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Project 1: Weather Extremes and Vortex Flow

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Abstract

We study extreme vortices in the atmosphere associated with hurricanes and intense blizzards, and explore the dynamical principles that underlie their structure. First we set up a spinning vortex in our fluids laboratory using a rotating turntable. By changing the rate of rotation of the turntable, we can study the influence of rotation on the vortex and set up analogues of atmospheric vortices. Second, building on what we have learned we study the observed structure of intense cyclones and hurricanes using meteorological observations. The non-dimensional number that we use to connect the laboratory vortex to the atmospheric vortex, is known as the Rossby number, and is a measure of the importance of rotation on the vortex motion.

1 Background and introduction

Extreme weather is associated with intense wind systems that can be seen on daily weather maps: tropical cyclones, hurricanes, intense middle latitude cyclones and severe winter storms. For example, Fig.1 shows Category 5 Hurricane Maria which devastated the island of Dominica on the night of September 18, 2017 and was headed for landfall on the heavily populated island of Puerto Rico on September 20, 2017. At the same time, a weakening Hurricane Jose approached the New England coast as it transitioned into a nor'easter-like extratropical storm bringing severe weather to Boston.

As we shall see, all these systems are profoundly affected by the fact that the Earth is rotating. Such phenomena are able to concentrate Earth's spin in to local, extremely intense swirling wind patterns, which can have devastating impacts on coastal communities should they reach landfall.

Let us consider how the timescale associated with the swirling wind patterns compares to that of the period of rotation of the Earth. We will define a non-dimensional number,

Figure 1: Hurricanes Maria and Jose heading toward, respectively, Puerto Rico and New England, during September 2017.

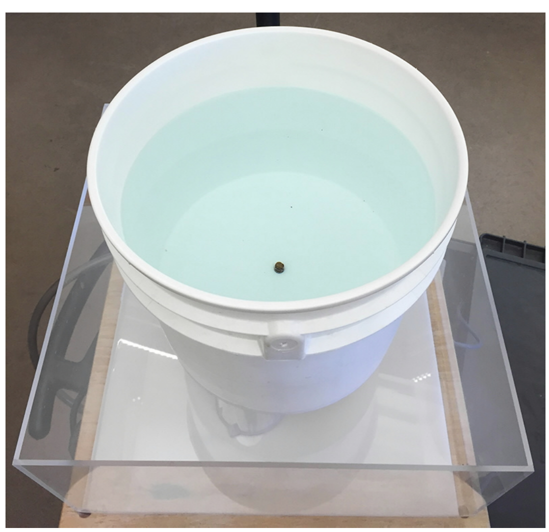

Figure 2: Apparatus used to create a fluid vortex in the laboratory. Water flows out through the hole at the center of a bucket which is rotating about its vertical axis. The bucket drains in to a tank which is seated on a rotating turntable.

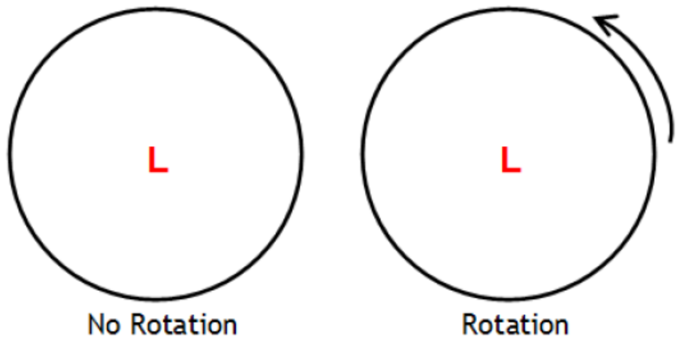

Figure 3: The bucket on the left is filled with water and sitting on the bench (and so not rotating) whereas the bucket on the right is on a turntable which is rotating counterclockwise. Sketch the expected trajectory of a particle of fluid as it exits from the hole at the center of the bucket, labeled L for 'low pressure'.

$R_{timescales}$, a ratio of two time scales — the period of rotation of the Earth (or the rotating tank in our laboratory analogue) and the timescale of the vortex:

$$R_{timescales} = \frac{\text{rotation period of the Earth (or turntable)}}{\text{time scale of the flow}}. \tag{1}$$

If $R_{timescales} << 1$, then the time scale of the vortex is much longer than that of Earth's rotation period, and the dynamics is profoundly influenced by the rotation of the system. However, if $R_{timescales} >> 1$, then the timescale of the vortex is much shorter than Earth's rotation period, and rotation is not important.

We now introduce some of the ideas in the following simple, but highly instructive laboratory experiment. A bucket of water with a hole in the middle but with a stopper in place to keep the water escaping (as shown in Fig.2), is placed on a rotating turntable. Upon unplugging the hole, water exits from the bucket setting up a pressure gradient with low pressure at the center denoted by the 'L' in Fig.3, and higher pressure on the periphery. This pressure gradient force is directed radially. Sketch the trajectory of a water parcel as it exits from the bucket when the bucket is not rotating and when the bucket is rotating.

1.1 Setting up a vortex in the laboratory

We are now going to carry out the experiments that you just visualized and see whether your predictions are correct! The apparatus comprises a plastic cylinder – a bucket — filled most of the way with water and with a stoppered hole in the center. We consider two cases, one in which the bucket is on a bench (and so not rotating) and one in which the bucket is on a turntable, spinning in an anticlockwise direction to represent the turning of the Earth.

Once the hole is unplugged, a pressure gradient will develop with lower pressure over the hole thus driving the water out of the bucket. Our goal is to note the trajectories of water parcels as they exit the tank and to calculate $R_{timescales}$, given by Eq.(1), at 3 different radii.

For each trial, we release a paper dot:

1. near the outer rim of the bucket (but not touching the edge),
2. at an intermediate radius,
3. close to the center.

What is the trajectory of particle in the two trials, and how does it compare to your predictions?

Note how, in the rotating case, water flows inward toward the axis of rotation acquiring an anticlockwise swirling motion which gets more and more vigorous as it approaches the center of the cylinder. Can you figure out why this happens?

Using your stopwatch and the video monitor, estimate the time it takes the paper dot to complete one revolution — we can use this as an estimate of the 'timescale of the motion'. Take note of the rotation rate of the rotating table and from this compute the period of rotation.

We estimate $R_{timescales}$ from Eq.(1) at three different radii:

$$R_{timescales\_outer} = \dots\dots\dots$$
$$R_{timescales\_middle} = \dots\dots\dots$$
$$R_{timescales\_center} = \dots\dots\dots$$

Where is $R_{timescales}$ large, small, and order unity? What does this tell us about the varying influence of rotation across the vortex?

Notice how the surface of the water plunges down toward the center of the cylinder resulting in a pressure gradient force directed radially inward. What outward force is balancing this inward pressure gradient force?

In the laboratory component of Project 1, which we now describe, we will carry out this experiment more carefully, and explore it in more detail, and develop some theory to go along with it. This will then help us interpret meteorological observations of intense vortices.