+\Delta\rho)^{-1}$ and the Coriolis frequency f, I may characterize the problem by the following four dimensionless parameters:

R_w/W, the ratio between the curvature of the wall at the exit and the width of the strait,

R_c/W, where $R_c = (g'h)^{1/2}/f$ is the internal Rossby radius of deformation,

$F = u(g'h)^{-1/2}$, the Froude number of the inflow, and

ζ/f, the non-dimensionalised relative vorticity. These parameters can be combined in different ways, but let's define a Rossby number, based on the wall curvature, by

$$Ro = u(fR_w)^{-1} = (R_c/R_w)F = (R_c/W)(W/R_w)F.$$

This Rossby number may, in turn, be regarded as the ratio of the inertial radius u/f to the wall curvature. Alternatively a Rossby number based on the strait width may be defined by

$$Ro_W = u(fW)^{-1} = (R_c/W)F.$$

PREVIOUS WORK

The problem of a steady inviscid reduced-gravity rotating flow around a sharp corner has been examined analytically by Nof (1978) and Cherniawsky and Leblond (1986) and numerically by Preller (1986), Loth and Crépon (1984) and Werner et al. (1988). Chao and Boicourt (1986) and Wang (1987) have adapted a 3D-primitive equation model with simplified geometry to consider both the momentum and buoyancy effects on a flow exiting from a strait.

Whitehead and Miller (1979) conducted a transient laboratory experiment on a rotating turntable of two-layer density flows in a narrow channel with different geometries connecting two large basins. Whitehead (1985a) also performed some similar experiments with a sharp exit corner. Their main conclusion was that gyre formation requires the Rossby radius to be greater than the exit wall curvature. But as the exit Froude number was one in their lock-exchange experiments, the criterion $R_c>R_w$ is equivalent to $u/f>R_w$ and it is not clear which criterion applies at other Froude numbers for which $u/f\neq R_c$.

Kawasaki and Sugimoto (1984) also conducted a series of laboratory experiments on the flow of water from one basin, through a narrow strait with sharp exit corners and into a second basin originally containing dense water. They observed coastal jets for small Ro_W, stationary loops (i.e. small gyres that did not increase in size) at intermediate values of Ro_W and growing gyres for still larger Ro_W. All of Kawasaki and Sugimoto's (1984) experiments were effectively at F=1 for which $Ro_W = R_c/W$.

The only studies which did not have a zero, or very small, radius of curvature for the wall at the strait exit were some of the laboratory experiments of Whitehead and Miller (1979). As mentioned above, their proposed criterion for gyre formation that $R_c>R_w$, cannot be taken as completely general as their experiments were all conducted at F=1. Further experiments at different Froude numbers seemed to be required, I report on some in the next section.

For sharp corners, the results from previous studies suggest that, with the exception of some laboratory results of Kawasaki and Sugimoto (1984) a coastal jet cannot occur with no-slip boundary condition and that result is independent of the relative vorticity of the flow through the strait.

LABORATORY EXPERIMENTS

Method

I have conducted a series of experiments on a rotating table of about 0.8m diameter. The strait consisted of two semi-circular arcs of 100mm radius, each joining two straight walls (Figure 1a), and separating two basins of equal size. The strait width was 30mm. In order for the strait to be shallower than the basins, in which the water depth was 0.2m, an artificial sill of crest height 0.14m was added. For experiments with $R_w<<W$ a sharp corner was added at the right hand exit from the strait (Figure 1a). These experiments have already been reported by Bormans and Garrett (1989).

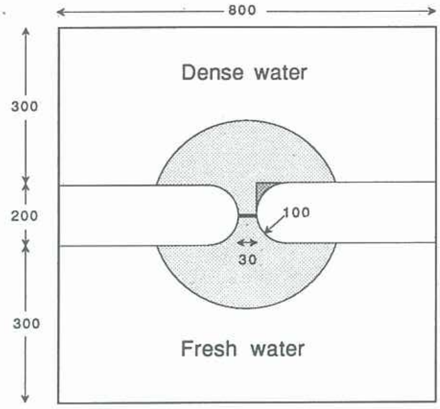

Fig. 1a. Plan view of the laboratory set-up with the two basins of equal size connected by a shallow and narrow strait. The sharp corner on the southern side of the strait at the entrance into the receiving basin was only added for the experiments with $R_w<<W$. The numbers are in mm.

I also performed some experiments where the sill was not present but where the exit corner had a radius of curvature increasing with depth, although with still a sharp corner from the surface down to a depth of 30mm, as shown on Figure 1b. The radius of curvature from 30mm down to 60mm was 30mm and from 60mm down to the bottom R_w=60mm. The depth variation of the geometry at the exit was step-like rather than linearly increasing to better assess the value of R_w at the depth where the interface intersects the bottom. This depth was easily recorded using a mirror in the Strait. In this setting, the exit corner was still sharp at the surface in order to investigate if the geometry where the sea surface meets the coast is important.

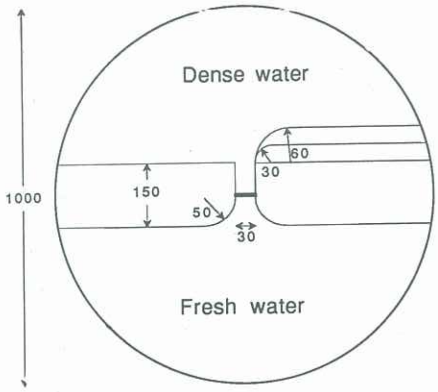

Fig. 1b. Plan view of the laboratory set-up with the two basins connected by a narrow strait with a depth dependent geometry of the exit corner at the entrance into the receiving basin containing the dense water initially.

A synchronous video camera mounted on the table filmed a top view of the experiment so that it could be examined later. The time was also recorded in order to calculate at least rough estimates of flow velocity.

Each experiment was done in two parts. First, both basins were filled with fresh water to a depth of 0.2m. A gate was then placed at the strait to isolate the basins. Salt was added to the receiving basin containing denser water and the water was stirred to homogenize it. The density of each basin was measured with a hydrometer with an accuracy of 0.5kgm^{-3}. The rotating table was then set into motion until the water in both basins reached solid body rotation. Some dye was injected into the basin containing fresh water close to the gate and the timer was started. The gate was then removed and the density currents started to move in opposite directions through the strait. The video camera was placed such that it recorded the inflow as it was entering into the receiving basin containing the dense water initially. As the basins' dimensions were rather small, after a few minutes the water had already circulated around each basin and was returning to the strait. After that, the experiment was no longer meaningful. Nevertheless, the exchange kept going up to a point where the fresh water had filled the surface of the receiving basin. The gate was then closed while the table was still rotating and I waited a half hour for the newly stratified receiving basin to settle into a two-layer system. The gate was then reopened and the video started again to record the pathway of the inflow. The second stage of each experiment was thus performed for the same rotation rate, the same density difference but with a reduced Froude number of the inflow. Of course, for the second stage of each experiment, the basin containing fresh water originally was also stratified with a layer of dense water at the bottom. As this change affects the potential vorticity of the inflow, it also slightly affects the relative vorticity of the inflow at the exit of the strait, though this does not appear to be critical for gyre formation (Werner et al.,1988), and I discount it.

Results for R_w<<W

Experiments conducted with a sharp corner always led to gyre formation except at very high rotation rates when instability, similar to that reported by Whitehead and Miller (1979), was observed. An initial gyre of radius approximately u/f formed quickly and would then grow steadily, apparently through recirculation into the gyre after the separated current hit the wall and split into coastal currents going in opposite directions along the wall, as predicted by Whitehead (1985b).

These results thus extend the previous work summarized earlier. In particular, some of the results were for R_w/W as small as about 0.5 with F from 0.5 to 1.5 or so.

Clearly further work is required, particularly at small value of R_c/W, but the present conclusion is that a gyre will be generated if R_w is very small, although sufficiently small R_c/W may lead to instability.

Results for non-zero R_w

The experiments for non-zero R_w/W performed with the geometry of Figure 1a for which R_w/W=3.3 were such that R_c/W and F were varied over a fairly wide range. The results are shown in Figure 2, plotted as a function of F and R_c/R_w.

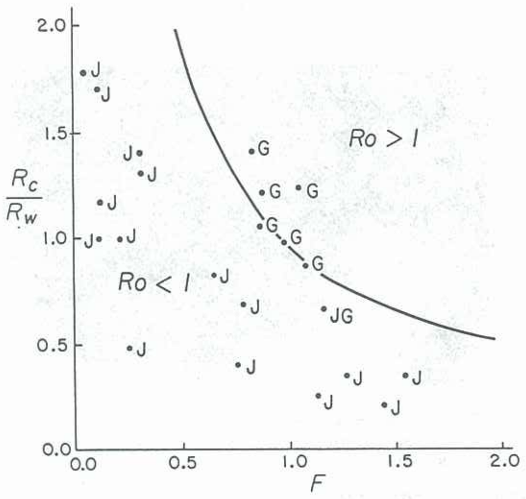

Fig. 2. Experimental results, for R_w/W=3.3, plotted in the (F,R_c/R_w) plane. J and G represent coastal jet and gyre formation respectively and JG a run in which a transition occured. The solid curve is Ro=(R_c/R_w)F=1.

At a Froude number of about 1 the criterion for gyre formation seems to be that R_c>R_w, as found by Whitehead and Miller (1979). My experiments did not, in fact, show gyres at other Froude numbers, but the regions of parameter space in which a coastal jet was observed strongly suggest that the appropriate generalisation of Whitehead and Miller's (1979) criterion is that Ro=(R_c/R_w)F>1 for gyre formation. This is equivalent to u/f>R_w.

The experiments for non-zero R_w/W performed with the depth-dependent geometry of Figure 1b also involved different F and R_c/W values. The results not shown here do clearly indicate that when u/f is smaller than the radius of curvature R_w at the level where the interface between the two layers intersects the bottom which is the depth on the right-hand wall, the flow follows the geometry as a coastal current attached to the coast (Figure 3a), eventhough the exit corner at the surface is sharp. This does suggest that the

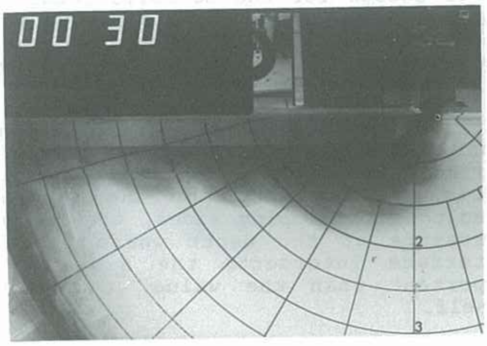

Fig. 3a. Photograph of a run where a coastal jet was observed with the depth dependent geometry taken 30s after the opening of the gate.

appropriate R_w is the one at the level of the interface rather than at the sea surface. When u/f is larger than R_w the flow separates from the coast at the exit and forms a growing gyre (Figure 3b).

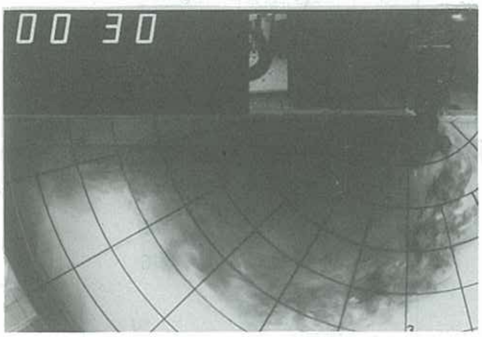

Fig. 3b. Photograph of a run where a growing gyre was observed with the depth dependent geometry taken 30s after the opening of the gate.

DISCUSSION AND CONCLUSION

Previous work and my own laboratory experiments suggest that the key parameter determining whether the exit flow from a strait forms a gyre or a coastal jet is the sharpness of the exit corner in relation to the inertial radius u/f.

If $u/f \ll R_w$ then it is well-recognised that the nonlinear terms in the equation of motion are very small so the current should follow the coast (e.g. Leblond, 1980), and it also seems reasonable that if R_w is less than the inertial adius, u/f, of the path taken by a free particle in a rotating system, then separation will occur. What does seem surprising is that the flow cannot easily reattach itself after this small "inertial bubble" and continue along the coast. In fact, Whitehead (1985b) showed that if a jet impinges on a straight coast in a rotating system it is split into two coastal jets heading in opposite directions. The relative size of the jets is a function of the angle of impact, but it seems that growth of the initial small gyre is inevitable.

I suggest that the dividing line between gyre and coastal jet formation is $Ro=u(fR_w)^{-1}=1$, so that the current simply turns the corner if the inertial radius is small enough for the Coriolis force to be able to keep the current attached to the curving coast. In practice, though, it seems likely that the precise criterion will involve other details of the flow such as the actual current profile across the jet. Most of the numerical and laboratory studies discussed in this paper deal with a surface current in a system with vertical walls, but as shown by the laboratory results with sloping sides, the radius of curvature at the depth where the fluid interface intersects the side is more important than the value at the shore itself.

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REFERENCES

BORMANS, M. and GARRETT, C. (1989) A Simple Criterion for Gyre Formation by the Surface Outflow from a Straint, with Application to the Alboran Sea. J. Geophys. Res. (in press).

CHAO, S.-L. and BOICOURT, W. (1986) Onset of estuarine plumes. J. Phys. Oceaogr., 16, 2137-2149.

CHERNIAWSKY, J. and LEBLOND, P.H. (1986) Rotating flows along indented coastlines. J.Fluid Mech., 169, 379-407.

KAWASAKI, V. and SUGIMOTO, T. (1984) Experimental studies on the formation and degeneration processes of the Tsugaru Warm Gyre. In Ocean Hydrodynamics of the Japan and East China Seas, 39, ed. T. Ichiye, pp.225-238. Elsevier Oceanography Series.

LEBLOND, P.H. (1980) On the surface circulation in some channels of the Canadian Artic Archipelago. Arctic, 33, 189-197.

LOTH, L. and M. CREPON (1984) A quasi-geostrophic model of the circulation in the Mediterranean. In Remote Sensing of Shelf-Sea Hydrodynamics, 38, ed. J.C.J. Nihoul,pp.277-285. Elsevier Oceanography Series.

NOF, D. (1978) On geostrophic adjustment in sea straits and estuaries: theory and laboratory experiments. Part II: Two-layer system, J. Phys. Oceanog., 8, 861-872.

PRELLER, R.H. (1986) A numerical study of the Alboran Gyre. Progr. in Oceanog., 16, 113-146.

WANG, D.-P. (1987) The strait surface outflow. J. Geophys. Res., 92, 10807-10825.

WERNER, F.W., CANTOS-FIGUEROLA, A. and PARRILLA, G. (1988) A sensitivity study of reduced-gravity channel flows with application to the Alboran Sea. J. Phys. Oceanogr., 18, 373-383.

WHITEHEAD, J.A. (1985a) A laboratory study of gyres and uplift near the Strait of Gibraltar. J. Geophys. Res., 90, 7045-7060, (Correction, J. Geophys .Res., 90, 12011-12013, 1985).

WHITEHEAD, J.A. (1985b) The deflection of a baroclinic jet by a wall in a rotating fluid. J. Fluid Mech., 157, 79-93.

WHITEHEAD, J.A. and MILLER, A.K. (1979) Laboratory simulation of the gyre in the Alboran Sea. J. Geophys. Res., 84, 3733-3742.