AOS 801- Tank Lab

Fronts

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Background:

Fronts can be found at various depths and locations in the ocean as well as in the atmosphere. Some areas like the Gulf Stream are prone to frontal boundaries due to the nature of the warmer waters being transported northward. The essential characteristic of a front is a transition zone between differing densities. In the atmosphere, fronts generally exist as a temperature gradient whereas in the ocean, fronts are mostly characterized by differences in salinity. Of course, there are other examples of fronts for both the atmosphere and ocean.

There are different methods for quantifying frontal boundaries. In the atmosphere, a frontal zone can be characterized using an equation known as Margules' relation, included as Eq. 1. This equation illustrates the relationship among differences in horizontal wind speed, density, and the slope of a frontal boundary. Also, depending on whether this system is a zero-th or first-order discontinuity there would be differing forms of the equation used to calculate the slope. For a first-order discontinuity geostrophic wind components are included in the equation as well as temperature gradient measurements, while for a zero-th order calculation you only need temperature and velocity values on each side of the front.

There is an analogous expression applicable to fronts in the ocean known as the thermal wind equation (Eq. 2). The thermal wind equation relates vertical differences in velocity to horizontal variations in salinity. The following two equations, along with their various forms, were implemented in the dry lab portion of this experiment, corresponding to actual atmospheric and oceanic data.

$$(u_2 - u_1) = g\frac{(\rho_1 - \rho_2)}{\rho_1}\frac{\tan\gamma}{2\Omega} \qquad \text{Eq. 1}$$

$$(\frac{\partial u_g}{\partial z}, \frac{\partial v_g}{\partial z}) = \frac{g}{f\rho_{ref}}(\frac{\partial \sigma}{\partial y}, -\frac{\partial \sigma}{\partial x}) \qquad \text{Eq. 2}$$

Methodology:

In preparation for this experiment, a mixture of dyed salty water was created for the purpose of producing a sharp density contrast between two fluids used during this experiment. Final calculations required information to be known regarding densities of both water masses. To measure the densities, 100 milliliters of both the fresh and salt water were weighed in individually tarred beakers. This process was completed five times before each experiment to ensure an appropriate density measurement. After averaging the weights and some simple dimensional analysis density measurements were recorded in kilograms/cubic meter (Table 1).

For the frontal experiment, the rotating tank was set up with freshwater surrounding a core cylinder containing salty, dyed water of a similar temperature. In order to create a secure seal between the cylinder and the tank itself, the rim of the cylinder was coated with petroleum jelly before filling it to a level that was approximately the same as the level of freshwater.

The experiment table was set to a rotation speed of 16 revolutions per minute. The tank was allowed to sit for at least 10 minutes in order to reach steady, solid body rotation. Permanganate crystals were used to test for solid body rotation, after which we could begin the experiment.

The cylinder filled with salty water was removed while the table remained in motion, causing the least disturbance possible. The resulting convergence of the salty and fresh fluids simulated a front with sloping sides all around. An estimate of the slope of the cone and the speed of the surface fluid in the middle of the cone were made shortly after the initial removal.

Table 1

Run #	ρ (freshwater) kg/m^3	Salt (grams)	ρ (saltwater) kg/m^3	Slope of cone	Est. Surf Speed (cm/sec)	RPM
1	976	2.56	996.8	35°	2.5	16
2	993	3.2	1025	30-35°	4	16
3	973.2	4.42	1017.4	45°	3	16

Results:

The results of the tank lab experiment are summarized in Table 1. A total of three runs were completed while attempting to keep all variables relatively constant. The average of the three reported freshwater densities is about 980 kg/m^3, slightly lower than the expected value of 1000kg/m^3. However, the second run reported a value very close to this expected value. The amount of salt in each of the three batches of saline solution ranged from slightly over 2.5 grams to under 4.5grams. These amounts result in salt-water densities with an average of 1013 kg/m^3, which are again, slightly lower than the accepted salt-water density of 1026 kg/m^3. Fortunately, for the purpose of this experiment, the main concern is the density difference between these two fluids, which will be sufficient to display the frontal properties we expect.

The speed of paper dots placed on the surface of the rotating water was estimated during the experiment. These estimated values range from 2 to 4 cm/sec (Table 1). A particle tracking software was used in order to calculate a more exact measurement of velocity. A DVD recording of the final experiment was transferred to an .avi file, which could then be analyzed by the software.

The particle tracking software was used to obtain measurements of locations for eight different particles on the surface of the water. Particle velocities for each particle path were computed by employing Matlab to accelerate the process. The particle velocities ranged from 2.64cm/sec to 10.6cm/sec, however by eliminating the extreme outlier value of 10.6cm/sec, the average velocity for the various particle paths is equal to 3.6cm/sec. This value falls within the estimated velocity values reported in Table 1.

Discussion:

The rotating tank experiment, which involved the introduction of salty, dense water into surrounding fresh water, acted as a proxy for real atmospheric and oceanic fronts. Variables required for use in Margules' relation and the thermal wind relation were gathered and estimated while experiments were in progress. Particle tracker software was employed to obtain accurate readings of particle velocities atop the simulated eddy (Figure 1). Differences in density between the fresh and salty waters were calculated while frontal slopes were estimated.

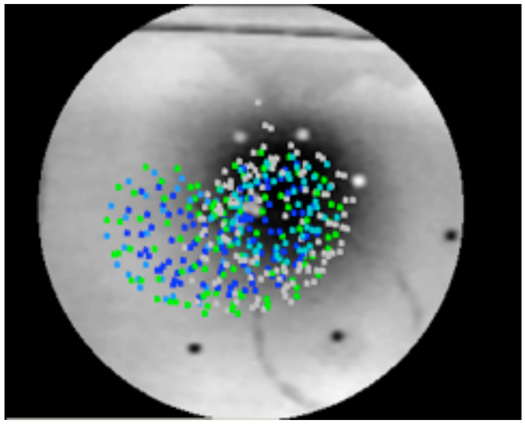


Figure 1: Image of tank lab experiment with during particle tracking process.
Colored paths are exported and analyzed using Matlab.

After completing the same experiment many times, certain observations were found to be consistent. The speed of the water at the surface of the oceanic front was somewhere between 2 and 5 centimeters per second. Also, while the slope of the cone of dense, salty water did vary between as well as throughout the experiments, we estimated a value somewhere around 30 to 40 degrees. This estimation corresponds reasonably well to the calculated result of Margules' equation using our velocity and density variations from the tank lab experiment. It seems that we slightly overestimated our angle during the tank experiment, as the calculated value is closer to 30 degrees. To prevent this in future experiments we could tape a reference sheet to the side of the tank with approximate angles drawn on it for comparison purposes.

While the tank lab experiment was a great visual example of a front, another useful depiction of a frontal boundary in the atmosphere is shown in Figure 2. Figure 2 is a cross-section taken from southern Kansas, southwest of Witchita, to eastern Texas, southeast of Dallas, plotting temperature (°C) in red and wind (m/s) in blue and valid on December 15, 2008 at 1200Z.

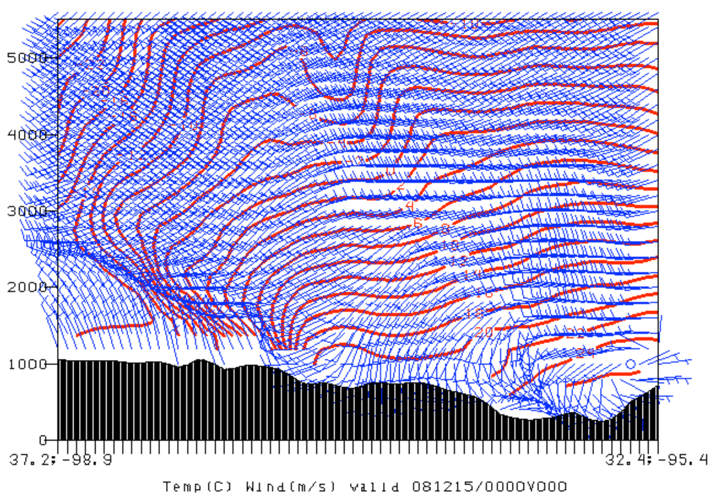
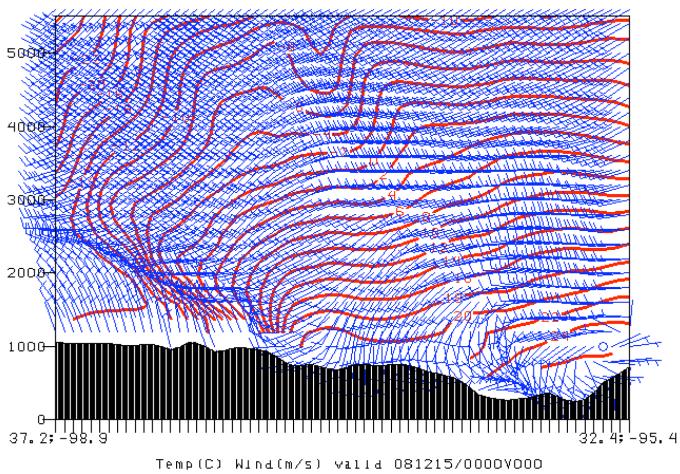


Figure 2: A vertical cross-section of temperature(°C, 2°interval) in red and wind speed(m/s) and direction in blue valid on December 15, 2008 at 1200Z. The cross-section is taken from Kansas(left) to Texas(right). The frontal boundary is clearly seen by looking for a large horizontal temperature gradient and changes in wind direction.

The frontal zone can be identified by the sharp horizontal temperature gradient and wind shift located near the Kansas side. The slope of the front was initially estimated as $\frac{\partial z}{\partial n}$=0.00589m/m. The use of Margules' relation for a zero-th order front in which the temperature field is discontinuous yielded a value of $\frac{\partial z}{\partial n}$=0.0038m/m. Finally, the use of Margules' relation for a first-order front for which the temperature gradient is discontinuous resulted in $\frac{\partial z}{\partial n}$=1.47*10^-9m/m. Based on these calculations, the initial estimate for the slope better matches the calculation using the zero-th order front. The discrepancy between the original estimate and the first-order front calculation could be the result of poor estimation of the lateral shear of the geostrophic wind and the temperature gradient, which are used in Margules' relation.



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Another way of illustrating the presence of an atmospheric frontal boundary is to investigate the distribution of potential temperature, which takes into account the effects of adiabatic heating and cooling that occur within parcels found in the atmosphere. A cross-section of potential temperature (K) for the same region described earlier is shown in Figure 3. The frontal boundary is shown as the region of tightly packed isotherms located closer to Kansas (the left side). Notice that on the left side it appears as though the isotherms are springing up from the surface, which is indicative of a colder air mass.

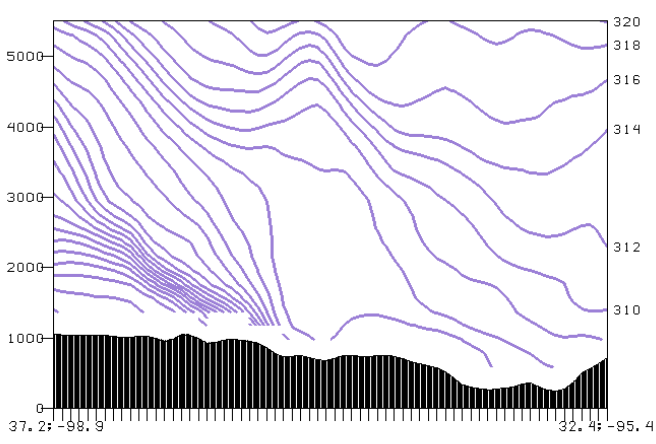
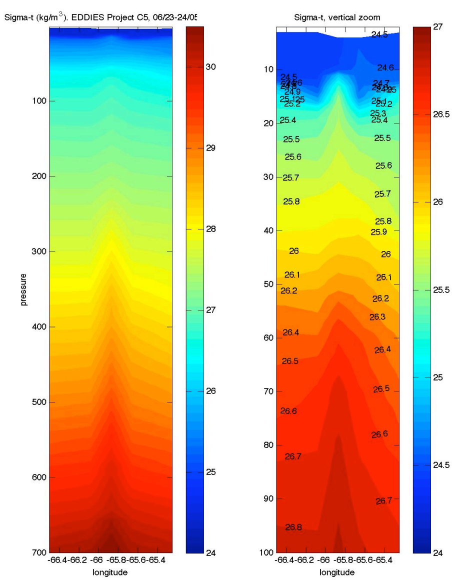


Figure 3: A vertical cross-section of potential temperature(K, 4° interval) valid on December 15, 2008 at 1200Z. The cross-section covers an area of land from Kansas(left) to Texas(right).

Oceans are characterized by frontal boundaries that take on a slightly different configuration than atmospheric fronts. Eddies are visual examples of these fronts. One way to identify fronts in the ocean is to investigate sea surface height (SSH) and sea surface temperature (SST) graphs. Regions with negative perturbation heights are generally colder than surrounding waters while regions with positive perturbation heights are warmer than surrounding waters. Figure 4 contains a graph of the vertical distribution of density from an eddy in the Gulf Stream near 33°N latitude. This eddy is an example of a cold core eddy, shown by its density profile. From the surface to a depth of 700m the center of the eddy has a larger value of density than the adjacent waters. The higher values of density at the center correspond to colder water.

Margules' relation can be applied in this example to estimate the velocity gradient on the western edge of the eddy from -105m to -5m in 20m intervals assuming that velocity at a depth of 7km is -0.25m/s. The total sum of the velocity gradients is 0. 118m/s making the estimated velocity at a depth of 5m equal to -0.132m/s.



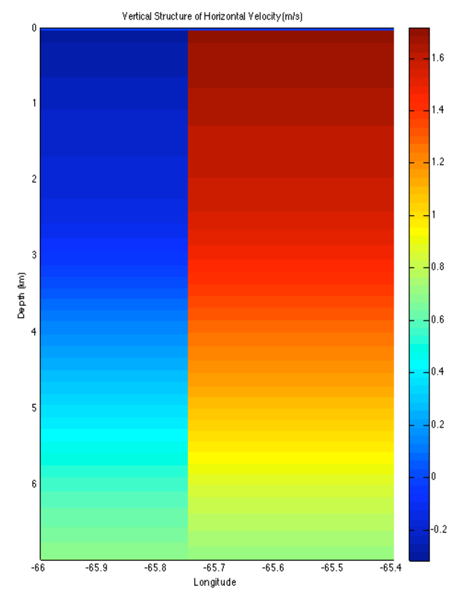


Figure 4 and 5: (left) A graph of the vertical distribution of density within a cold core eddy. An enlarged image is presented to illustrate the subtle density changes in adjacent waters. (right)A graph of the vertical distribution of meridional velocity from 700m to the surface calculated using the thermal wind relation. Notice that at the surface the meridional velocities are in opposite directions, indicating cyclonic flow around the eddy.

A second method for determining the vertical velocity structure is to employ the thermal wind relation for the meridional component of velocity. This was done by calculating the vertical change in velocity at 1m intervals starting from a depth of 700m up to a depth of 5m. The given meridional velocity at 700m was 0.7m/s. Figure 5 is a graph of the vertical structure of velocity calculated using the thermal wind relation. The data appear as columns because of lack of observations along longitude lines and the methods used for calculating horizontal differences in salinity. The key feature of the meridional eddy velocities is the occurrence of strong opposing flow near the surface, which indicates this eddy is rotating cyclonically, or counterclockwise. The vertical gradient in meridional velocity from 700m to 5m is approximately the same on both sides of the eddy core and equal to 1m/s. The thermal wind relation then yields a meridional velocity at -5m equals -0.3m/s. The two methods for calculating near surface velocities (Margules' and thermal wind) resulted in reasonably similar answers, but most importantly, they were in agreement with regard to the direction of flow on the western boundary of the eddy.

Pressure surfaces sketched atop the density contours would indicate a baroclinic fluid because the two sets of lines would be opposite. This setup would indicate a sea surface minimum above the cold core eddy. Alternatively, the pressure surfaces sketched on density contours of a warm core eddy would also indicate a baroclinic fluid however, the sea surface height would be at a local maximum above the warm core.

Conclusions:

Frontal boundaries can be found in the atmosphere and ocean, while also being simulated in a laboratory setting. Results from the rotating tank experiment indicate that as the density gradient between two water masses increases, the vertical gradient in meridional velocity also increases. Interpreting the thermal wind relation can help illustrate this relationship. Atmospheric and oceanic sample data are also helpful for looking at relationships between density and horizontal velocities.

References

Knauss, J.A., *Introduction to Physical Oceanography*, Second Edition, Waveland Press, 2005

Marshall, John, and R. Alan Plumb. *Atmosphere, Ocean, and Climate Dynamics: An Introductory Text*. Boston, MA: Elsevier Academic Press, 2007