12.307 Project 2: Tracer Transport

Adapted from notes by Lodovica Illari and John Marshall

Note: blue text indicates an embedded link you can follow by downloading the online notes.

1 Introduction

During Project 1, we introduced some basic concepts about forces acting on fluid flows in rotating reference frames. These concepts provide powerful tools for understanding a wide range of phenomena. In Project 2, we'll apply them to the topic of "tracer transport": how currents in the ocean and winds in the atmosphere transport materials ("tracers") from one location to another. Understanding tracer transport is particularly important for tracers that pose some risk to human life or natural ecosystems.

We'll spend much of Project 2 studying the transport of plastics in the surface ocean. Plastic isn't produced naturally in the ocean, but some of the plastic waste that humans make ends up in the ocean near coastlines of continents. Plastics are often less dense than water, so they often float near surface of the ocean and are transported by surface currents. Measurements from ships suggest that most of the plastic in the surface ocean eventually becomes concentrated in oceanic "garbage patches" (Figure 1). Oceanic garbage patches are a major environmental challenge: debris in garbage patches can entangle marine animals, and animals may mistake plastics for food and eat them. But why do ocean garbage patches form at all? What's special about the places we find them?

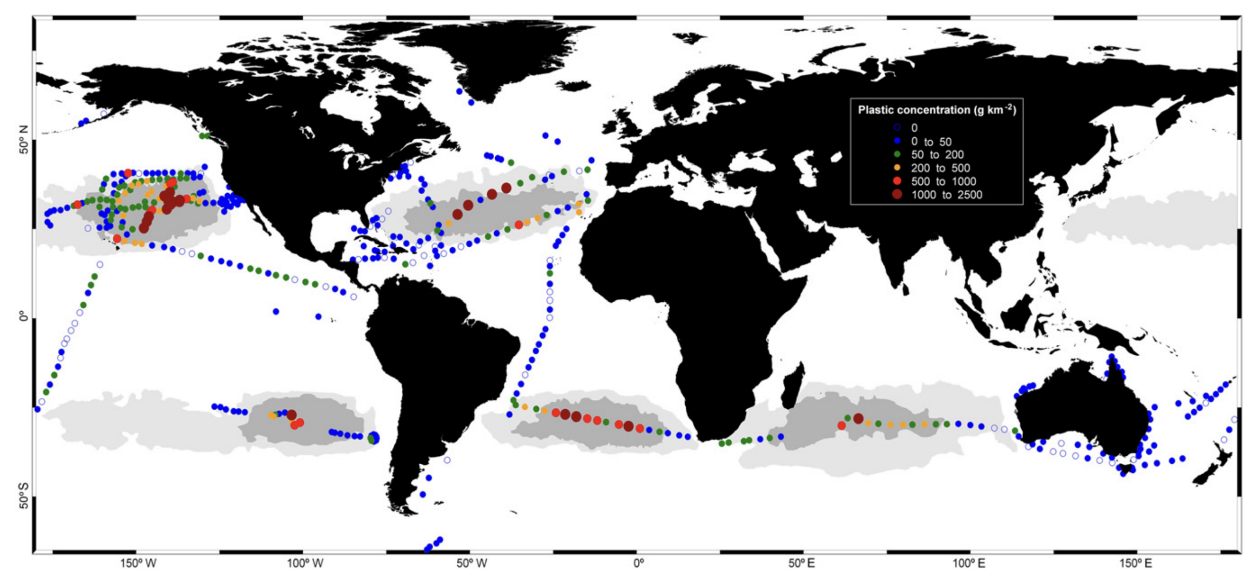

Figure 1: In this figure, taken from a 2014 paper in PNAS, colored dots show the concentration of plastics in the surface ocean measured in grams of plastic per square kilometer. Large red dots indicate abundant plastics, and small blue dots indicate scarce plastics. Gray shaded areas show predicted regions of plastic accumulation based on calculations with a numerical ocean circulation model.

We can begin to answer these questions by looking at currents in the surface ocean. Comparing a map of surface ocean currents (Figure 2) with the location of garbage patches (Figure 1) reveals that garbage patches are located in subtropical gyres: regions to the north and south of the Equator

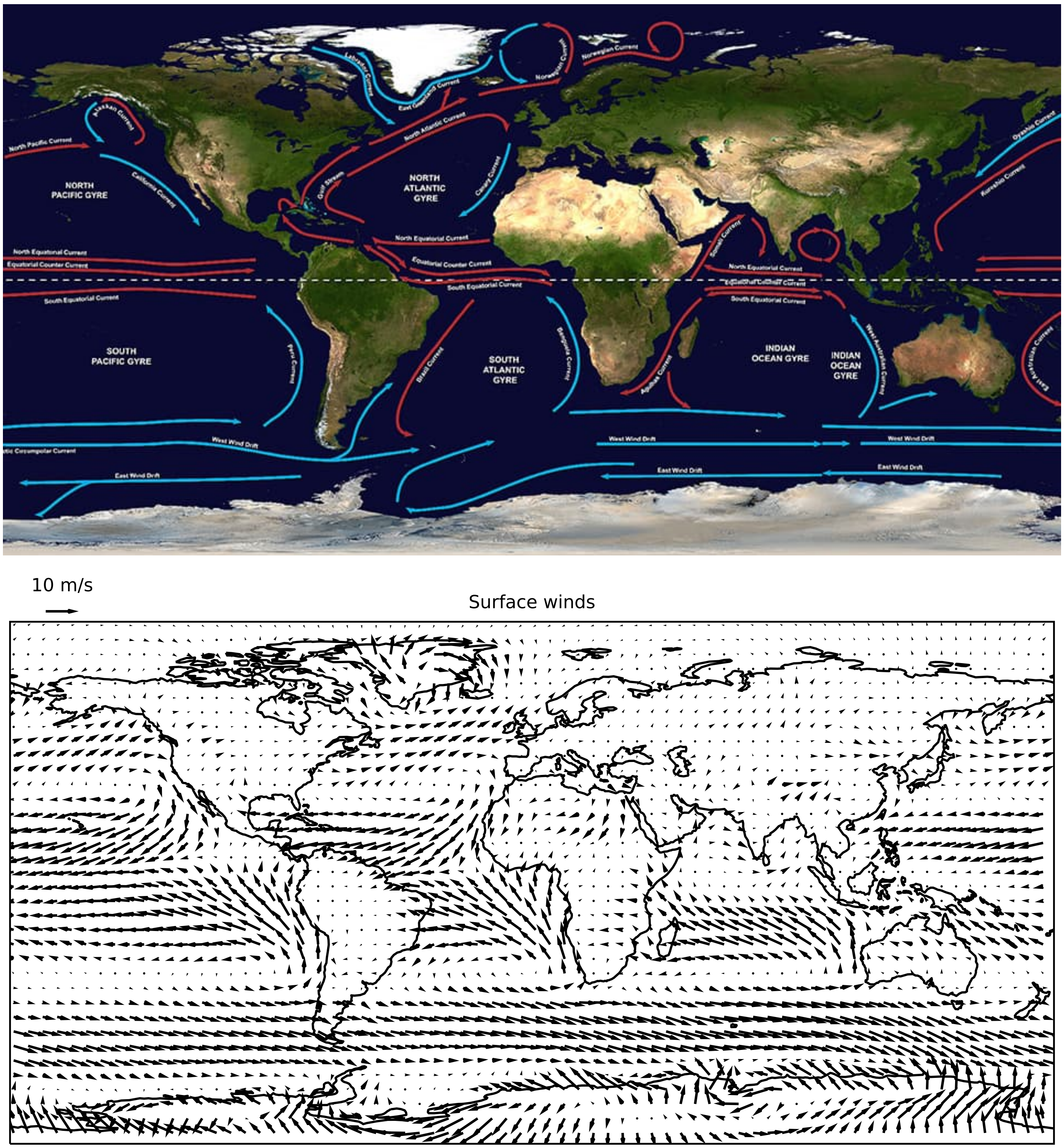

Figure 2: Major ocean currents (top) in a schematic produced by NOAA. Subtropical gyres (labeled simply as "gyres" in the figure) are located in every major ocean basin and are driven by near-surface winds, which flow eastward in midlatitudes and westward near the Equator (bottom).

where currents circulate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. These currents are driven by near-surface winds, which blow westward near the Equator and eastward in midlatitudes (Figure 2). We'll use these observations as a starting point for the fluids lab and data lab, during which we'll focus on answering a more specific question:

1. Why do wind-driven currents in the surface ocean concentrate plastics in garbage patches found near the center of subtropical gyres?

We'll also spend some time during the data lab thinking about tracer transport in the atmosphere, and will focus specifically on the transport of volcanic ash by atmospheric winds. Because volcanic ash is harmful if inhaled and a major aviation hazard, it's important to have accurate forecasts of ash dispersal following volcanic eruptions. We'll attempt to "forecast" the dispersal of an ash plume produced by the 2010 eruption of Eyjafjallajökull, a volcano in Iceland, by combining measurements of the atmospheric pressure field with some simple theory based on geostrophic balance. We'll think about two questions while we construct our forecast:

1. How well does our (fairly crude) forecast technique explain the evolution of the Eyjafjallajökull ash plume?
2. What additional data might allow us to produce a more accurate forecast?

1.1 Schedule

March 1: Guest lecture (Glenn Flierl), introduction.

Homework (ungraded): Read notes on fluids lab (section 2). Reminder: project 1 reports due by 11:59pm on March 3.

March 3: Fluids lab session 1. Meet in 15th floor fluids lab.

Homework (ungraded): make plots of $v_\theta(r)$, $Ro(r)$, and $v_r(r)$ from data collected during first fluids lab session.

March 8: Fluids lab session 2. Meet in 15th floor fluids lab.

Homework (graded): Read notes on part 1 of the data lab (section 3) and complete the data lab warmup assignment (section 3.2). Due on Canvas by start of next class.

March 10: Data lab session 1. Bring a laptop if possible!

Homework (ungraded): Read notes on part 2 of the data lab (section 4) and test the plot_atmos_data.m script (item 1 in section 4.2).

March 15: Guest lecture (Susan Solomon), data lab session 2. Bring a laptop if possible!

March 17: Presentations (in class).

March 31: Reports due by 11:59pm.

April 28: Revisions due by 11:59pm.

2 Fluids lab: wind-driven gyre experiment

During the Project 2 fluids lab, we'll study how interactions between near-surface winds and Earth's rotation influence the distribution of plastics in the surface ocean by constructing a laboratory analog of a wind-driven ocean gyre. To construct the laboratory gyre, we'll set up a water-filled tank rotating counterclockwise at around 10 rpm with two fans clamped to opposite edges about 0.5 cm above the water surface (Figure 3). The fans, which provide "wind" to drive the laboratory gyre, can be configured to blow either clockwise ("anticyclonic", opposite the direction of rotation) or counterclockwise ("cyclonic", with the direction of rotation) (Figure 3). The strength of the wind can be adjusted using potentiometers that control the fan speed. We'll run the fans as slowly as possible to minimize disturbances from ripples on the surface of the tank.

Wind stress from the fans will drive flow in the water and produce (depending on the fan configuration) either an anticyclonic or cyclonic gyre in the tank. We'll mimic plastics in the surface ocean by placing paper dots on the surface of the water. Like plastics in the surface ocean, the paper dots will be transported by flow at the surface of our laboratory gyre. Because our eventual goal is to understand why plastics in the surface ocean congregate at the center of subtropical gyres, our analysis of the tank experiments will focus on understanding the conditions required for paper dots to congregate at the center of the laboratory gyre. In addition to tracking surface particles, we'll record video from cameras above and to the side of the tank, and use dye to visualize flows in the tank interior and near the bottom.

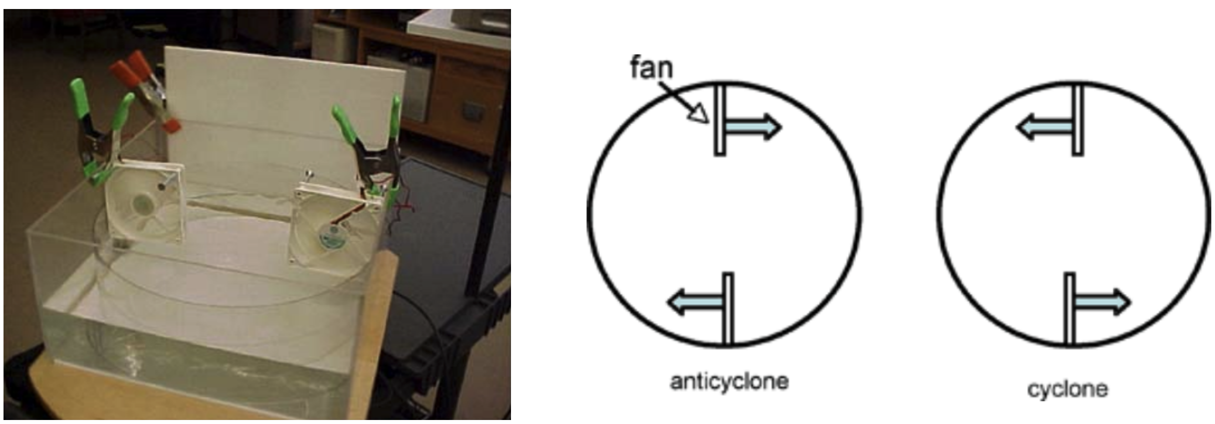

Figure 3: Tank setup for the wind-driven gyre experiment (left) and anticyclonic and cyclonic fan configurations (right). Arrows show the direction of the "wind", i.e., the direction that fans are blowing air.

2.1 Theory

Similar to Project 1, we'll develop theory for the gyre experiment working in a radial coordinate system centered on the tank (Figure 4), which we'll assume is rotating counterclockwise with rotation rate Ω. We'll refer exclusively to velocities measured in the rotating frame of the tank, and use v_θ and v_r to denote azimuthal and radial components. We'll also adopt the convention of referring to Coriolis effects as forces. Remember: when rotation is counterclockwise, the Coriolis force is always directed 90 degrees to the right of the direction of flow (see this visualization). Finally, we'll assume that velocities and forces are azimuthally-symmetric (i.e., that they don't vary with θ), and that the Rossby number of the flow is small, which allows us to ignore centrifugal forces. The first assumption is an approximation—forces produced by the fans will be stronger near the fans, for example—but

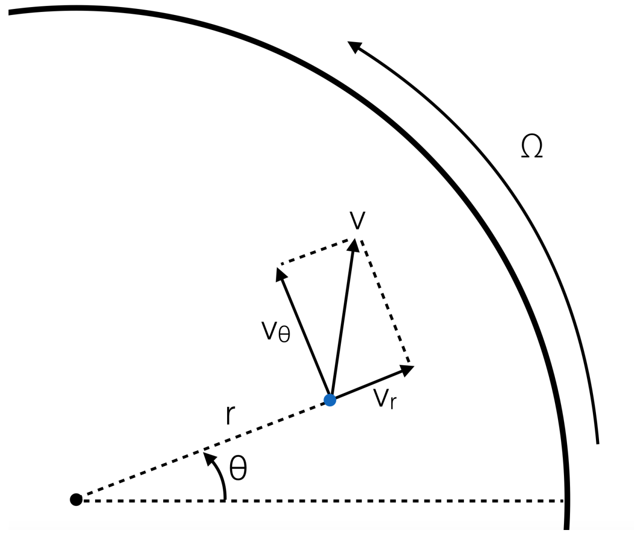

Figure 4: Cylindrical coordinate system used during the wind-driven gyre experiment.

it's accurate enough to provide some basic understanding of the flow in the laboratory gyre, and we'll verify during the lab that the assumption of small Rossby number is reasonable.

During the lab experiment, we'll observe flows with two components: a relatively strong azimuthal circulation that extends through the entire depth of the tank, and much weaker radial flow that exists only at the surface and the bottom of the tank. Our goal in developing theory for the lab experiment is to work out how the direction of the wind force imparted by the fans (cyclonic vs. anticyclonic) determines the direction of the azimuthal and radial components of the flow.

We'll begin by thinking about the flow at the surface driven by the force imparted by the fans on the water. The fans produce an azimuthal wind force F_{wind} that initially produces azimuthal flow in the direction of the wind force. However, the Coriolis force deflects the flow to the right, and the flow eventually reaches a state where the wind force is balanced by a Coriolis force acting on *radial* flow. In this state, the azimuthal force balance is given by

$$F_{wind} - 2\Omega v_{rS} = 0, \tag{1}$$

where v_{rS} is the radial velocity at the surface. This means that we expect outward radial flow ($v_{rS} > 0$) when the wind stress is cyclonic (F_{wind} and Ω have the same sign), and inward radial flow ($v_{rS} < 0$) when the wind stress is anticyclonic (F_{wind} and Ω have opposite signs).

Because water can't accumulate indefinitely at the center or edges of the tank, the radial flow at the surface of the tank must be balanced by radial flow of the opposite sign at the bottom of the tank (Figure 5). As at the surface, a Coriolis force will act on radial flow at the bottom of the tank, and some other force must balance the Coriolis force in order for the radial flow to remain steady. This is provided by an azimuthal drag force $F_{drag,\theta}$, giving an azimuthal force balance of

$$F_{drag,\theta} - 2\Omega v_{rB} = 0, \tag{2}$$

where v_{rB} is the radial velocity at the bottom of the tank. Because v_{rB} and v_{rS} are in opposite directions (have opposite signs), we expect the azimuthal drag force to be directed in the opposite direction of the wind force.

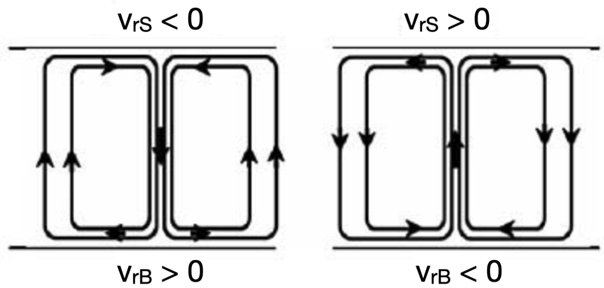

Figure 5: Possible configurations of radial velocities at the top and bottom of the tank, shown in cross-sections through the tank viewed from the side. Vertical motion at the center and edge of the tank connects regions with inward and outward radial flow.

Because drag forces at the bottom of the tank are produced by flow past the tank boundary and point in the direction opposite the flow, knowing the direction of the azimuthal drag force tells us the direction of the azimuthal circulation in the tank. Because $F_{drag,\theta}$ and F_{wind} point in opposite directions, the azimuthal velocity at the bottom of the tank ($v_{\theta,B}$) is in the same direction as F_{wind}.

Maintaining steady azimuthal flow requires another radial force to balance the Coriolis force acting on the azimuthal flow. There is a radial drag force $F_{drag,r}$ at the bottom of the tank associated with non-zero v_{rB}, but it acts in the same direction as the Coriolis force and can't help balance it. (You can verify this based on the relationship between v_{rB} and v_θ.) Instead, the Coriolis force must be balanced by a pressure gradient force produced (as in the radial inflow experiment) by radial variations in the height of the free surface. This gives a radial force balance of

$$-g\frac{\partial h}{\partial r} + 2\Omega v_{\theta,B} + F_{drag,r} = 0, \tag{3}$$

where h is the height of the free surface measured as a deviation from a reference parabolic profile and g is the acceleration from gravity. The radial force balance tells us that we expect h to increase the edges of the tank if v_θ is positive (since this produces positive $\partial h/\partial r$ and an inward pressure gradient force), and to increase at the center of the tank if v_θ is negative.

Away from the bottom of the tank, where drag forces vanish, the azimuthal flow is in geostrophic balance with the pressure gradient force. This gives a radial force balance of

$$-g\frac{\partial h}{\partial r} + 2\Omega v_{\theta,I} = 0, \tag{4}$$

where $v_{\theta,I}$ is the azimuthal velocity in the "interior" of the tank (away from the bottom). Because the pressure gradient force is independent of depth, $v_{\theta,I}$ must be larger than (but the same sign as) $v_{\theta,B}$ to compensate for the absence of a radial drag force. Because drag is zero both in the interior and at the surface, the azimuthal velocity at the surface should be identical to $v_{\theta,I}$.

Some notes on terminology: the azimuthal circulation away from the bottom is often called the "geostrophic" component of the flow (since it's in geostrophic balance with a pressure gradient force) and the radial component is often called the "ageostrophic" component (since it's not in geostrophic balance) or the Ekman velocity (after an oceanographer who studied wind-driven currents in the surface ocean).

2.2 Your tasks

Carry out two experiments: one with anticyclonic wind, and the other with cyclonic wind.

During each experiment,

1. Measure and record the radius of the tank.
2. Record video using the overhead camera and a phone camera mounted on the table to view the tank from the side.
3. Release 5-10 paper dots at various radii on the surface of the tank, and allow the dots to move with the surface flow for about 10 minutes.
4. Release some potassium permanganate to visualize the flow at the bottom of the tank, and drop some dye into the tank to visualize the flow in the interior. After adding the permanganate and dye, allow the experiment to run for an additional 15 minutes, and look for evidence of vertical motion near the center and/or perimeter of the tank.

For this project, you don't need to track particles during the experiment. We're going to use a new particle tracker (see Section 2.3) to extract tracks from recorded videos.

After you're finished collecting data,

1. Follow the instructions in Section 2.3 to trim your recorded video and collect particle tracks. Aim to collect tracks for 3-5 particles with a range of initial radii, and focus on parts of the video when particle radii are changing the most.
2. Use particle tracker data to calculate and plot $v_\theta(r)$ and $Ro(r)$. Is our assumption of geostrophic balance appropriate throughout most of the gyre?
3. Use particle tracker data to calculate and plot $v_r(r)$ at the surface. Because v_r is small and the data are noisy, overlay a plot of $v_r(r)$ where noise is reduced by binning the data (see Section 2.4). Does the direction (sign) of v_r agree with theory?
4. For each experiment, draw a schematic that shows
   (a) the direction of the surface wind produced by the fans,
   (b) v_θ and v_r at the surface and at the bottom of the tank,
   (c) regions with upward and downward vertical motion,
   (d) regions where the free surface height h should be relatively high and relatively low, and
   (e) radial and azimuthal force balances at the surface and bottom of the tank.

In your presentation and report, use the plots and schematics to discuss how rotation and wind forcing combine to determine when particles at the surface congregate at the center of laboratory gyres. What would change if we rotated the tank clockwise instead of counterclockwise, so that Ω changes sign? (This is relevant for the southern hemisphere, where the Coriolis parameter is negative.)

2.3 Particle tracking

We'll use new particle tracker for Project 2. This particle tracker runs on recorded videos and only tracks one particle at a time, but it should let you collect tracks that require little or no cleaning, and so should ultimately save you some time. The new particle tracker is already set up on the lab computer, and these instructions assume that's where you're using it. It should be relatively easy to install and use on your own computers, too, though—ask about it during office hours if you're interested.

To prepare your recording for particle tracking, trim the video file to isolate the period you want to track:

1. Find your recording by clicking the "Recorded Videos" shortcut on the desktop, right-click, and select "Open with → Photos".
2. Click on the edit button (pencil and paintbrush icon on the top right) and select "Trim".
3. Drag the two white circles to select the period during which you want to track particles. Aim for a 1-3 minute segment.
4. Click "Save a copy". This will create a new file with "_Trim" appended to the file name. You can rename it if you want.
5. Move your trimmed video into the "videos" subdirectory of the "PyTrack" folder on the desktop.

To start the particle tracker,

1. Open "Anaconda Prompt (miniconda3)" using the start menu.
2. Enter

   ```
   cd Desktop\PyTrack
   conda activate pytrack
   ```

   in the command prompt to go to the particle tracking folder and set up the Python environment for the particle tracker.
3. Start the particle tracker by entering

   ```
   python pytrack.py videos\<file>.mp4
   ```

   in the command prompt (replacing "<file>" with the name of your trimmed video) to start the particle tracker.

The particle tracker loads the entire video into memory at once, so it may take a minute or so for the particle tracker window to open.

To use the particle tracker,

1. Record pixel coordinates for the center and edge of the tank by reading the cursor location shown at the bottom of the particle tracker window. (You'll need this, along with measurements of the radius of the tank in physical units, to calculate velocities from particle tracks.)
2. Check "Show binary" and confirm that dots appear as black circles surrounded by white. If they don't, adjust the "Threshold" slider and click "Update" to refresh the image until they do. (You'll see some other features from the fans, edges of the tank, and table—that's fine.) Then uncheck "Show binary" to display the video again.
3. Check "Show centroids" and confirm that a white x appears over each dot. Then uncheck "Show centroids".

4. Try pressing enter and backspace a few times to advance and rewind the video, and adjust the "Step size" slider to control how many frames you step past each time you advance and rewind. You want the video to be sampled relatively frequently, but you also don't want to spend hours tracking particles. A step size of 3 (which samples the video 10 times per second) is a reasonable starting place for this experiment.

5. Rewind the video to the beginning, then click on a particle you want to track. A red x should appear above the particle. Check "Show track" and "Track", then start to advance the video. (You can hold down enter to advance continuously.) You should see a blue trail of dots appear as the program tracks the particle.

   The particle tracker will try to make an intelligent guess at the location of the particle in each frame, but it will probably get confused when the particle is near the fans. There are several things you can do to correct errors:

   (a) If some incorrect points are added to the track, you can hit backspace (rewind) to clear them.

   (b) If the red x appears in the wrong location when the particle is still visible, you can change its location by clicking on the particle before advancing.

   (c) If the particle is out of view, uncheck "Track" to prevent new points from being added to the track, then click on the particle and re-check "Track" once the particle appears.

6. Once you're finished tracking, click "Save". This will save the particle track to a text file with a random filename (shown next to the save button) in the PyTrack directory. You can (and probably should) change the filename to something more informative after saving. If you want to reset the particle tracker after saving (to, for example, collect a track for a different particle), check "Reset on save" before clicking "Save".

The format of the text files produced by this particle tracker is identical to the output of the particle tracker you used during Project 1, so you should be able to read them using the same MATLAB scripts.

2.4 Binning

Data binning is a useful technique for reducing the effects of errors ("noise") on measurements of the relationship between two or more variables. It works by separating data into "bins" and calculating averages within each bin.

As an illustrative example, consider a function $y = e^{-x}$. We'll simulate noisy measurements of y for 1000 values of x (evenly spaced between 0 and 5) by adding random noise to y. Specifically, we'll generate a set of measurements $(x, y_m(x))$, where

$$y_m(x) = e^{-x} + N(0, 0.25) \tag{5}$$

and $N(0, 0.25)$ is number drawn randomly from a normal distribution with mean 0 and variance 0.25. The true function y and our set of measurements y_m are shown in the top panel of Figure 6.

Binning these measurements requires three steps:

1. Define locations of bin edges. We'll use bins of width 0.5, and our data goes from $x = 0$ to $x = 5$, so this gives 10 bins with edges at $x = 0, 0.5, 1, 1.5, ..., 9.5, 10$.

2. Assign measurements to bins. For each of our 1000 measurements of (x, y_m), we'll look at the value of x and place it in the first bin if $0 \leq x < 0.5$, in the second bin if $0.5 \leq x < 1$, in the third bin if $1 \leq x < 1.5$, and so on.

3. Average the data within each bin. This will give us a set of 10 new data points $(\overline{x}, \overline{y_m})$, one for each bin.

In addition to calculating average values, it's good practice to estimate the error remaining in the averages. If we assume that errors are independent between different samples, and construct bins so that error-free values vary little within each bin, then we can estimate the remaining error on averages by estimating the root-mean-square error of the samples within each bin and dividing it by the square root of the number of samples in each bin. For a single bin with mean $\overline{y_m}$ and samples $y_{m,i}$, $i = 1, 2, N$, this gives an error ϵ of

$$\epsilon = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(y_{m,i} - \overline{y_m}\right)^2}}{\sqrt{N}} \tag{6}$$

You'll learn more about error analysis in statistics courses. For now, if you're interested in details about this error estimate, look up "standard error of the mean" in a statistics textbook.

The bottom panel of Figure 6 shows the results of binning our noisy measurements. Circles show average values $(\overline{y_m})$, and vertical error bars show average values plus and minus the estimated error $(\overline{y_m} \pm \epsilon)$. There is still some noise after binning, but much less than in the raw data, and remaining deviations from the true value are comparable to the size of the estimated error. (Note: we haven't constructed error estimates in a way that carefully controls *how often* error bars encompass true values, so there may be some bins where the true value is outside of the error bars. If you want to learn how to calculate error bounds that almost always include true values, look up "confidence intervals" in a statistics textbook.)

When binning data, it's important to choose an appropriate bin width. If bins are too narrow, averaging within each bin won't reduce noise very much. If bins are too wide, you'll reduce noise but may also lose information about the underlying relationship. There are a lot of rules of thumb that can help estimate appropriate bin widths (see e.g. here), but ultimately the choice is usually subjective, and relies on your own ability to distinguish noise from real features in the raw data.

How you implement a binning algorithm differs between programming languages, but most languages used for data analysis (including MATLAB, Python, and R) have functions you can use to assign measurements to bins and calculate statistics within bins. The MATLAB script used to generate Figure 6 is available on the course website (`binning.m`) and can be used as a starting point when binning measurements from the fluids lab.

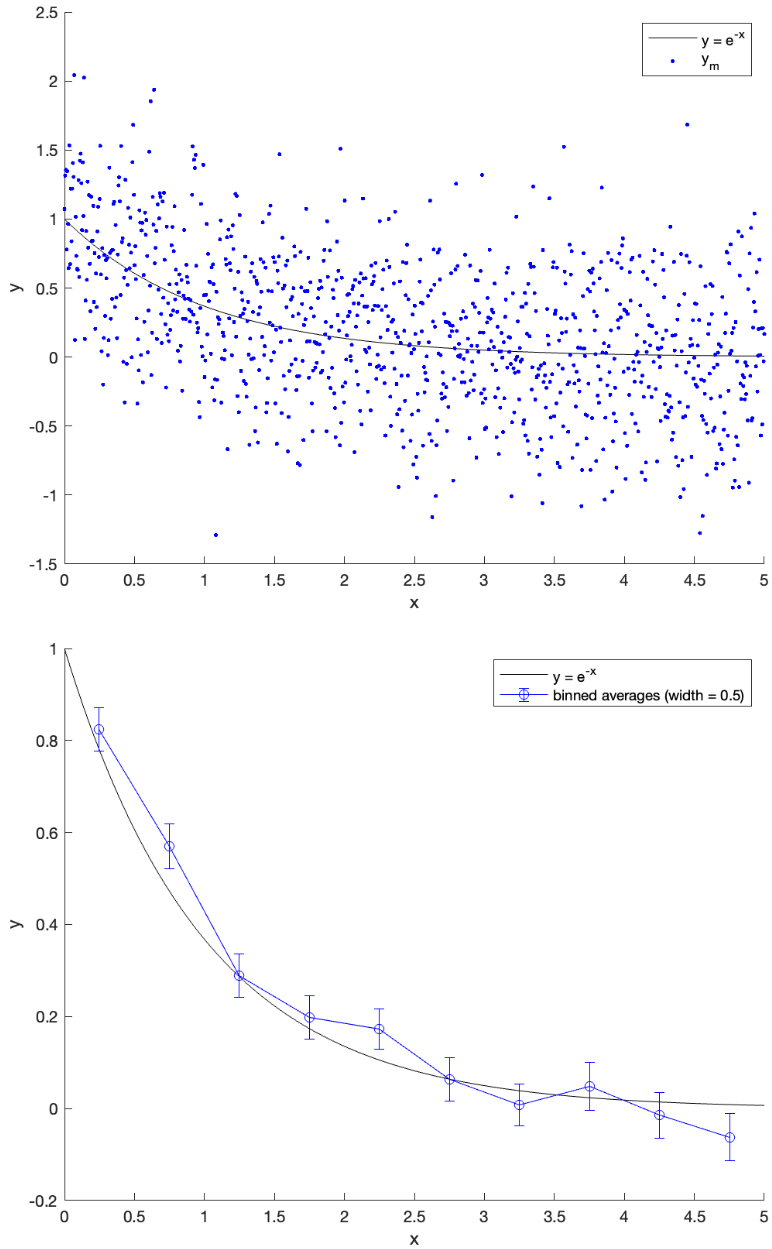

Figure 6: Top: function $y = e^{-x}$ (black curve) and synthetic measurements with added noise (blue points). Bottom: function $y = e^{-x}$ (black curve) and binned averages with errorbars (blue circles and lines).

3 Data lab part 1: plastics in the ocean

In the introduction to this project, we noted that plastics in the ocean tend to accumulate in subtropical gyres. During the fluids lab, we studied laboratory models of wind-driven gyres, and established that particles at the surface tend to accumulate at the center of gyres with specific wind patterns. During the first part of the data lab, we'll use observations of surface winds and sea surface heights, plus ocean particle tracks from the EsGlobe, to help connect results from the fluids lab with observed locations of ocean garbage patches.

3.1 Theory

During the data lab, we'll provide surface wind data from the NCEP/NCAR Reanalysis (a dataset that uses a combination of models and observations to produce a "best guess" estimate of winds over the entire globe from 1948 to present) and sea surface height data produced by the University of Hawaii based largely on measurements from satellite altimeters (instruments that measure the height of the ocean surface based on the return time of electromagnetic pulses).

The surface wind data provides wind velocities near the surface, which we'll visualize in a "quiver" plot that shows both magnitude and direction. Similar to the tank experiment, the near-surface wind produces a wind force acting on the surface ocean and induces an ageostrophic flow directed 90 degrees to the right (in the northern hemisphere) or the left (in the southern hemisphere) of the direction of the near-surface wind.

The sea surface height data provides measurements of deviations of the height of the free surface of the ocean from a reference "geoid" (the spherical equivalent of the reference parabolic surface from tank experiments), and can be used to infer pressure gradients and the geostrophic component of near-surface currents. If we adopt a local Cartesian coordinate system where x points toward regions where the sea surface height h is high and y is parallel to contours of constant h (Figure 7), then the geostrophic component v_g of the flow in the surface ocean (the flow that exactly balances near-surface pressure gradients) is given by

$$f v_g = g \frac{\partial h}{\partial y}. \tag{7}$$

(Remember: the Coriolis parameter f is positive in the Northern Hemisphere but negative in the Southern Hemisphere!) Note, also, that *the geostrophic component of the flow must be parallel to contours of constant sea surface height*. This is required because the pressure gradient force is perpendicular to contours of constant height, so the Coriolis force that balances the pressure gradient must also be perpendicular to height contours, which requires the flow that the Coriolis force acts on to be parallel to height contours.

As in the tank experiment, plastics in the surface ocean are affected by ageostrophic flows in balance with wind forces and geostrophic flows in balance with pressure gradient forces. By estimating the directions of the two components, we can try to identify locations where plastics are likely to congregate, and see if those correspond to the locations of ocean garbage patches.

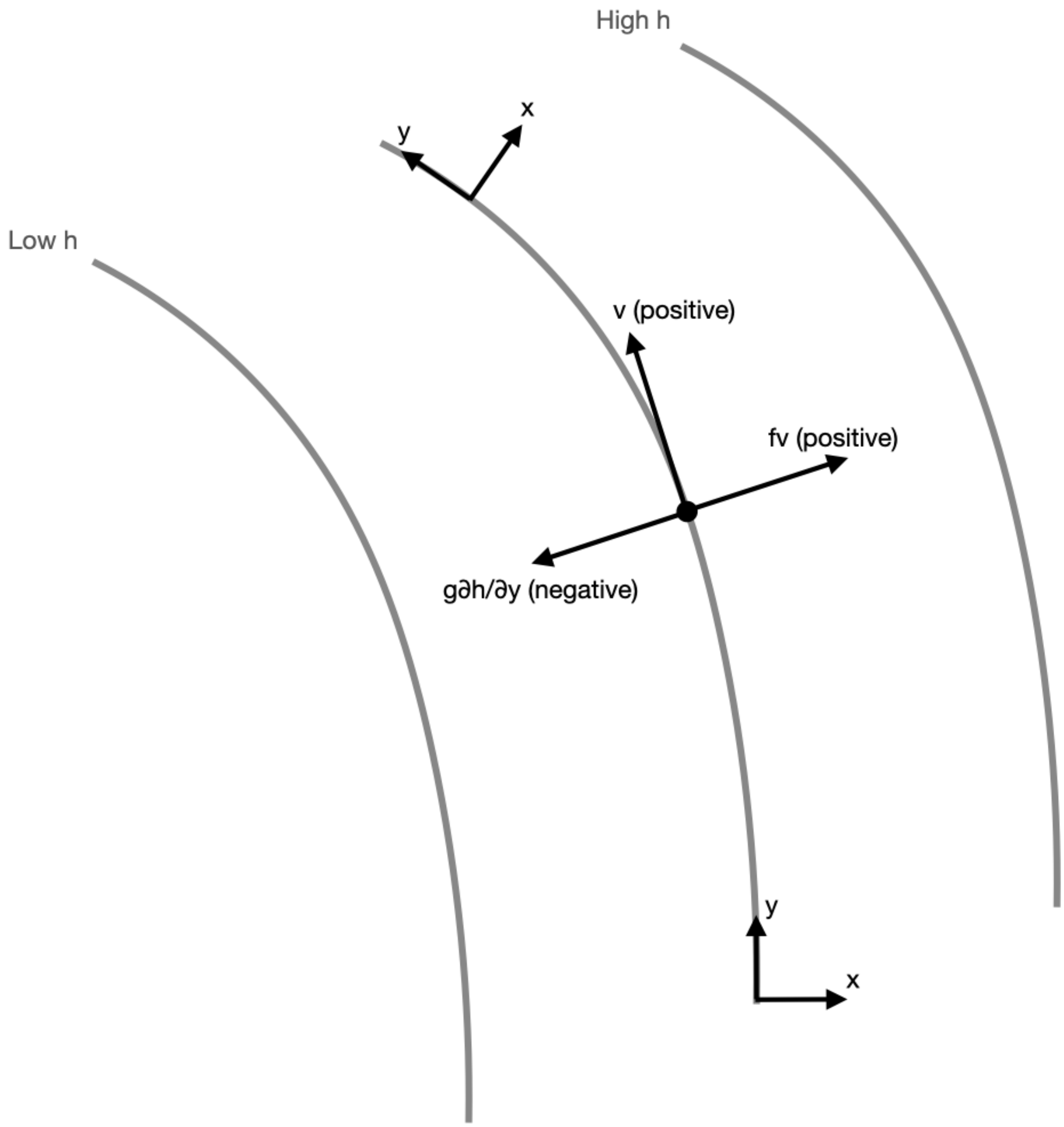

Figure 7: Force balance at low Rossby number in a local Cartesian coordinate system aligned with sea surface height contours. Gray lines show contours of constant height. Vectors labeled x and y show the orientation of the local Cartesian coordinate system at two locations. Other vectors show the velocity v of a parcel in geostrophic balance with the height field, and the pressure gradient and Coriolis forces acting on the parcel. Note: the signs and directions of velocity and force vectors are correct for the North Hemisphere, where f is positive, but not the Southern Hemisphere, where f is negative.

3.2 Warmup assignment

The data lab uses the MATLAB mapping toolbox. To install it (or check if it's already installed), go to the Home tab in MATLAB, click the arrow under Add-Ons, and select "Get Add-Ons". Search for "Mapping Toolbox", select it from the list of add-ons, then click "Sign in to Install". Enter your account information, then click "Install". Then:

1. Go to the course materials webpage, find the section for part 1 of the Project 2 data lab, and download the three netCDF (.nc) files (which contain surface winds from NCEP/NCAR reanalysis and sea surface height anomalies from the University of Hawaii dataset) and plot_ocean_data.m. Run plot_ocean_data.m. This should produce a plot (Figure 8) that shows climatological (i.e., long-term average) near-surface winds and sea surface height anomalies over and in the North Pacific. The script will save the plot in a file called ocean_data.png.
2. Go back to the course materials webpage and download example EsGlobe particle tracking data (example_esglobe_tracks.txt) and plot_esglobe_tracks.m. Run plot_esglobe_tracks.m. This should produce a plot (Figure 9 showing three particle tracks generated using EsGlobe. (Note: you'll generate your own tracks to analyze during the lab—this is just a check that you're able to plot them.) The script will save the plot in a file called example_esglobe_tracks.png.
3. Submit the two plots in a single PDF document on Canvas—or if something went wrong and you couldn't make the plots, submit a brief description of the problem, including any error messages.

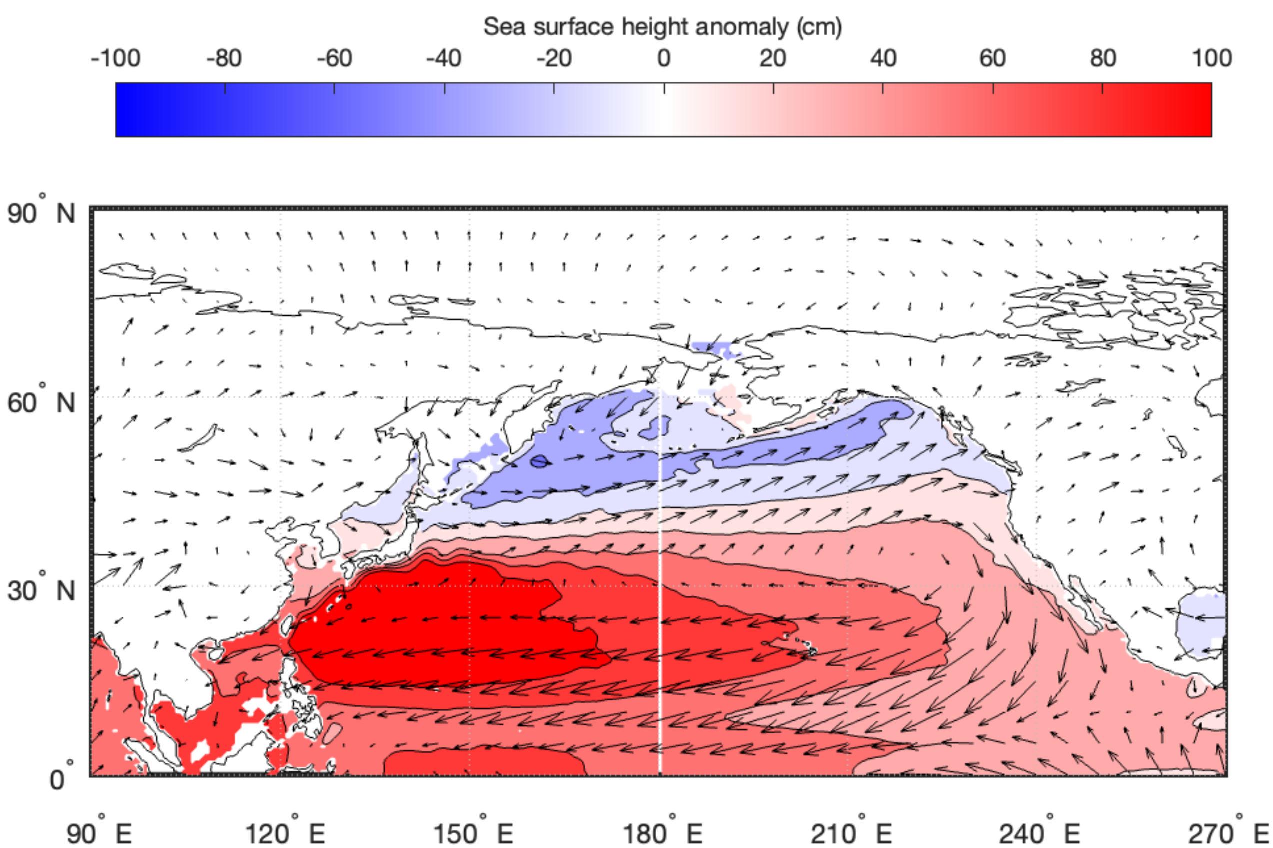

Figure 8: Climatological near-surface wind (vectors) and sea surface height anomalies (contours) over and in the North Pacific.

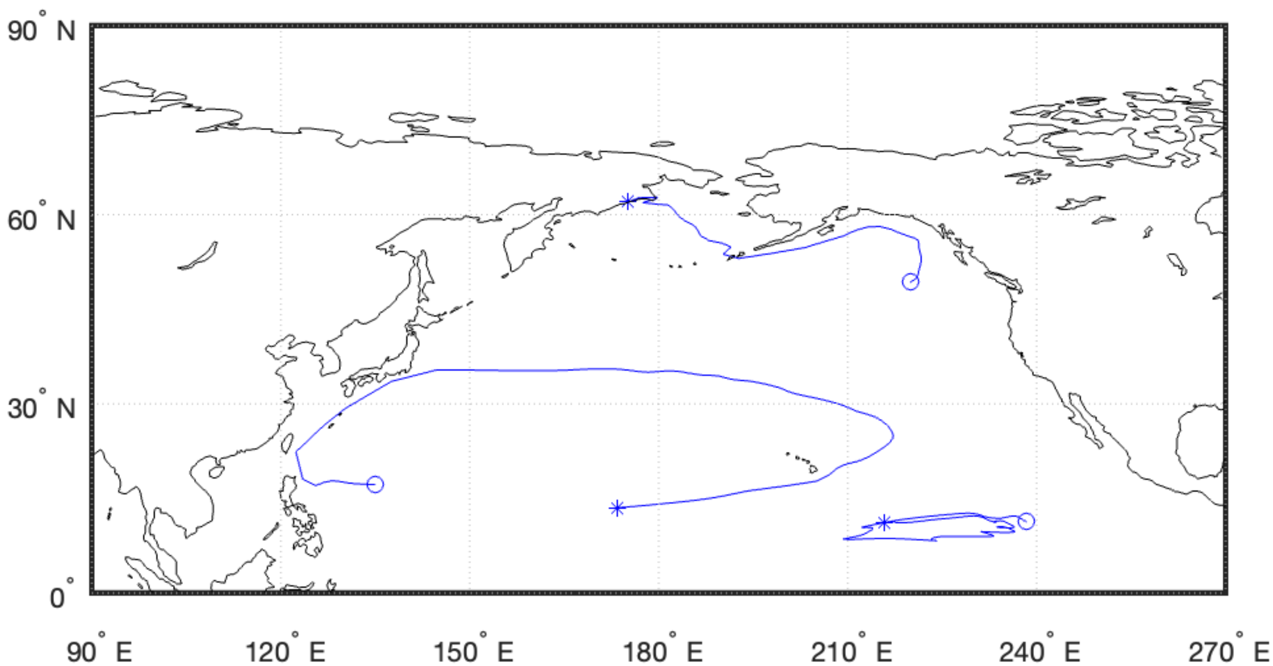

Figure 9: Example ESGlobe tracks in the North Pacific. Circles mark the start of tracks and stars mark the ends.

3.3 Your tasks:

1. Modify plot_ocean_data.m so that vectors show the direction of the wind-driven ageostrophic flow rather than the direction of the near-surface wind. Based on the direction of the wind-driven ageostrophic flow and the geostrophic flow (which follows contours of constant sea surface height), highlight regions where you expect plastics in the North Pacific to converge.
2. Go to the EsGlobe ocean particle tracking interface (detailed instructions in section 3.4), set the depth to 5 meters, and release particles from several locations somewhat offshore along the North Pacific coastline. Once the calculation has finished, download the tracking data.
3. Modify plot_ocean_data.m to overlay the 5m EsGlobe tracks on your plot showing the direction of the wind-driven ageostrophic flow. (Feel free to re-use code from plot_esglobe_tracks.m.) Save the resulting figure.
4. Go back to the EsGlobe, set the depth to 105 meters, and release particles from several locations along the North Pacific coastline. Once the calculation has finished, download the tracking data.
5. Modify your script to overlay 105m EsGlobe tracks on the plot of near-surface winds and sea surface height anomalies. Save the resulting figure.
6. Finally, modify plot_ocean_data.m to plot near-surface winds and sea surface height anomalies for a second subtropical gyre, then repeat steps 1-4 for the second gyre. (This will require adjusting the latitude and longitude limits of the plot to view the gyre, and releasing particles from coastlines surrounding that gyre.)

In your presentations and reports, compare results from ocean particle tracking with results from the laboratory gyre experiment and with observations of the location of plastics in the surface ocean. Do particles released at the surface (5 m depth) end up in locations where we observe plastic accumulating at the ocean surface? What determines these locations? Is this consistent with the fluids lab experiments? Finally, should we expect plastics in the subsurface ocean (∼100 m deep) to concentrate in locations where we observe plastics in the surface ocean? Why or why not?

3.4 EsGlobe ocean particle tracking

To access the EsGlobe ocean particle tracking interface, go to http://cmpo5.mit.edu/307, then select "Menu" → "Ocean particles". Dropdown menus at the top allow you to set the depth where particles are released and the background field displayed while particles are tracked. To set release locations of particles, click on the globe, then click "Go" to start tracking. You should see tracks appear starting from your release locations. Particle are tracked for 10 years, and the EsGlobe will plot a white dot after each month and a purple dot after each year. After tracking is complete, click "Get data". This will open a text file in a new browser tab; to save the file, right click and choose "Save Page As". If needed, you can clear the list of release locations by clicking "Clear".

4 Data lab part 2: volcanic ash in the atmosphere

During the second part of the data lab, we'll remain focused on the general theme of transport by large-scale flows, but we'll shift our focus from the transport of plastics in the surface ocean to the transport of volcanic ash in the atmosphere. More specifically, we'll use some simple theory based on geostrophic balance to "forecast" the dispersal of the ash plume produced by the 2010 eruption of Eyjafjallajökull, a volcano in Iceland. We'll focus on several days between April 16 and April 19, 2010, a period during which the plume shut down air travel over much of northern Europe.

4.1 Theory

The atmosphere is often close to geostrophic balance at large scales (where, as we discovered during Project 1, the Rossby number is usually small) and away from the surface, where drag is unimportant. As always, geostrophic balance requires a balance between pressure gradient and Coriolis forces. In tank experiments and the surface ocean, we typically express the pressure gradient force in terms of the derivative of the height of the water surface. In the atmosphere, we can do something similar and express the pressure gradient force in terms of the derivative of the height of a surface of constant pressure. If we denote the height of a surface with pressure p using h_p, and work in a local Cartesian coordinate system where y is aligned with contours of constant h_p (as in the first part of the data lab; recall Figure 7), geostrophic balance in the atmosphere requires

$$fv = -g\frac{\partial h_p}{\partial x}. \tag{8}$$

As in the ocean, geostrophic balance requires that the velocity v be directed along contours of constant pressure, and oriented so that the Coriolis force and pressure gradient forces are in opposite directions. Additionally, geostrophic balance allows us to estimate the speed of the flow by estimating the slope of the height surface ($\partial h_p/\partial x$). This will be the basis for our "forecast" of the location of the Eyjafjallajökull ash plume: we'll look at maps of the height of a pressure surface and the location of the ash plume, use the height surface to estimate the speed and direction of the flow (assuming the flow is in geostrophic balance), and then estimate where the flow will transport the ash plume over the subsequent day.

The data we'll provide for this part of the lab includes maps of the location of the ash plume from a NASA volcanic ash forecast model and heights of pressure surfaces from NCEP/NCAR reanalysis. Because the eruption plume reached heights of around 4 km on April 16-19, we'll estimate pressure gradients based on the height of the 600 mb pressure surface, which sits at heights of around 4 km.

4.2 Your tasks:

1. Go to the course materials webpage, find the section for part 2 of the Project 2 data lab, and download the three PNG files (which contain images of the ash plume from the NASA volcanic ash forecast model), the netCDF file (which contains the heights of pressure surfaces from NCEP/NCAR reanalysis), and plot_atmos_data.m. Run plot_atmos_data.m. This should produce a series of plots (Figure 10) showing the location of the ash plume from the Eyjafjallajökull eruption (shading) and the height of the 600 mb pressure surface (contours) over four days in April 2010. You'll have to manually select a few contours to label as the script runs—try not to select locations that hide the ash plume behind contour labels.
2. Use the height field around the location of the ash plume on April 16 to estimate the speed of the geostrophic flow. Based on this speed, estimate the time required for the ash plume to

make landfall over northern Europe. (Note: this will require converting between distances and changes in latitude and longitude—we can talk about how to do this in class if needed.) Is this estimate accurate?

3. Add vectors to the figures (by hand or using PowerPoint/Keynote/Illustrator is fine) showing the direction of the geostrophic flow at several locations within the ash plume on April 16-19. Can you use these vectors to explain, at least qualitatively, the pattern of ash dispersal? In particular, can you explain why some of the ash plume ends up over Europe, while other portions are transported westward towards North America?

In your presentations and reports, document your answers to the above questions, and discuss potential limitations of this approach to "forecasting" the dispersal of the ash plume. Is knowing the flow on a single pressure surface likely to be enough to accurately forecast the dispersal of a three-dimensional plume? Are there locations on these maps where you might expect the flow to deviate from geostrophic balance? What additional data might allow you to improve the forecast?

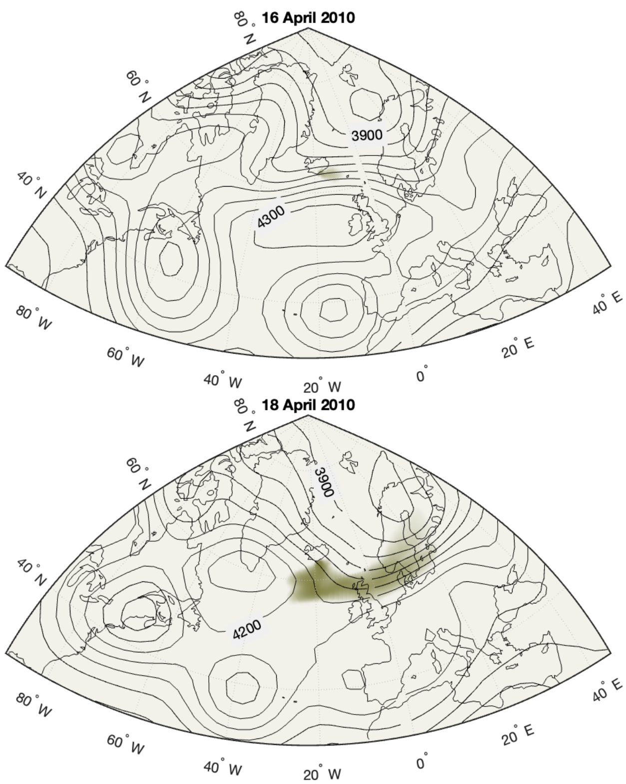

Figure 10: Eyjafjallajökull ash plume (shading) and height of the 600 mb pressure surface (contours, labels in meters, contour interval 50 m) over four days in April 2010.