3 Fluid Laboratory: Plastics in the ocean

3.1 Laboratory Experiment

Here we study the mechanism by which the wind blowing over the ocean brings it in to motion setting up patterns of surface convergence and divergence. We will induce cyclonic and anticyclonic circulation by blowing air over the surface of a rotating tank of water using fans co-rotating with the turntable, as sketched in Fig.11. The circulation, and its associated patterns of convergence and divergence, can be made visible through the use of dye crystals and paper dots. The experiment demonstrates that particles drifting on the surface of the ocean, such as plastics, are expected to become concentrated in regions of wind-driven convergence, such as the ocean's subtropical gyres. This is indeed where the great 'garbage patches' of the global ocean are found.

You can read about how to set up the experiment from the 'Weather in a Tank' project website here:
http://weathertank.mit.edu/links/projects/ekman-layers-introduction/ekman-pumping-suction-how-to

We will focus on the anticyclonic case sketched in Fig.12. Make sure that the fans are set up in the appropriate configuration!, as shown in Fig.11, left. The wind from the two fans blows over the water creating a circulation which has broadly the same sense as the wind. In the case of anticyclonic (clockwise) driving, there is a 'pile-up' of water in the middle, convergence and downwelling in the center, as sketched in Fig.12. In the limit of small Rossby number, the resulting outward-directed pressure gradient force — from high to low pressure — is balanced by the Coriolis force, resulting in anticyclonic geostrophic flow which extends downward in the fluid column all the way to the bottom. There is also an ageostrophic (meaning not geostrophic) component driven directly by the wind at the top and by the geostrophic flow rubbing against the tank bottom.

3.1.1 Activity

Anticyclone. Set up the experiments with the fans arranged to induce anticyclonic circulation, as shown in Fig.11(lhs). Leave the experiment running for 10 minutes or so to reach an equilibrium state. Then:

1. Introduce black paper dots to the surface and study their trajectories. Try inserting particles out toward the periphery and monitor how they move both around the tank and radially. Examples of some tracks are shown in Fig.13.

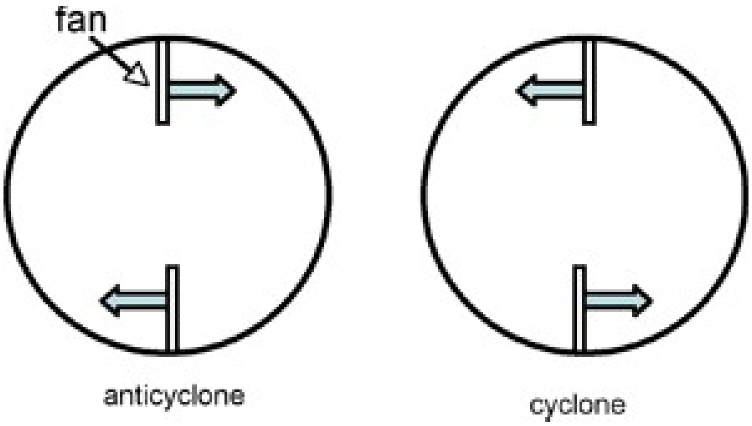

Figure 11: Cyclonic and anticyclonic circulation are induced by blowing air over the surface of a rotating tank of water using co-rotating fans.

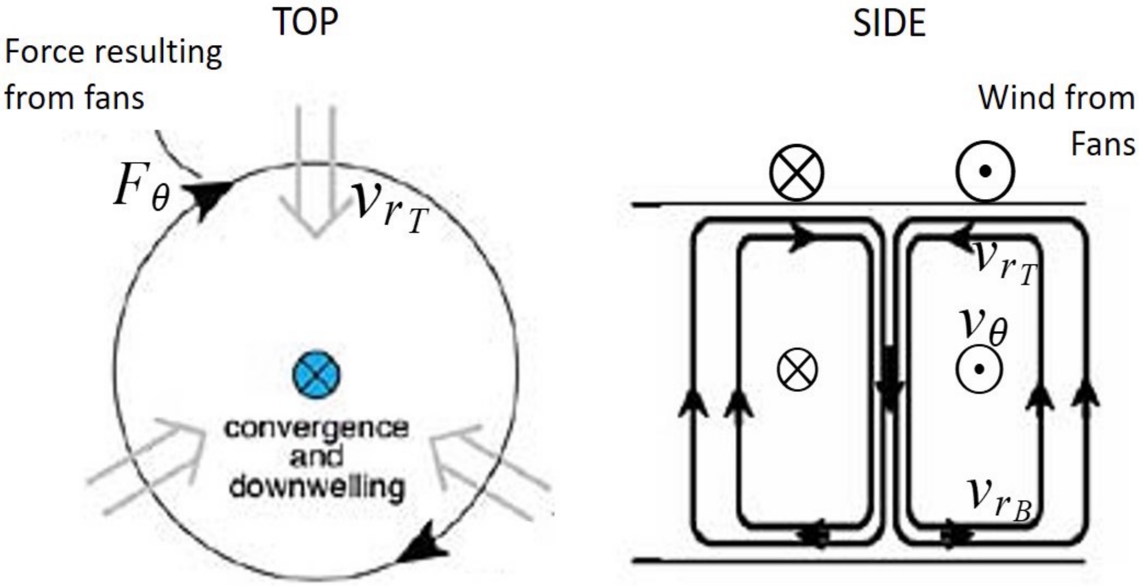

Figure 12: Fans blow air over the surface of water in a rotating tank resulting in a force F_θ being exerted. The water is brought in to motion creating currents v_θ in the azimuthal direction and a component v_r in the radial direction. The anticyclonic case is sketched here. On the left we show a view from the top, on the right a side view.

2. Attempt to track the particles with the particle tracker so that we can gather quantitative information. Estimate the Rossby number.
3. Introduce a (very few) crystals of potassium permanganate. From these attempt to measure:
   (a) flow speeds interior to the water column from the lateral translation of vertical streaks created by the crystals falling in the column.
   (b) the angle formed by dye plumes emanating from potassium permanganate crystals at the very bottom of the tank.

Fig.13 shows the trajectories of paper dots from our wind-driven ocean gyre experiment at early (top) and later (bottom) times. 10-second streaks are shown.

Cyclone. The activity is the same as the anticyclonic case, except the fans are arranged as in Fig.11(rhs).

3.2 Theory

The theory is an extension to that developed to understand the radial inflow experiment of Project 1.

3.2.1 Momentum balance

Let us adopt an (r, θ) coordinate system as sketched in Fig.14, just as in Project 1. We now write down the momentum equations in component from in the (r, θ) direction assuming that the Rossby number is small. Currents and symbols are defined in Fig.12.

At the top (subscript T for top)

$$\begin{aligned} -2\Omega v_{\theta_T} + g\frac{\partial h}{\partial r} &= 0 \quad \text{radial momentum equation} \\ 2\Omega v_{r_T} &= F_\theta \quad \text{azimuthal momentum equation} \end{aligned} \tag{8}$$

where h is the local depth of the water,[2] g is gravity, F_θ is the force in the azimuthal direction imparted to the water by the air-flow from the fans.

Note that:

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[2] We are referring here to the deviation of the free surface from the reference parabolic surface of the water in solid body rotation, $h = H - H_{\text{solid body}}$ — see notes in Project 1.

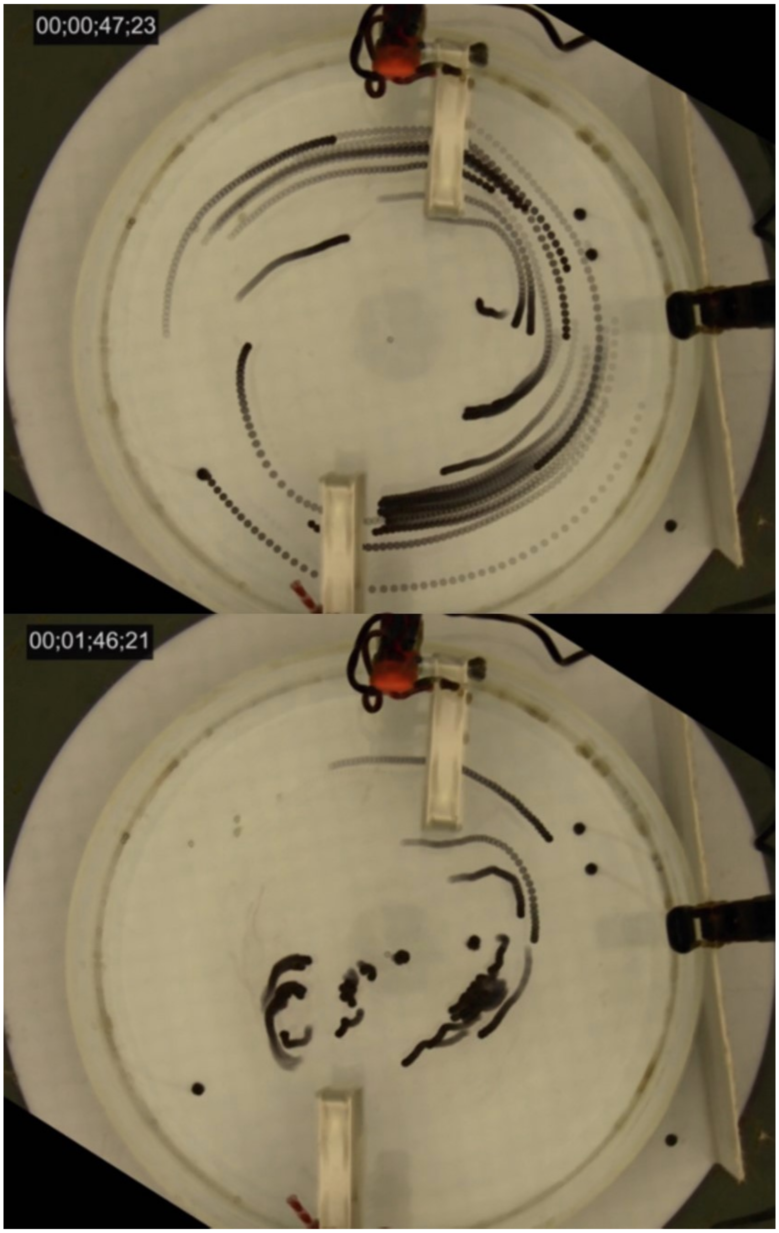

Figure 13: 10 second particle streaks from our wind-driven ocean gyre experiment at early (top) and later (1 minute later, bottom) times. Notice how the particles spiral inwards as time progresses.

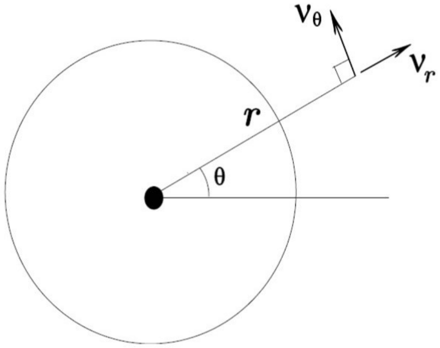

Figure 14: The (r, θ) coordinate system used to develop the theory. Note that in the anticyclonic case, $F_\theta < 0, v_\theta < 0, v_r < 0$ at the top and $v_\theta < 0, v_r > 0$ at the bottom.

1. The radial force balance is geostrophic, as in the small Rossby number limit of the radial inflow experiment — see Eq.(13) of Project 1 notes. The radial momentum equation does not have an applied force because we assume that the stress due to the air stream from the fans is entirely in the azimuthal direction.
2. The azimuthal force balance is between the azimuthal force due to the air stream from the fans, F_θ, and the Coriolis force acting 'to the right' of the radial current, v_{r_T}. Note F_r, the applied surface force in the radial direction, is zero. The azimuthal pressure gradient force is also zero because water cannot 'pile up' in the azimuthal direction.

At the bottom (subscript B for bottom)

$$\begin{aligned} g\frac{\partial h}{\partial r} - 2\Omega v_{\theta_B} &= -\varepsilon v_{r_B} \\ 2\Omega v_{r_B} &= -\varepsilon v_{\theta_B} \end{aligned} \tag{9}$$

Note that in Eq.(9) we have expressed the effect of the flow rubbing over the bottom of the tank as a linear drag depending on the strength of the bottom flow and a drag coefficient ε:[3]

$$\mathbf{F}_B = -\varepsilon \mathbf{v}_B, \tag{10}$$

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[3] Vagn Ekman developed a theory of the boundary layer in which he set $\mathbf{F} = \nu \frac{\partial^2 \mathbf{u}}{\partial z^2}$ in Eq.(10) where ν is the viscosity. He obtained what are now known as 'Ekman spirals' in which the current spirals from its most geostrophic to its most ageostrophic value. But such details depend on the precise nature of $\mathbf{F}$, which in general is not known. Qualitatively, the most striking and important feature of the Ekman layer solution is that the currents in the boundary layer have a component directed toward lower pressure; this feature is independent of the *details* of the turbulent boundary layer.

with the minus sign ensuring that $\mathbf{F}$ acts as a drag on the flow.

Note that at the top v_{θ_T} is entirely geostrophic and flows parallel to h contours: v_{r_T} is entirely ageostrophic and is directed outwards across h contours. The flow at the bottom, $\mathbf{v}_B = (v_{r_B}, v_{\theta_B})$ has both geostrophic and ageostrophic components.

Solving Eq.(9) gives:

$$v_{\theta_B} = \frac{1}{1+\left(\frac{\varepsilon}{2\Omega}\right)^2} v_{\theta_T}; \ \frac{v_{r_B}}{v_{\theta_B}} = -\frac{\varepsilon}{2\Omega} \tag{11}$$

Note that v_{θ_B} is *less* than the geostrophic value v_{θ_T}; v_{r_B} is directed down the pressure gradient, from high to low pressure. Note that by comparing v_{θ_B} to v_{θ_T}, we can infer $\frac{\varepsilon}{2\Omega}$ and hence ε since Ω is known.

We can obtain an expression for F_θ by noting that mass continuity tells us that $v_{r_T} + v_{r_B} = 0$ and so, from Eqs.(8&9)

$$F_\theta = \varepsilon v_{\theta_B}. \tag{12}$$

Thus the stress acting at the surface, F_θ, can be inferred from v_{θ_B}.

3.2.2 Interpretation of laboratory experiment in terms of theory

Key measurements to take are:

1. v_{θ_T} and v_{r_T} from tracking paper dots.
2. v_{θ_T} from the lateral displacement of vertical streaks in the water column
3. the angle of the spiral pattern of permanganate plumes on the bottom, which will yield the ratio v_{r_B}/v_{θ_B} from Eq.(11) and hence ε.

Interpret your observations in terms of the theoretical predictions given by Eqs.(11, 8b & 12).

3.3 Transport of particles in the global ocean and the dynamics of 'garbage patches'.

We use EsGlobe to explore the patterns and timescales of ocean circulation and how ocean currents transport properties around the globe. Trajectories are computed from flow fields obtained by blending global observations of the ocean with an ocean model. We will contrast the trajectories of particles released in the surface ocean to those released in the near-surface interior ocean. The former enable us to detect regions of surface divergence and convergence. We will see that the subtropical gyres of the oceans are regions of surface convergence and so might be expected to be places where particles accumulate. This is highly relevant to the formation of the great garbage patches of the world ocean. Clear contact points can be made with the wind-driven ocean circulation experiment described above in Section 3.2.

EsGlobe supports an 'ocean tracker' which enables one to launch virtual particles in to an evolving ocean circulation and track them around. The tracker allows one to launch particles at a depth of 5m (equivalent to the surface), 55m and 105m — see Fig.15 for an example. Particles launched at the surface will be under the direct influence of the wind blowing over it and so will be carried by both geostrophic and ageostrophic currents. Lower down in the water column — e.g. at 105m — the direct driving of the wind will not be felt and one might expect the flow to be geostrophic.

Our activity comprises two parts:

1. Exploration of space scales and timescales of ocean circulation in the interior, subsurface ocean.
2. Exploration of trajectories at the surface of the ocean. This is of relevance to the fate of floating plastics in the surface ocean.

To interpret your trajectories in the context of the general circulation of the ocean, if you have time you can inspect key observed properties of ocean circulation — currents, winds, temperature, salinity etc — also using the EsGlobe.

3.3.1 Space scales and timescales of interior ocean circulation

Launch particles (both single and multiple) in to the interior ocean (depth of 105m) to explore typical space and timescales.

Focus on the:

- North Atlantic

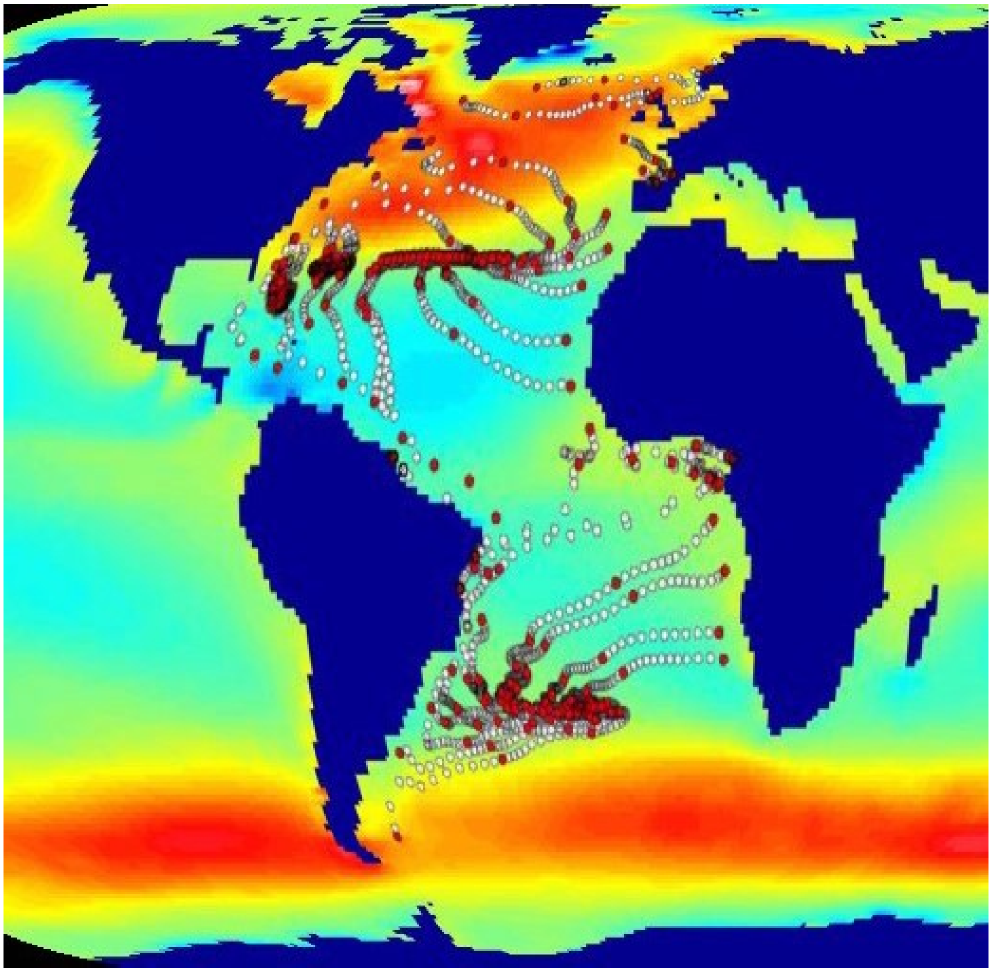

Figure 15: Trajectory of particles launched in to the surface of the Atlantic ocean from places around the coasts. White dots are plotted every month along the trajectory, red particles every year. The background color indicates the pattern of prevailing windstress: red eastward, blue westward.

- North Pacific
- Southern Ocean and Circumpolar flow around Antarctica.

White dots represent the position of particles after 1 month, red dots after one year.

Can you identify closed circulation patterns? These are known as ocean gyres — you can find them in subtropical and subpolar regions in all the major basins, both in the northern hemisphere and the southern hemisphere.

What are typical space and time scales?

Use them to estimate $R_{timescales}$ — Eq.(1) of Project 1 notes — and hence the Rossby number appropriate to an ocean gyre. Is it large or small?

Is the interior flow in geostrophic balance?

3.3.2 Trajectories of particles in the surface ocean

Launch particles (both single and multiple) in to the surface ocean (depth of 5m) to explore typical space and timescales.

In which ways are the trajectories similar and/or different from the subsurface ones?

Launch particles in to regions where the wind stress is predominantly from west to east, colored red in Fig.15? What do you observe?

And east to west: colored blue in Fig.15?

Can you make contact points with your laboratory experiment in which the stress was created by fans?

Contrast the behavior of particles released in to wind belts in the SH vs the NH. Do you notice any difference?

Creating 'garbage patches' Launch particles in to the ocean basins from their margins representing the entry of particles in to the ocean from the continents.

- Track them and determine regions where the particles preferentially congregate.
- Why do the particles congregate in these particular places? What is special about them?

3.3.3 Laboratory, real-life connections

Fig.13 shows the trajectories of paper dots from our wind-driven ocean gyre experiment at early (top) and later (bottom) times. 10-second streaks are shown.

Discuss:

- ways in which the laboratory experiment is a good/poor analogue of the behavior of your virtual trajectories driven by observed ocean currents.
- how you might improve the laboratory experiment to make it a truer analogue?