12.307 Project 1: Weather and Extremes
Adapted from notes by Lodovica Illari and John Marshall

1 Introduction

If you look at images and maps of weather systems that produce extreme weather, you'll notice two things. One is that winds in the weather systems are typically organized into vortex-like structures, and the second is that the vortex is typically centered on a region of low atmospheric pressure. In tropical cyclones (called hurricanes when they form near the eastern U.S.), winds are organized around regions of low pressure marked by a central eye (Figure 1). Midlatitude cyclones, which can produce heavy snowfall during the Boston winter, have a similar vortex-like structure organized around a low-pressure center but are typically much larger (Figure 1). The jet stream (strong west-to-east winds that form in midlatitudes), which can produce frigid winter weather by bringing Arctic air southward, is part of a planetary-scale vortex centered a region of low pressure at the pole. On much smaller scales, localized regions of low pressure beneath severe thunderstorms can produce tornadoes: small-scale vortices with damaging winds.

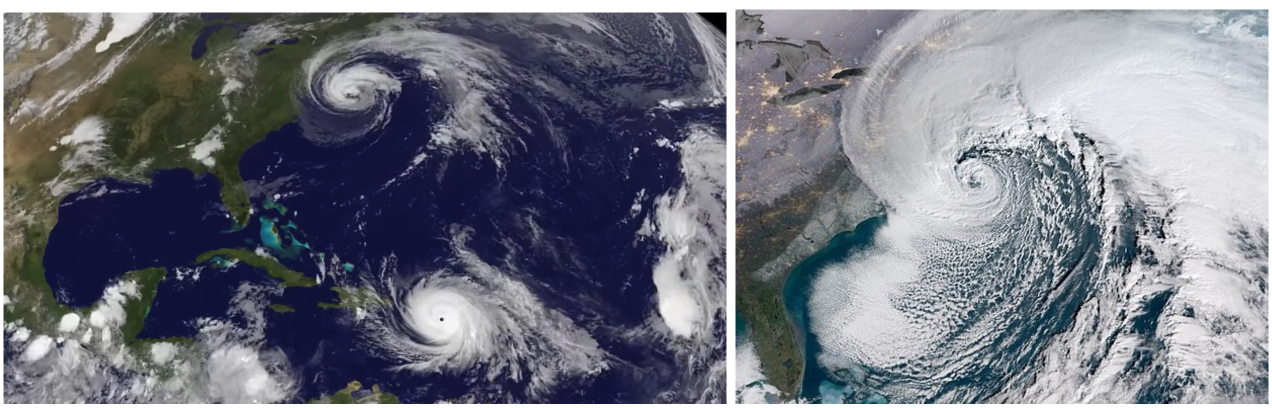

Figure 1: Left: hurricanes Jose (north) and Maria (south) in GOES-13 satellite imagery from September 2017. Right: midlatitude cyclone in GOES-16 satellite imagery from January 2018.

Understanding the structure and dynamics of low-pressure weather systems is important for forecasters who need to assess severe weather risks in a forming storm and for climate scientists who need to project how severe weather risks might change in the future. During this project, we'll try to get a handle on two basic questions:

1. Why is the circulation in low pressure systems primarily around the region of low pressure rather than towards it?
2. How (if at all) is the balance of forces in low-pressure systems influenced by Earth's rotation?

We'll do this using a fluids experiment that allows us to create a model low pressure system in the lab, and by analyzing observations of winds in hurricanes and other low-pressure systems.

1.1 Schedule

February 3: Guest lecture (Tim Cronin), introduction and warmup experiment.

Homework (ungraded): read fluids lab theory (section 2.4) and come to next class with questions.

February 8: Fluids lab session 1. Meet in 15th floor fluids lab.

Homework (ungraded): test provided scripts for plotting particle tracks (linked on project webpage), read notes on computing particle velocities (section 2.3), and come to next class with questions.

February 10: Fluids lab session 2. Meet in 15th floor fluids lab.

Homework (graded): Complete data lab warmup assignment (section 3.1). Due on Canvas by start of next class. Additionally, read data lab theory (section 3.5) and come to next class with questions.

February 15: Guest lecture (Kerry Emanuel), data lab session 1. Bring a laptop if possible!

Homework (ungraded): make plots of $Ro(r)$ *from scatterometer data and bring them to next class.*

February 17: Data lab session 2. Bring a laptop if possible!

February 22: No class (Monday schedule)

February 24: Presentations (in class).

March 3: Reports due by 11:59pm.

April 7: Revisions due by 11:59pm.

1.2 Warmup experiment

Atmospheric vortices are organized by pressure gradients, which produce forces that accelerate flows toward regions of low pressure. We can mimic a low pressure system in a simple laboratory experiment using a bucket of water with a hole in the middle but with a stopper in place to keep the water from escaping. Upon unplugging the hole, water exits from the bucket, setting up a pressure gradient with low pressure at the center and higher pressure on the periphery. This produces a pressure gradient force directed radially inward.

We'll run two versions of this experiment: one where the bucket is placed on a non-rotating table, and one where the bucket is placed on a rotating turntable. Before unstopping the bucket, we'll place some paper dots on the surface of the water to trace the path of the flow after removing the stopper. For the rotating experiment, we'll set up an overhead camera that rotates in sync with the turntable. This co-rotating camera lets us view the experiment in a rotating reference frame—much as we view weather systems from a reference frame where we rotate along with Earth. Because the experiments are identical except for the presence and absence of rotation, differences between the two will highlight how rotation influences the organization of fluid flows around regions of low pressure.

Before running the experiments, use Figure 2 to sketch trajectories you expect particles to take as they exit through the central hole in non-rotating and rotating experiments.

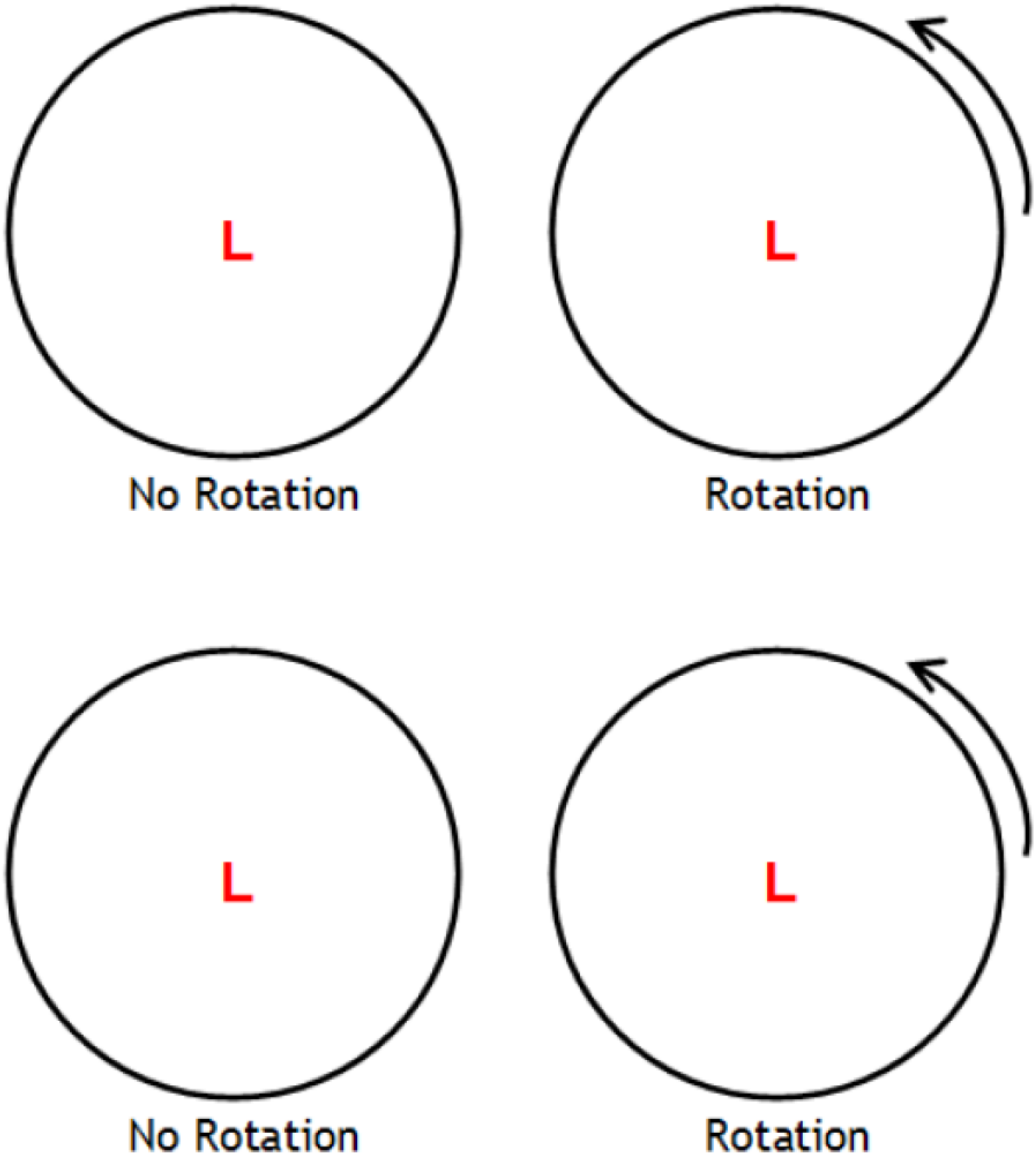

Figure 2: The bucket on the left is filled with water and sitting on a non-rotating table, whereas the bucket on the right is on a turntable which is rotating counterclockwise. Sketch the expected trajectory of a particle of fluid as it exits from the hole at the center of the bucket, labeled L for low pressure. (You can use the second set of schematics, if you want, to record what you observe when we run the experiments.)

2 Fluids lab: radial inflow experiment

In the radial inflow experiment (a more sophisticated version of the warmup experiment), we rotate a cylindrical tank of water about its vertical axis (Figure 3). The cylinder has a circular drain hole in the center of its bottom. Water enters at a constant rate through a diffuser on its outer wall and exits through the drain. The water is then pumped back around, enabling a steady state to be achieved. The system is viewed from above by a camera which is rotating with the turntable—i.e., in the rotating frame of reference.

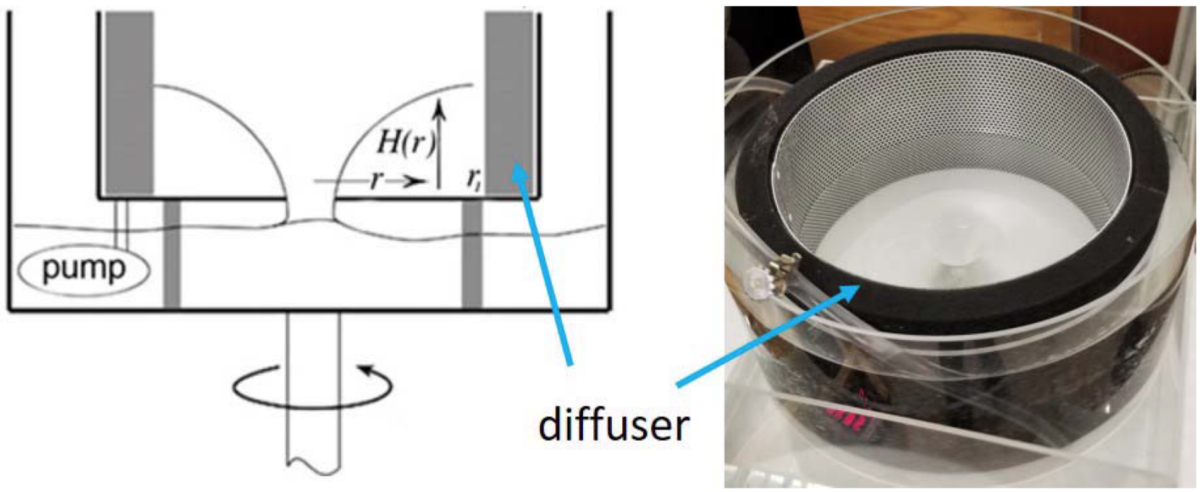

Figure 3: The radial inflow apparatus. A cylindrical diffuser is placed in a larger tank and used to produce an axially symmetric inward flow of water toward a drain hole at the center. Below the tank there is a large catch basin, partially filled with water and containing a submersible pump whose purpose is to return water to the diffuser in the upper tank. The whole apparatus is then placed on a turntable and rotated in an anticlockwise direction. The path of the fluid is visualized by tracking paper dots on the free surface.

When the apparatus is rotating the water acquires a pronounced swirling motion as it exits the tank: fluid parcels spiral inward (Figure 4, right). Even at modest rotation rates of $\Omega = 1$ radian per second (corresponding to a rotation period of around 6 seconds)[1], the effect of rotation is marked and parcels complete many circuits before finally exiting through the drain hole. In the presence of rotation the free surface becomes markedly curved, high at the periphery and plunging downwards toward the hole in the center. When the apparatus is not rotating, particle trajectories are less distinctive but are generally directed radially inward (Figure 4, left) and the free surface is observed to be rather flat.

The main objective of our experiment is to measure, and interpret in terms of mechanics and angular momentum principles (see "Theory" section below), the flow field and its dependence on rotation rate. We will also think about the relation between the flow field and the pressure field, given by the height of the free surface.

[1]If Ω is the rotation rate of the tank in radians per second, then the period of rotation is $T_{tank} = \frac{2\pi}{\Omega}$.

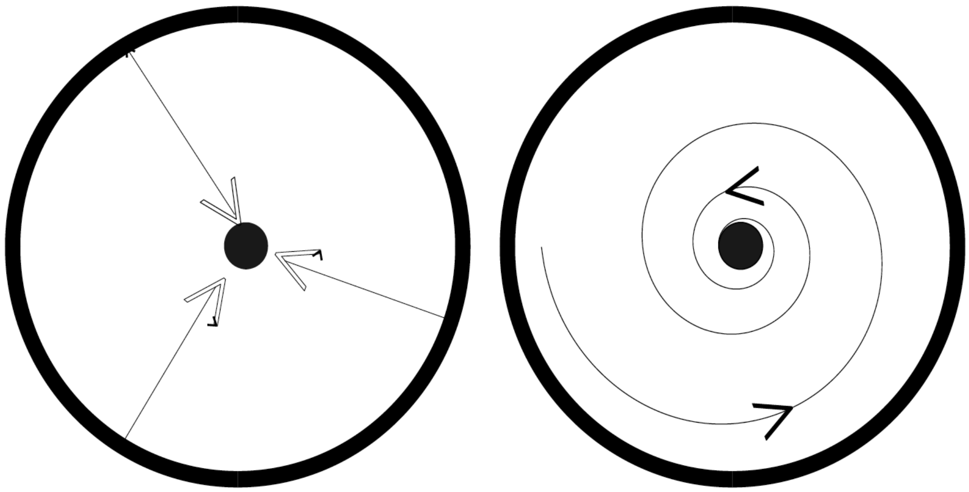

Figure 4: Idealized flow patterns in the absence of rotation (left) and when the apparatus is rotating in an anticlockwise direction (right).

2.1 Your tasks

Carry out three experiments at a low rotation rate (1 rpm), medium rotation rate (6 rpm) and high rotation rate (your choice—but don't break the apparatus by making it fly off the table).

During each experiment,

1. record data from the overhead camera, rotating with the turntable, showing the position of particles (small paper dots placed on the surface of the water) as a function of time using the particle tracker,
2. plot trajectories of chosen particles (using Excel, MATLAB, Python, or another program of your choice),
3. compute and plot particle velocities as a function of radius,
4. compute and plot the Rossby number (defined in section 2.4) as a function of radius, and
5. compare velocities and Rossby numbers with predictions from theory, and discuss your results.

Focus your time in the fluids lab on step 1—this is the only step that involves data collection, and others can be completed outside of the fluids lab. Detailed instructions for using the particle tracker and for computing particle velocities are provided in the following sections.

2.2 Particle tracking

During fluids lab sessions, we'll configure the particle tracker to track particles in a live feed from overhead cameras. Once started and connected to an overhead camera, the particle tracker window (Figure 5) will show a video feed from the camera (left two-thirds of the window) overlaid with masks (black regions) that exclude certain parts of the video from particle tracking and with tracks (colored sequences of dots) showing the history of tracked particles. Particle tracker controls appear in panels on the right side of the window.

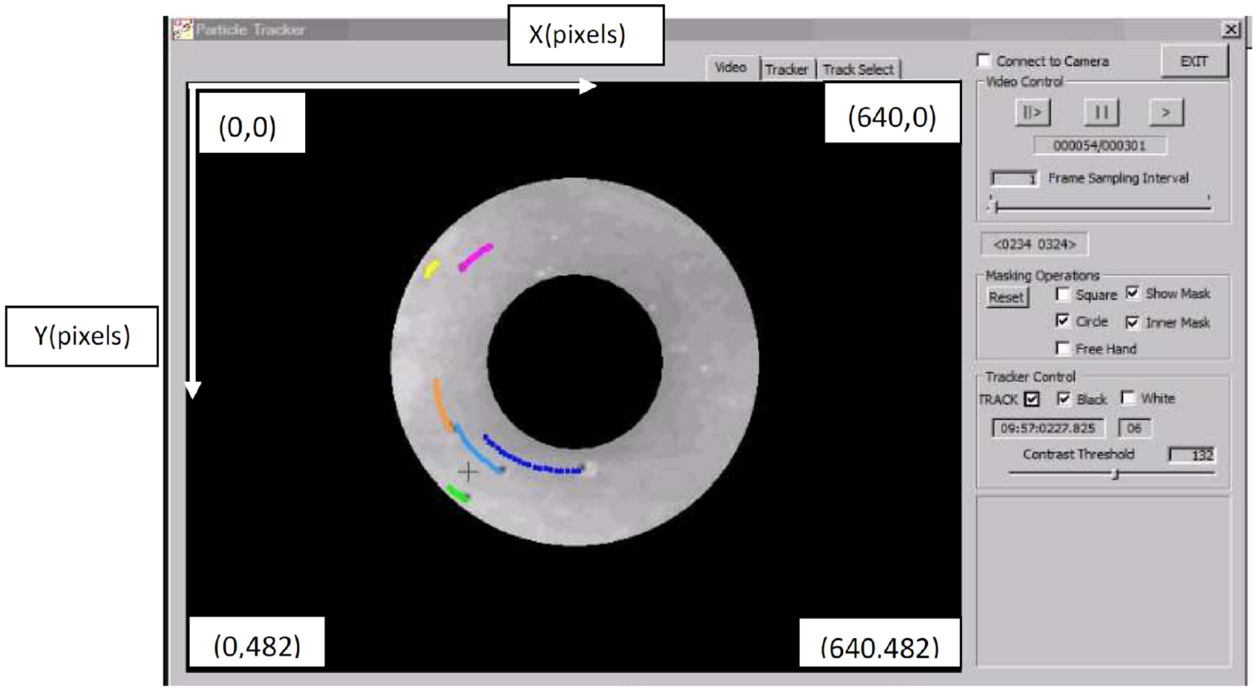

Figure 5: Particle tracker interface.

Before adding particles to the tank, check the "Show Mask", "Circle", and "Inner Mask" boxes in the "Masking Operations" panel. Double-click with the left mouse button to center the masks on the center of the tank, then click and drag with the left mouse button so the outer mask excludes the edge of the tank and the inner mask covers the drain hole.

In the "Tracker Control" panel, check the "Black" box and uncheck the "TRACK" box. Place a particle near the perimeter of the tank, then check the "TRACK" box. (Make sure your hand is out of view before checking "TRACK" to avoid accidentally tracking your hand.) A sequence of colored dots should appear following the particle as it spirals inward. Once the particle exits through the drain hold, uncheck "TRACK", then right click on the track in the video feed and select "Tracking > Select Track" to save data from the particle track. This will highlight a particle track over a black background, and data will be saved in the "My Documents" folder in a file called "ptracks" followed by the date and time the particle tracker was started. Click on the "Video" tab to return to the live view, then right click and select "Tracking > Clear Logs". Additional particles can be tracked by repeating these steps.

The particle tracker records data in pixel coordinates that increase from the upper left corner of the video feed (Figure 5). Converting pixel coordinates to physical coordinates requires additional information: (1) pixel coordinates for the center of the tank, (2) the radius of the tank in pixels, and (3) the radius of the tank in physical space. Items (1) and (2) can be obtained by moving the mouse over the center and perimeter of the tank and recording its location in pixels (shown in a small unlabeled panel between "Video Control" and "Masking Operations"). Item (3) can be obtained by measuring the radius of the tank while in the fluids labs. (Note: you should measure the tank radius in pixels wherever the surface of the water touches the edge of the tank. This may change between experiments as the height of the free surface adjusts to different rotation rates, so make sure you re-measure item (2) at the start of each experiment!)

Particle tracks in output files are formatted as follows:

```
$NEW TRACK
HR MIN SEC MSEC X(px) Y(px)
09 57 21 0432 0209 0247
09 57 21 0772 0208 0244
...
09 57 25 0249 0211 0212
$$END TRACK
```

The $NEW TRACK and $$END TRACK lines delimit a single track. If an output file contains multiple tracks, each will be delimited by their own $NEW TRACK and $$END TRACK tags. Numbers within a track provide the time (in hours, minutes, seconds, and milliseconds) and location (in pixel coordinates) of successive points in particle tracks. Some scripts for parsing particle tracker output and making plots of particles tracks are available on the project 1 website (plot_ptrack.m for MATLAB and plot_ptrack.py for Python).

2.3 Computing particle velocities

Comparing laboratory measurements with theory requires calculating particle velocities in a cylindrical coordinate system centered on the middle of the tank (Figure 6).

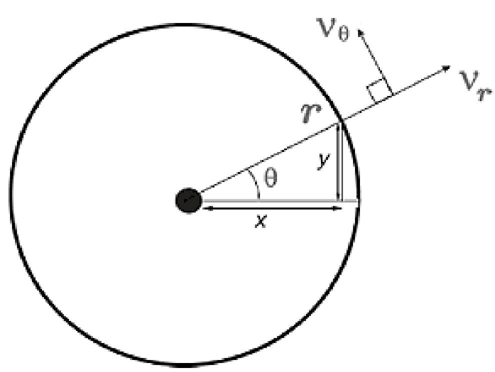

Figure 6: Cylindrical coordinate system centered on the tank.

To do this, let x_p, y_p, and t denote locations (in pixel coordinates) and times from particle tracking data, let x_c and y_c denote the center of the tank in pixel coordinates, and let s denote the ratio of the tank radius in physical units to its radius in pixels. We can transform particle positions to a Cartesian coordinate system in physical space with its origin at the middle of the tank by calculating

$$x = s(x_p - x_c) \tag{1}$$

and

$$y = -s(y_p - y_c), \tag{2}$$

and then transform particle positions to a cylindrical coordinate system by calculating

$$r = \sqrt{x^2 + y^2} \tag{3}$$

and

$$\theta = \arctan(y/x). \tag{4}$$

We can estimate particle velocities in the physical-space Cartesian coordinate system by calculating

$$v_x = \Delta x/\Delta t \tag{5}$$

and

$$v_y = \Delta y/\Delta t, \tag{6}$$

where Δ indicates the change between successive points along particle tracks, and we can convert these to velocities in a cylindrical coordinate system by calculating

$$v_r = v_x \cos\theta + v_y \sin\theta = v_x \frac{x}{r} + v_y \frac{y}{r} \tag{7}$$

and

$$v_\theta = v_y \cos\theta - v_x \sin\theta = v_y \frac{x}{r} - v_x \frac{y}{r}. \tag{8}$$

2.4 Theory

Frames of reference. Because the overhead camera used for particle tracking rotates with the tank, the azimuthal velocity v_θ calculated from particle tracking is a velocity in a rotating frame of reference. It is related to the azimuthal velocity V_θ in the absolute frame (i.e., the frame of the laboratory) by

$$V_\theta = v_\theta + \Omega r, \tag{9}$$

where Ω is the tank rotation rate in radians per second and r is the distance from the axis of rotation.

Prediction for azimuthal velocities based on angular momentum conservation. Fluid entering the tank at the outer wall will have non-zero angular momentum because the apparatus is rotating. At r_1, the radius of the diffuser, fluid has azimuthal velocity Ωr_1 and hence angular momentum Ωr_1^2. As parcels of fluid flow inwards toward the central hole, they might be expected to conserve this angular momentum (provided that they are not rubbing against the bottom or the side, so that we may ignore friction). Conservation of angular momentum then requires that

$$V_\theta r = \Omega r_1^2, \tag{10}$$

or that the angular momentum of the particle at radius r (given by the product of r and the azimuthal velocity in the absolute frame) is the same as when it entered the tank at radius r_1. Combining Equations 9 and 10 lets us solve for

$$v_\theta(r) = \Omega \frac{r_1^2 - r^2}{r}, \tag{11}$$

providing a prediction for the radial profile of azimuthal velocity (measured in the rotating reference frame of the tank) that we can compare with measurements from the particle tracker.

Pressure field in the tank. Because vertical accelerations in the tank are weak, we can use an assumption called "hydrostatic balance" to derive an expression for the pressure field in the tank. Hydrostatic balance assumes that the vertical acceleration is zero, which requires a balance between the downward acceleration from gravity g and an upward acceleration from a vertical pressure gradient force, or that

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} - g = 0, \tag{12}$$

where p is pressure and ρ is the density of the fluid. Rearranging gives

$$\frac{\partial p}{\partial z} = -\rho g. \tag{13}$$

Integrating this expression from a height z to the height of the free surface H, which we assume can vary with the distance to the center of the tank, gives

$$p(r, z) = p(r, H(r)) + \rho g(H(r) - z). \tag{14}$$

Pressure varies continuously across the free surface, so the pressure at the free surface $p(r, H(r))$ is equal to the atmospheric pressure in the lab. Because atmospheric pressure doesn't vary substantially across the surface of the tank, though, we can set $p(r, H(r)) = 0$. This gives

$$p(r, z) = \rho g(H(r) - z) \tag{15}$$

as an expression for the pressure field within the tank.

Radial force balance in the laboratory frame. If the pitch of the spiral traced out by fluid particles in tight (i.e., if $|v_r|/|v_\theta| << 1$ and particles move approximately in circles), then a centripetal acceleration V_θ^2/r that accelerates particles toward the center of the tank must be supplied by a pressure gradient force. This gives a radial force balance of

$$\frac{V_\theta^2}{r} = \frac{1}{\rho}\frac{\partial p}{\partial r}. \tag{16}$$

Combining Equation 16 with Equation 15 lets us express the radial force balance as

$$\frac{V_\theta^2}{r} = g\frac{\partial H}{\partial r}. \tag{17}$$

Radial force balance in the rotating frame. Using Equation 9 lets us express the centripetal acceleration in terms of the azimuthal velocity in the rotating frame of the tank as

$$\frac{V_\theta^2}{r} = \frac{(v_\theta + \Omega r)^2}{r} = \frac{v_\theta^2}{r} + 2\Omega v_\theta + \Omega^2 r. \tag{18}$$

Substituting this into Equation 17 gives

$$\frac{v_\theta^2}{r} + 2\Omega v_\theta + \Omega^2 r = g\frac{\partial H}{\partial r}. \tag{19}$$

Simplifying the radial force balance. If the water in the tank is at rest relative to the tank (i.e., in "solid-body rotation") so that $v_\theta = 0$, Equation 19 gives

$$\frac{\partial H}{\partial r} = \frac{\Omega^2 r}{g}. \tag{20}$$

Integrating this expression from $r = 0$ gives

$$H(r) = H(0) + \frac{\Omega^2 r^2}{2g}. \tag{21}$$

This tells us that, in solid-body rotation, the height of the free surface should be parabolic, and this can be seen clearly in rapidly-rotating tanks (Figure 7). This also tells us that variations in $H(r)$ are only dynamically meaningful (i.e., only require non-zero v_θ) if they deviate from this parabolic profile. (Otherwise, $g\partial H/\partial r - \Omega^2 r = 0$ and Equation 19 can be satisfied with $v_\theta = 0$.) This allows us to simplify the radial force balance by defining a new variable

$$h = H - \frac{\Omega^2 r^2}{2g} \tag{22}$$

that measures the height of the free surface relative to the parabolic profile attained in solid-body rotation. Combining Equation 22 with Equation 19 gives

$$\frac{v_\theta^2}{r} + 2\Omega v_\theta = g\frac{\partial h}{\partial r}. \tag{23}$$

Figure 7: The free surface of a fluid in solid body rotation takes up a parabolic shape, as can be seen in this large square tank of water rotating at 20rpm.

Balance of forces and the Rossby number. The simplified force balance in the rotating frame,

$$\frac{v_\theta^2}{r} + 2\Omega v_\theta = g\frac{\partial h}{\partial r}, \tag{24}$$

looks similar to the force balance in the laboratory frame,

$$\frac{V_\theta^2}{r} = g\frac{\partial H}{\partial r}, \tag{25}$$

except that

1. the pressure gradient force is expressed in terms of the deviation of the fluid depth from a reference parabolic surface, and

2. an extra acceleration, $2\Omega v_\theta$, appears on the left hand side alongside the centripetal acceleration. This is called the "Coriolis acceleration", and appears because the force balance is expressed in a rotating (i.e., accelerating) reference frame.

We can determine which terms in the force balance are important by defining a non-dimensional quantity called the "Rossby number" as the ratio of the centripetal and Coriolis accelerations:

$$Ro = \frac{|v_\theta^2/r|}{|2\Omega v_\theta|} = \frac{|v_\theta|}{2\Omega r}. \tag{26}$$

A small Rossby number ($Ro << 1$) indicates that rotation plays a dominant role in the radial force balance, that the centripetal acceleration is small compared to the Coriolis acceleration, and that the radial force balance is approximately

$$2\Omega v_\theta = g\frac{\partial h}{\partial r}. \tag{27}$$

This is called "geostrophic balance." A large Rossby number ($Ro >> 1$) indicates that rotation is unimportant, that the Coriolis acceleration is small relative to the centripetal acceleration, and that the radial force balance is approximately

$$\frac{v_\theta^2}{r} = g\frac{\partial h}{\partial r}. \tag{28}$$

This is called "cyclostrophic balance". If $Ro \sim 1$, rotation is important but not dominant, and neither the centripetal or Coriolis accelerations can be ignored. This situation is called "gradient wind balance".

Prediction for the Rossby number based on angular momentum conservation. Combining the azimuthal velocity profiles predicted based on angular momentum conservation (Equation 11) with the expression for the Rossby number (Equation 26) gives

$$Ro(r) = \frac{1}{2}\left(\left(\frac{r_1}{r}\right)^2 - 1\right). \tag{29}$$

This expression can be compared with Rossby numbers calculated from laboratory measurements and used to interpret the relevant forces acting on the flow at different radii.

3 Data lab: vortices in the atmosphere

The theory we developed for understanding the dynamics of vortices in the radial inflow experiment can also be used to reason about the dynamics of vortices in the atmosphere. The atmosphere contains many types of vortices, all of which circulate around regions of low atmospheric pressure, but which form on different scales and for different reasons. Atmospheric vortices include:

The jet stream (radius ∼3000 km): a current of winds, strongest at an altitude of around 10 km, that forms around a region of low pressure centered on the pole and produced by the pole-to-equator temperature gradient.
Midlatitude cyclones (radii ∼1000 km): vortices that form at latitudes near the jet stream as the result of a dynamical instability that extracts energy from the pole-to-equator temperature gradient.
Hurricanes/tropical cyclones (radii ∼100-1000 km): vortices that form over subtropical oceans during the summer and fall and are fueled by energy extracted from warm ocean surface water.
Tornadoes (radii <1 km): small-scale vortices with extremely strong, damaging winds that can form beneath strong thunderstorms.

In the project 1 data lab, we will analyze observations of the surface wind field in hurricanes, and compare the balance of forces in hurricanes to other atmospheric vortices. As in our study of laboratory vortices, the Rossby number will be a key tool for reasoning about force balances, and will allow for direct comparison between measurements from the fluids lab and atmospheric data.

3.1 Warm-up assignment

Satellite scatterometers—instruments that used measured radar backscatter from the ocean surface to infer surface roughness and wind speed—can provide detailed maps of the near-surface wind field in hurricanes. This warm-up assignment will help you prepare to work with scatterometer data during the first data lab session. Analyzing hurricane winds during the data lab may require using data from one of two scatterometer instruments—QuickScat, which operated from 1999-2009; or WindSat, which began operation in 2003—so this assignment checks that you can read and plot both QuickScat data (step 2) and WindSat data (step 3).

1. Go to the Project 1 page on the course site and download qscat_20080711v4.gz, wsat_20180911v7.0.1.gz, and one of readscat.m (for MATLAB users) and readscat.py (for Python users). Put all of these files in the same directory and unzip the two .gz files. (Mac users can use the Archive Utility; Windows users can use 7-Zip.)

2. Run the readscat script. It will read scatterometer data from the qscat file and plot a variety of fields centered around 29°N, 297.7°E. These should show an anti-clockwise circulation produced by Hurricane Bertha (Figure 8). Save the streamline plot.

3. Edit your readscat script so that `filename = 'wsat_20180911v7.0.1'`, `storm = 'Florence'`, and `cntr = [27.5, 292.7]`. Then run the readscat script again. This should show another anti-clockwise vortex, this time produced by Hurricane Florence (Figure 8). Save the streamline plot.

4. Submit the two streamline plots in a single PDF on Canvas—or if something went wrong and you couldn't make the plots, submit a brief description of the problem, including any error

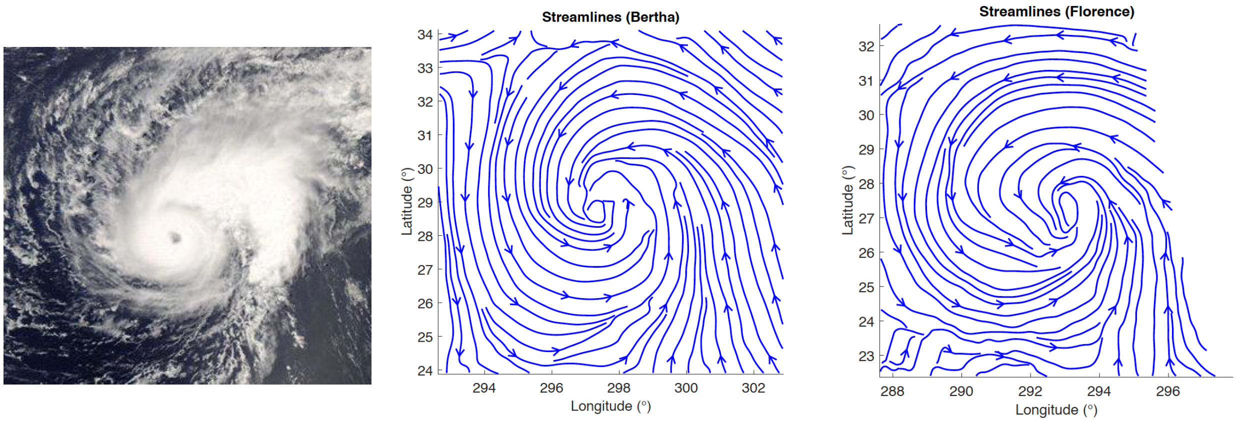

Figure 8: Satellite image of Hurricane Bertha on July 11, 2008 (left) and streamlines (trajectories of particles following the instantaneous flow) constructed from scatterometer winds for Hurricane Bertha (center) and Hurricane Florence (right). Scatterometer winds for Hurricane Bertha are from the QuickScat instrument on July 11, 2008. Scatterometer winds for Hurricane Florence are from the WindSat instrument on September 11, 2018.

messages.

3.2 Your tasks

Analysis of hurricane wind fields.

During the first part of the data lab, you will analyze the balance of forces in hurricanes using scatterometer wind measurements.

1. Modify the readscat script to compute Rossby numbers (see section 3.5) from scatterometer data for one of Hurricane Bertha or Hurricane Florence, and plot Rossby numbers as a function of radius.

2. Compare this plot with a prediction for the Rossby number as a function of radius based on angular momentum conservation. (Note: there's not a clear "correct" value for r_1 when analyzing hurricane winds. Instead, you should treat this value as a tunable parameter, and adjust it to see if you can obtain a good fit.)

3. Download scatterometer data for a different tropical storm (see instructions for accessing scatterometer data below) and repeat steps 1-2.

4. Discuss your results, particularly in relation to the radial inflow experiment. How does the Rossby number vary with radius, how does this compare with results from the tank experiment, and what does this imply about the balance of forces at various radii within a hurricane? Does theory based on angular momentum conservation predict $Ro(r)$ equally accurately for the lab experiment and the hurricane, and if not, why might that be?

Analysis of force balances in other atmospheric vortices.

During the second part of the data lab, you will estimate Rossby numbers for the jet stream, mid-latitude cyclones, and tornadoes, and use your results to discuss the importance of Earth's rotation for low pressure systems on large versus small scales.

1. Open the ESGlobe particle tracking interface (see instructions below) and set the pressure level to 250 mb (about 10 km, near the altitude where the jet stream is strongest). Rotate the globe so you're looking down at the north pole. You should see a band of strong winds circling the pole. This is the jet stream. Release a balloon in the jet stream, estimate the typical time required for it to complete a circumnavigation, and use this time scale to estimate a Rossby number for the jet stream (see Theory).
2. Change the pressure level to 500 mb (about 5 km, near the level where winds in midlatitude cyclones are strongest). Rotate the glove so you're looking down at the northern hemisphere midlatitudes. Try to identify a midlatitude cyclone, which typically look like anti-clockwise vortices embedded within the jet stream. (This can be tricky—we'll talk about what to look for in class.) Release a balloon in it, estimate the time required for it to circulate once around the cyclone, and use this time scale to estimate a Rossby number for the midlatitude cyclone.
3. Tornadoes—which are much too small to view in the ESGlobe interface—typically have radii around 100 meters, wind speeds around 50 m/s, and form in the subtropics and midlatitudes (latitudes of 30-45 degrees). Use these values to estimate a typical Rossby number for a tornado.
4. Discuss your results. How does the Rossby number vary with scale? Does this suggest that Earth's rotation is most important for flows on large or small scales?

3.3 Accessing scatterometer data

Scatterometer data is available at www.remss.com. When searching for a hurricane to analyze, begin by going to www.remss.com/tropical-cyclones/storm-watch. Scroll down to find a list of past named storms, organized by year. Click on the name of a storm. This will bring you to an interface for viewing scatterometer wind fields over that storm's lifetime (example in Figure 9). Finally, click on different locations in the upper bar to view scatterometer data from different days. Try to find a storm and a day where scatterometer data is available (i.e., where wind barbs are visible) over most of the region shown in the left-most panel.

After finding a suitable storm, make note of the date and instrument at the bottom of the window. Then, go to www.remss.com/measurements/wind and, depending on which instrument was used for the plots you viewed, click on either "WindSat" or "QuikScat" in the second table. Next, click "HTTP" in the sidebar. For WindSat data, click "bmaps_v07.0.1", and for QuickScat, click "bmaps_v04". Follow links for the year and month corresponding to your date. Finally, find and download the file labeled with the date (format yyyymmdd) of your storm. For WindSat, download files that end in "v7.0.1.gz", not "d3d.gz". For QuickScat, download files that end in "v4.gz", not "3day.gz".

To plot the downloaded data, you'll have to unzip the downloaded data and modify the `filename` variable in your readscat script to read from the right file. You'll also have to re-center plots around the center of the storm by modifying the `cntr` variable—you can estimate the approximate center from the online viewer, and tune it once you have initial plots. Finally, each file you download will contain data from two passes of the satellite, and you'll have to select the right pass by modifying the `pass` (MATLAB) or `ipass` (Python) variable so that your plots match the online viewer.

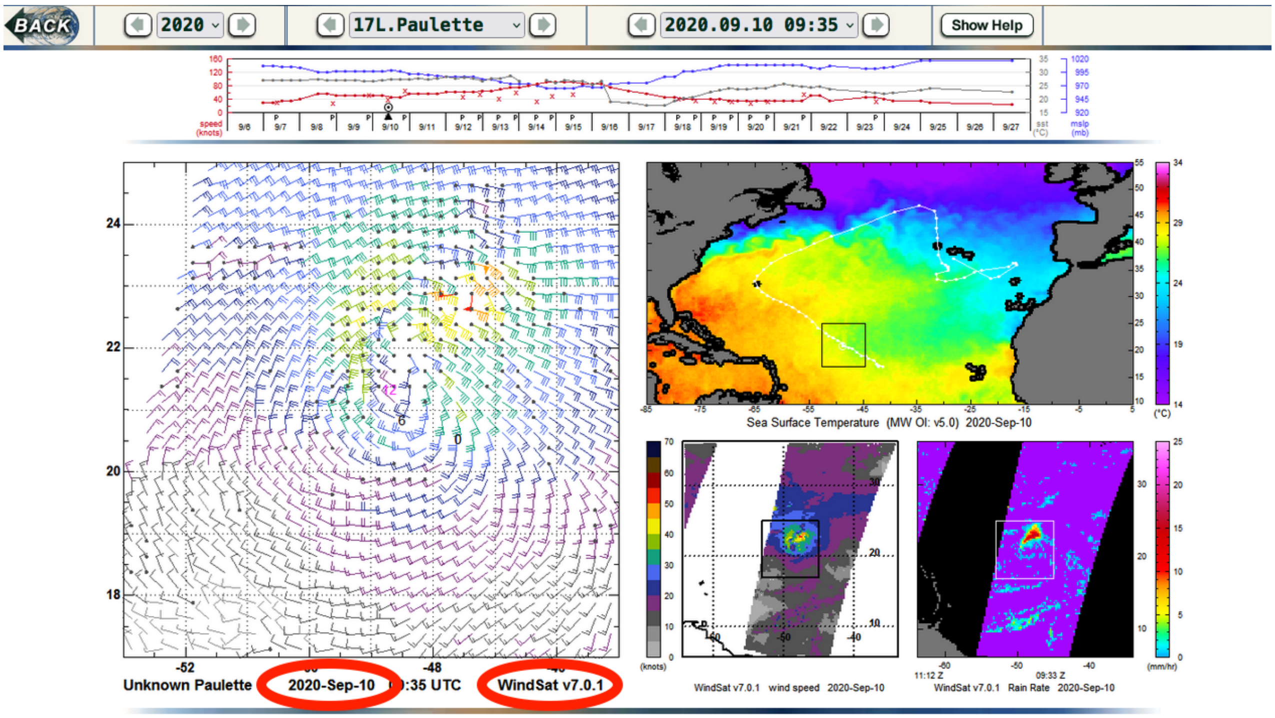

Figure 9: Interface for viewing scatterometer data from the REMSS storm archive. The scatterometer wind field is shown in the left panel, and the date and instrument are circled in red.

3.4 Particle tracking in ESGlobe

The ESGlobe allows you to release virtual particles (which the ESGlobe calls "balloons") in the atmosphere and track their transport by atmospheric flows. To access the ESGlobe particle tracking interface, go to cmpo5.mit.edu/307, mouse over "Menu", and click on "Atmospheric patch of particles" under "Particle tracking". This will display wind speeds at a single pressure level (controlled through the "Pressure level" dropdown menu) on the globe, with a colorbar in the lower left corner. The wind data is from forecasts using the Global Forecasting System (GFS) initialized at the date and time shown on the right control panel. Some orange dots with white tails will be overlaid on the winds. The white tails show the initial trajectories that balloons would take if released from the orange dots. The globe can be rotated by left-clicking and dragging, and you can display latitude-longitude coordinates of a specific point on the globe by control-clicking. If the globe appears too large or small in your browser, you can adjust the zoom level by increasing or decreasing the number at the end of the URL.

To track the trajectory of a balloon, select a pressure level from the "Pressure level" dropdown, and set "Number of balloons" to 1. Click on a location on the globe to set launch coordinates, then click "Launch". An animation will play showing the path of the balloon as time moves forward and the wind field evolves. A white dot will appear on the balloon's path after each day, and the animation will stop after 16 days. You can track its progress in the bar in the lower center of the window. (Note: you can release a cluster of balloons all at once by increasing "Number of balloons", and control the initial spread using the "Spread" dropdown, but this stops the particle tracker from drawing dots after each day of tracking.)

3.5 Theory

Radial force balance. The radial force balance in atmospheric vorticies is very similar to the radial force balance in the radial inflow experiment. Again, the balance is between a pressure gradient force, a centripetal acceleration, and a Coriolis acceleration such that

$$\frac{v_\theta^2}{r} + f v_\theta = \frac{1}{\rho}\frac{\partial p}{\partial r}. \tag{30}$$

Here, v_θ is the azimuthal velocity, r is the distance from the vortex center, ρ is the density of air, and p is pressure. The main difference from the radial inflow experiment is that the Coriolis parameter is given by $f = 2\Omega \sin\phi$, where $\Omega = 2\pi/T$ is Earth's rotation rate, T is Earth's rotation period (1 day = 86400 s), and ϕ is latitude. The Coriolis parameter is modified because Earth is a rotating *sphere*, and the radial force balance in atmospheric vortices is affected by the component of the rotation vector orthogonal to Earth's surface.

Rossby Number. As for the radial inflow experiment, we can use the radial force balance to define a Rossby number

$$Ro = \frac{|v_\theta|}{fr} \tag{31}$$

that characterizes the relative magnitude of the centripetal acceleration v_θ^2/r and the Coriolis acceleration $f v_\theta$. Again, the size of the Rossby number allows us to reason about dominant terms in the radial force balance, and about whether the flow is significantly influenced by Earth's rotation.

The Rossby number as a ratio of time scales. Some algebra allows us to re-write the Rossby number as follows:

$$Ro = \frac{|v_\theta|}{fr} = \frac{1}{2\sin\phi} \times \frac{T}{2\pi r/|v_\theta|}. \tag{32}$$

This provides a simple way to interpret the Rossby number. The first factor, $1/2\sin\phi$, depends only on latitude and tells us what the Rossby number tends to be lower near the poles, where the Coriolis parameter is larger. The second factor, $T/(2\pi r/|v_\theta|)$, is a ratio of two timescales. The numerator, T, is Earth's rotation period. The denominator, $2\pi r/|v_\theta|$, is the time required for a particle with azimuthal velocity v_θ to complete one circuit around a circle with radius r. This tells us that the Rossby number tends to be small in vortices where particles take much longer than one day (one rotation period) to complete a circuit.