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The effect of density stratification and a cape in a baroclinic western boundary current separation experiment

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Abstract

Western boundary current separation has long been a mystery. For the Gulf Stream, different factors such as the coastal shape, inflow and outflow location, wind stresses, continental shelf slope, shallow underwater plateaus, and interaction with the deep circulation potentially play unique and important roles in separating the Gulf Stream from the coast. To study these effects, a model consisting of a circular tank of water rotating on a spinning table was set up. Sloping planes form the upper and lower boundaries of the enclosed tank, approximating the Coriolis force. Then, water was pumped through gaps in the tank, producing a western boundary current and an artificial cape having the geometry of Cape Hatteras at the Gulf Stream's point of separation was introduced into the system. Finally, to study the effects of stratification on the point of separation, a 2-layer system was used. The results of varying different parameters, such as flow rate or density difference between layers, were compared with observations of the Gulf Stream and output from a numerical model. Ultimately, the experimental results showed that density differences alone do not affect the separation point to a meaningful degree, but rather that it is the position of inflow and outflow gaps that are much more significant. Density differences alone do not significantly affect the separation point. The relationship between high flow rates tending to create more modes of oscillation and a moving separation point was also observed. More so than any other setup, a cape at high density difference and low flow rate deflects the western boundary current flow. The results suggest that the interplay between the 1-layer and 2-layer modes is relevant to the oceanic case.

Keywords

Western boundary currents: *Warm, deep, narrow, and fast flowing currents that occur on the west side of an ocean basin*; **ocean circulation**: *Any permanent or continuous, directed movement of ocean water that flows in one of the Earth's oceans*; **rotating table experiments**: *Experiments involving a rotating table to study the effects of planetary rotation on fluid flow*; **geophysical fluid dynamics**: *The study of the naturally occurring, large-scale flows in the atmosphere and oceans, such as in weather patterns, atmospheric fronts, ocean currents, coastal upwelling, and the El Niño phenomenon*; **β-effect**: *A planar approximation for the latitudinal dependence of the Coriolis frequency. Normally, the Coriolis force exhibits a sinusoidal dependence on latitude. After Taylor expansion and elimination of higher order terms, a linear approximation is obtained, with β as the coefficient*; **barotropic**: *A flow characterized by pressure varying as a function of density only. This essentially describes a one-layer experimental setup*; **baroclinic**: *A flow whose pressure varies as a function of both density and temperature. It basically gives a measure of the stratification of the fluid. In the case of this experiment, it describes the vertical variation of density in a 2-layer experimental setup*.

Introduction

Western boundary currents are intensified jets found on western edges of major ocean basins. They are the result of the variation of the Coriolis parameter with changing latitude. Eastern boundary currents do exist, but are significantly lower in strength. A large portion of a western boundary current's length follows continental boundaries, transporting heat and nutrients. The separation point between the western boundary current and the coast has been a hot spot in oceanographic research, as it is important to ocean and current predictions.

The Gulf Stream, found in the Atlantic Ocean basin, flows along the North American continent from the Gulf of Mexico to Cape Hatteras, North Carolina. It is then deflected seaward, crosses over the Mid-Atlantic ridge and heads toward Europe. The core of the Gulf Stream current is about 90 km wide and has peak velocities of greater than 2 m/s, or 5 knots. The mechanisms involved in Gulf Stream separation have long been a mystery to physical oceanographers.

Henry Stommel pioneered general ocean circulation modeling in the 1940s. Since then, many experiments involving rotating tables have been performed to examine a spectrum of different effects ranging from mixing of turbulent eddies, wind stresses, gap leaping, and many others. The rotating table setup allows a small-scale modeling of an entire ocean basin in a rotating frame in which the Coriolis force can be easily approximated. For Gulf Stream separation experiments in particular, many different setups have been examined. There have been many one-layer rotating table experiments (Baines et. al., 1996) as well as flow analysis around cylindrical barriers. There have been few experiments done with more than one layer.

A two-layer model of the ocean basin is used in our study of Gulf Stream separation. This idealization of the ocean's density stratification allows one to experiment with physics involving a free, parabolic interface. The bathymetry under the northern portion of the Gulf Stream is thought to act as a sort of streamlining or pumping mechanism that could direct the current's flow. Inflow and outflow locations are used to simulate this effect and provide a way to control the

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separation point of our artificial western boundary current. Experiments with a cape are used to determine the impact of geographical coastal features. Results obtained from various setups are then compared to an output of a preliminary numerical model made to mimic the parameters of our tank. This model essentially solves the stream function given the boundary conditions of the tank until a steady state is reached. A comparison between the model and experimental results can be made to verify the correctness of the model. The model is intended to be used in situations which are difficult to achieve in experiment.

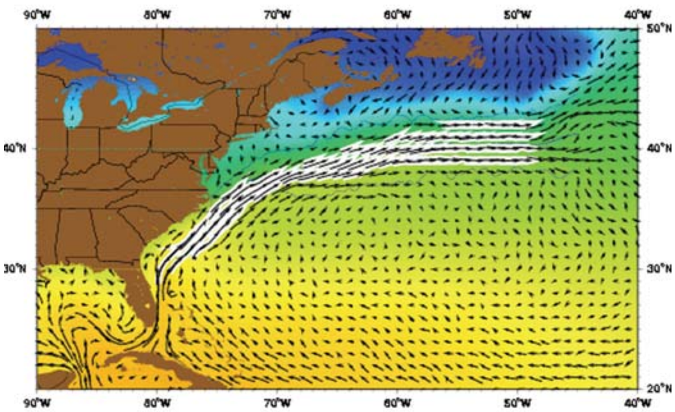

Figure 1. The Gulf Stream as represented by the Mariano Global Surface Velocity Analysis (MGSVA). The Gulf Stream is the western boundary current of the N. Atlantic subtropical gyre. The Gulf Stream transports significant amount of warm water (heat) poleward.

Methods

Tank Setup

A 1 m diameter cylindrical tank is used to create the western boundary current needed for our experiment. The tank is centered on a rotating table and has three compartments: an active area, a northern outflow collection region, and a southern inflow region. An aerial view of the tank is shown in **Figure 1a**. The outer tank walls rise to 45 cm in height. For all experiments, the rotation rate of the tank was set at 1 rad/s. A north-south gradient in the thickness of the water column is created by the sloping bottom and top lids in the tank's active area. These slopes create the β-effect, which approximately simulates the effect of latitudinal dependence of the Coriolis force. This approximation can be made because fast rotating fluids tend to flow with rigid columns aligned parallel to the vertical rotational axis. Since ocean depth increases from high to low latitude measured parallel to the rotational axis, the tank equivalent is to make the depth vary in a similar manner. The bottom lid begins at the southern point of the active region, sloping at +0.05. The top lid is added to prevent a parabolic surface from forming in a freely rotating non-lid experiment, and allows for the β-effect to act upon the top layer of a baroclinic experiment. The top lid also begins at the southern point, and slopes at -0.05, so that the height of the water column in the active region ranges from 14 cm at minimum (north end) to 24 cm at maximum (south end). Lines of constant depth run east-west. The sloped bottom is marked with radial lines every 15 degrees arc and with concentric lines from the midpoint at 5 cm increments.

Both the inflow and outflow gaps of the active tank region are 8 cm wide and are cut out from the first 10 cm layer under the top lid. The inflow and outflow compartments are lined carefully with sponges, taking care to not disturb the flow in or around the gap regions. These sponges serve to diffuse the flow. A digital pump takes water from the northern outflow area, and forces it into the southern inflow compartment, thus creating a pressure difference and causing water to be pushed into the active tank region.

Neutrally buoyant dye was used to trace time-averaged currents in the active region of the tank. A series of small holes was drilled into the top lid of the tank along radial lines at 180, 225, and 270 degrees, concentrated toward the outer rim of the tank. Needles were inserted about 5 cm down from the top lid, and were connected to micro-pumps to inject the dye at a slow rate of 20 mL/hr. A remote-controlled camera was mounted above the active region of the tank, allowing photos to be taken in the rotating tank's frame. Its output was sent by wireless transmitter to a television monitor as well as to a memory card within the camera.

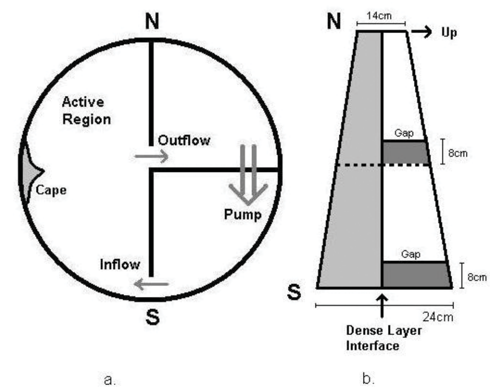

Figure 2. Diagram 2a is a plane view of the tank setup. 2b shows a vertical cross section through the tank from north to south.

Baroclinic System and Cape

To create a stable baroclinic system in the tank, a seawater solution was mixed to our desired density. This layer is allowed to equilibrate to a uniform distribution of temperature. To avoid any currents produced by a vertical temperature gradient, the temperature of all the water used is kept constant at room temperature. The densities tested ranged from 1025 kg/m^3 (pure seawater from Narragansett Bay) to 1002.5 kg/m^3 (diluted seawater). In order to determine the density difference, one defines δ=Δρ/ρ, where Δρ is the difference in densities between the bottom and top layers, ρ is the density of the top layer, and ρ being that of fresh water, 1000 kg/m^3. For example, a setup with a bottom layer density of ρ=1025 kg/m^3 gives δ=0.025. A "high density difference" setup refers to a two-layer system with high δ (δ=0.025 for pure seawater), whereas a "low density difference" refers to a setup with low δ (δ=0.0025 for seawater diluted to 1/10 the amount of seawater compared to pure seawater for a given volume). Testing the extremes of the density range allows us to gauge to what extent the density profile has an effect on separation point. The denser solution is attached to an inflow tube that rotates with the table. Fresh water is put in the tank while the table is stationary – the quantity is measured such that when the tank is completely full with the two-layer system, the denser liquid will rise to the bottom of the inflow and outflow gaps, shown in the vertical section in **Figure 1b**.

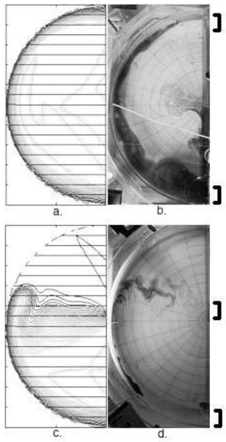

Figure 3. Black brackets designate gaps. Image a shows a barotropic model output for a gap at the north end of the active region. Image b shows the results of the experiment in this setup. Image c is the barotropic model output for a gap in the middle region of the active tank. Image d shows the experimental result of this setup.

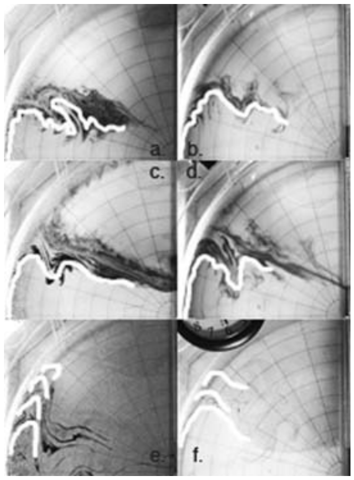

Figure 4. Image a shows results from an experiment at Q=10cm^3/s and δ=0.0025. Image b shows results at Q=10cm^3/s and δ=0.025. Image c shows results at Q=20cm^3/s and δ=0.0025. Image d shows results at Q=20cm^3/s and δ=0.025. Image e shows results at Q=40cm^3/s and δ=0.0025. Image f shows results at Q=40cm^3/s and δ=0.025. White lines are digitally enhanced traces of the dye path for easy viewing.

Once the fresh water is filled to the marked height, the tank is spun up for roughly 10 to 15 minutes until solid body rotation is achieved. The denser seawater solution is then very slowly pumped into the lowest part of the active tank region: the southern point. Neutrally buoyant dye matching the top layer density was injected into the bottom of the tank. This dye would rise through the denser fluid until it reached the interface between layers, allowing us to visually monitor the boundary height. In less dense solutions, dye was used to color the denser solution so that the interface between the bottom and top layer could be monitored more easily. Once the dense water layer is at the correct height, the water pump begins to push the flow, creating the western boundary current.

An artificial cape was made to imitate the presence of Cape Hatteras. It was fit so that its protruding point would line up vertically with the due-west (270 degrees) line of the tank at all heights of the active region. Both sides of the cape were smooth and vertical.

Numerical Model

The numerical model was made to mimic the parameters of the tank setup, including a new addition of a baroclinic, two-layer fluid having a parabolic interface. It finds a numerical solution to the Shallow Water Equations in the cylindrical coordinates of our rotating tank system. The progress of the stream function with trapezoidal time stepping until a steady state is reached can then be tracked. In the case of the baroclinic system, the bottom layer is assumed to be at rest with respect to the rotating table. Contours of the stream function are plotted in the tank's coordinate system. It should be noted that the results of the numerical model depend on the resolution of the model and viscous parameters.

Results and Discussion

Gap Placement

The inflow gap was kept at the southern-most point. Outflow gaps varied from the northern edge to the middle of the tank. Lines of constant depth run east-west. Usually, the western boundary current flows perpendicular to these lines. The global geostrophic contour at which bathymetric features are located is hypothesized to affect the Gulf Stream separation point. Our experimental results show that the point of separation is determined by the placement of the gaps. **Figure 2** shows model output for two different gap placements compared to experimental results at given flow rates.

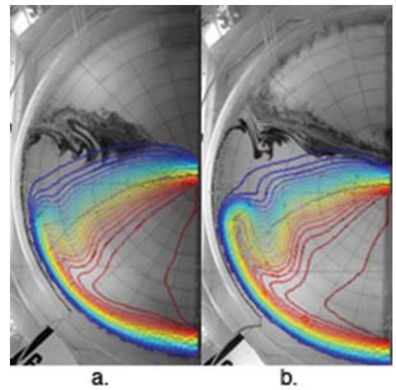

Figure 5. Image a shows the numerical model (colored lines) superimposed over data from an experimental run at Q=10cm^3/s and δ=0.0025. Image b shows the same for Q=20cm^3/s and δ=0.025.

Density Stratification and Flow Rate

By adjusting the flow rate, Q, the amount of water moved through the pump per unit time (measured in cm^3/s), one can compare the effects of density differences between layers at different flow rates. **Figure 3** shows results from both high and low density difference runs at two different flow rates. The dye lines have been digitally enhanced to emphasize the path and separation point of each run. Dye experiments at varying densities exhibit little variation in separation point. This same observation can be made at different flow rates.

At low flow rates, the separation point is easily visible with dye experiments. When the flow rate is increased, dramatic shifts in the point of separation occur, as if the high flow rate is causing the separation point to drift. Many different modes of oscillation make the ink path difficult to map. This observation can be made for different densities. Therefore, flow rate has rather ambiguous effects on the separation point, and further study is needed by more accurate methods. An assessment between instantaneous velocity fields at a number of different times may be more useful in the case of high-oscillation flow rates.

Discrepancies between the model output and the experi-

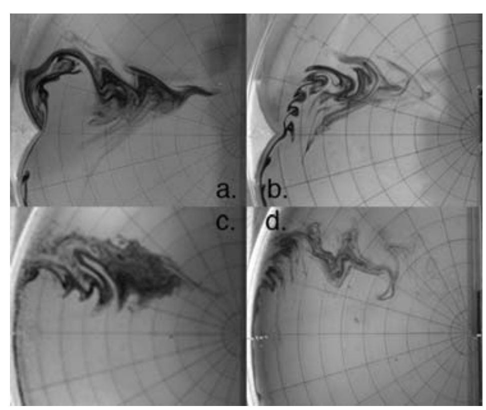

Figure 6. Image a shows results from an experiment at Q=10cm^3/s and δ=0.0025 with the cape insert. Image b shows results at Q=10cm^3/s and δ=0.025 with the cape insert. Image c shows results of the same setup as in a, without the cape. Image d shows results of the same setup as in b, without the cape.

mental setup are shown in **Figure 4**. The model predicts a separation point much further south than what is observed in the lab, even at different flow rates. The experimental setup more closely mimics model outputs of a barotropic system, where there is no velocity change with respect to height of the water column. This can be explained by the baroclinic model's assumption that the lower, denser layer rotates with the tank with a zero relative velocity. Experimental tests with neutrally buoyant dye matching the lower level density show that at sufficiently high flow rates, there is a considerable amount of flow exhibited by the bottom layer, which was previously assumed stationary with respect to the tank. A hypothesis to explain this anomaly is that the bottom layer flow generated enough energy to flow into the outflow gap. At this gap, water from the lower layer was being sucked up and into the outflow compartment. This generated a low-level flow that was less energetic than its upper-layer counterpart. However, the effect was enough to make the system substantially more barotropic, pushing the separation point more northward to match flow patterns predicted and observed in a barotropic equivalent of the setup.

Cape

The cape was tested at multiple density differences and flow rates. **Figure 5** shows the results of runs with the cape compared to those without the cape. At the low density difference extreme, the cape deflects very little water, and the western boundary current literally curls along the cape, back to the side of the tank, and separates at the same point it would have had there not been a cape. The cape's ability to deflect the western boundary current seems greatest at a high density difference, low flow rate situation. This effect can be contributed to the balance between the Rossby waves traveling westward from the outflow gap along the geostrophic contour and the western boundary current's originally intended separation path. In a more baroclinic, or high density difference, system, the upper layer Rossby waves tend to be weaker, thus pushing the current less westward. This allows the current to be deflected away from the tank side more easily.

Conclusions

The Gulf Stream was modeled as a two-layer baroclinic system to examine the impact of different density stratifications on the artificial boundary current. In creating a baroclinic setup, different parameters were adjusted. These included density differences between layers, gap inflow and outflow restriction, flow rate, and presence of a cape. The separation point of the western boundary current from the tank edge was closely examined under each of the different tank setup circumstances.

As seen by the result shown in **Figure 3**, the separation point of an artificial western boundary current in a barotropic, one-layer system is easily controlled by moving the location of the outflow gap in the active area of the tank. Disturbances propagating along geostrophic contours tend to affect the western boundary current's movement. This effect simulates the Gulf Stream flow around Grand Banks, Newfoundland.

The introduction of the two-layer system is a better approximation of the density stratification found in the ocean. It allows for examination of the effects of extreme density differences in the layer and of a parabolic free surface at the interface. At both extremes of very low and very high density differences between layers, results shown in **Figure 4** suggest that the baroclinicity of a two-layer system alone do not affect the separation point in a meaningful way. At high flow rates, this effect is even less obvious, because the flow develops oscillations in the separation point. The baroclinic setup used in this experiment assumed a zero-velocity heavy layer, which was not the case; the bottom layer showed movement, which may explain the discrepancies between the model output and the experimental outcome. A more barotropic system tends to push the separation point further north than a baroclinic system. This result suggests that deep ocean currents may affect western boundary current flow.

A cape insertion is placed due west in the active region to mimic its presence in Cape Hatteras, North Carolina. As seen in **Figure 6**, the cape has little or no effect on the separation point at low density difference setups. However, at a high density difference, there seems to be a clear deflection of the western boundary current from its originally intended path. This suggests that under certain circumstances, the cape does indeed play a role in diverting the western boundary current from the continent.

Further experimental setups should be used in examining bathymetric effects such as constructing underwater plateaus. As this was a preliminary exercise in creating a feasible experimental setup, future tests can expand on these methods with instantaneous velocity field tracking of the flow, as opposed to the time-averaged dye tracing method used, in order to mathematically correlate the experimental results with the numerical model. Effort should be put in to experiment with movable capes and physical barriers in order to examine different flow patterns. Lastly, the effects of deep water circulation should be examined by controlling different lower-layer flows and examining the effects.

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