12.307: Project 3
Heat and Moisture Transport in the Atmosphere

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1 Introduction

The atmosphere is warm and moist in the tropics, cold at dry at the poles. The equator-to-pole temperature gradient drives atmospheric winds which carry heat and moisture from the equator to the pole, offsetting the imbalance. Because the timescale of the resulting winds is days rather than hours, the Rossby number is small and the motion is strongly influenced by the rotation of the earth.

We will carry out a series of laboratory experiments and explore meteorological data to illustrate how the tropical Hadley Circulation and middle latitude weather systems work together to transport heat and moisture from the tropics toward the poles. Along the way we will learn about the underlying mechanisms that lead to "storms" and "weather". What causes relatively warm temperatures one day and cold the next? Why are weather systems there and what is their role in the global climate?

As sketched in Fig.1, the two primary "ingredients" required to create weather are:

- Earth's rotation, Ω
- differential heating, ΔT, (i.e. warming of the equator, cooling of the pole)

In this project we explore the interplay of these two factors in controlling atmospheric circulation and its weather patterns.

On the Earth, we observe two distinct regimes:

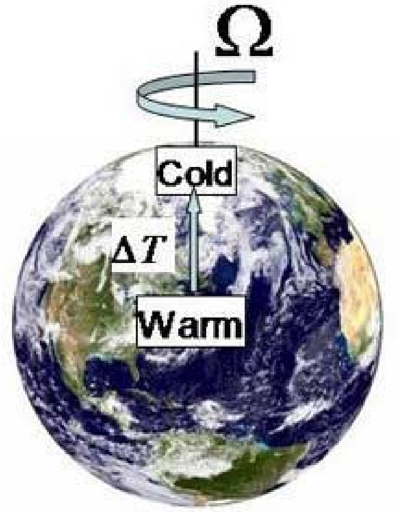


Figure 1: A schematic of the two major ingredients controlling the general circulation of the earth atmosphere: ΔT the pole-equator temperature gradient and Ω the rotation of the earth.

1. the tropical circulation at low latitudes, where the Earth's rotation vector does not have a large component in the direction of gravity and rotation has a less effect on the motion. Here Ω is small. This circulation is sometimes called the Hadley circulation, from Hadley (1735), who was the first to discuss it.

2. the extra-tropical circulations at high latitudes, where the effect of rotation is more pronounced. Here Ω is large.

We can study both regimes in the controlled setting of the laboratory. The pole-equator temperature gradient can be represented by "chilling" the water near the center of a tank of water (the pole). The tank is placed on a turntable to capture rotation, as shown in Fig.2, and rotated slowly to represent the tropics and faster to represent middle latitudes.

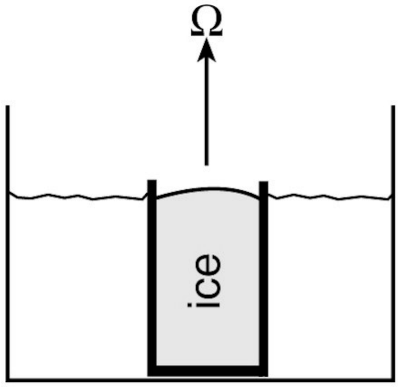


Figure 2: The laboratory set up of the general circulation experiment. A cylindrical tank of water, containing a can of ice at its center, is placed on a turnatable. The ice represents the cold poles. The water in the tank represents the atmosphere. The spinning turnatable represents the rotating Earth.

1.1 Laboratory illustration

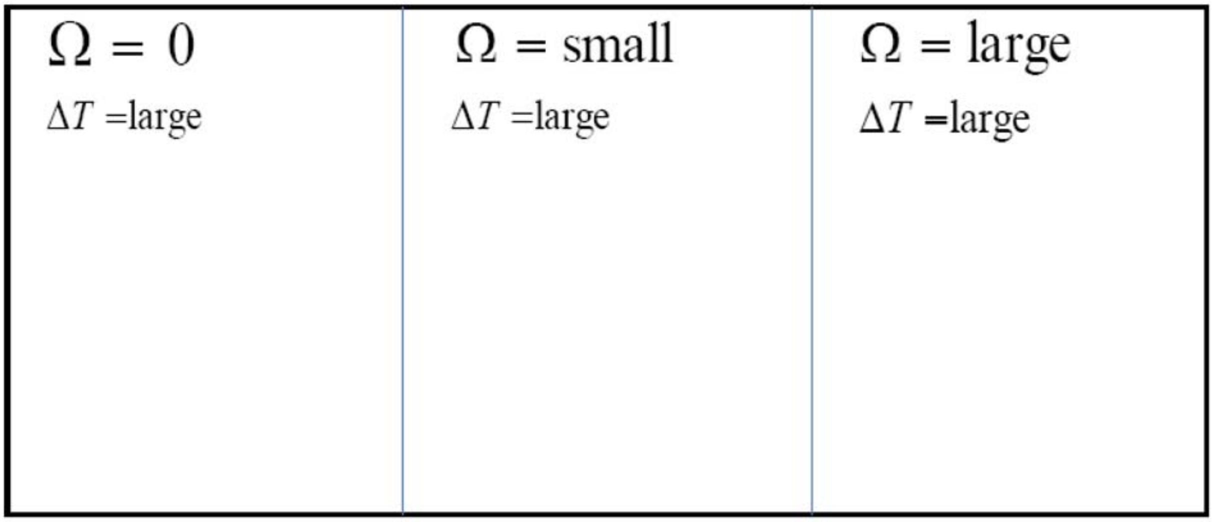
In this introductory class, we will perform a set of three experiments, as presented in the matrix in Fig.3.

1. $\Omega = 0 \quad \Delta T = \text{large}$
2. $\Omega = \text{small} \quad \Delta T = \text{large}$
3. $\Omega = \text{large} \quad \Delta T = \text{large}$

Before each experiment we will make predictions by sketching (filling in the matrix, Fig.3) what we expect the flow patterns to look like and comment on our reasoning.

After each experiment, we'll sketch what we see and rationalize the flow patterns. What part of the atmosphere is the experiment most reminiscent of?

A more detailed description of the experiments can be found here:
http://weathertank.mit.edu/links/projects/general-circulation-an-introduction



$\Omega = 0$	$\Omega =$ small	$\Omega =$ large
$\Delta T =$large	$\Delta T =$large	$\Delta T =$large

Figure 3: The matrix of three experiments, investigating the effect of rotation and temperature difference. Ω is the rotation rate and ΔT, the temperature difference between water next to the ice can (representing the Pole) and water at the periphery (representing the equator), as sketched in Fig.2

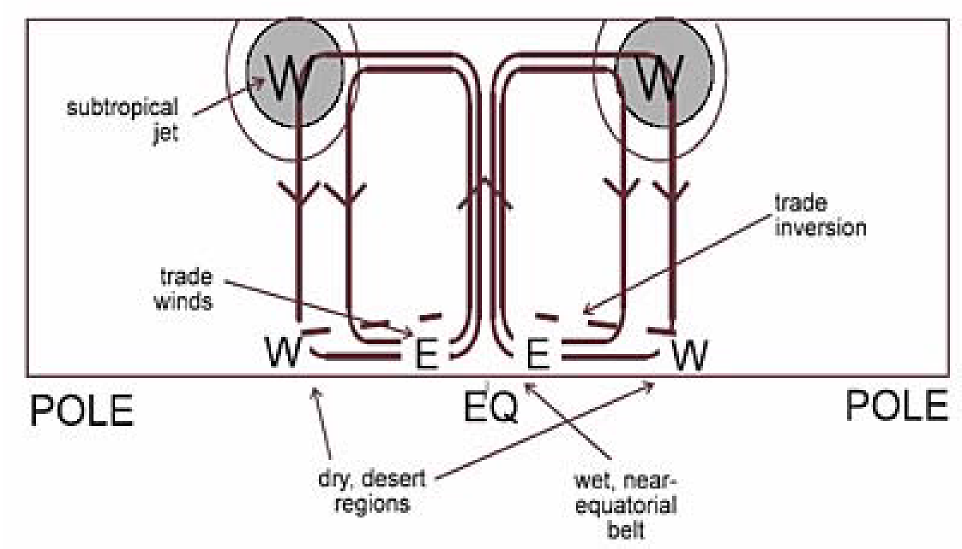


Figure 4: A schematic of the Hadley Circulation and its associated zonal flow and surface circulation. Westerlies are marked W; easterlies E.

1.2 Atmospheric Hadley Circulation and Weather Systems

We can use atmospheric data to compare the above experiments to the observed regimes on Earth. Here is a brief summary of what we observe.

1.2.1 The Tropical Hadley Circulation

A schematic diagram of the annually-averaged Hadley cell, typical of the tropical regions (Ω small), is shown in Fig.4. Upper level, poleward flowing air, is deflected eastward by the Coriolis force to form the westerly subtropical jets in both hemispheres with predominantly eastward flow at the surface (i.e. surface westerlies). Equatorward motion near the surface is deflected westwards (i.e. to form surface easterlies) creating the trade winds. Subsidence in the subtropics creates warm, dry desert regions through adiabatic compression of dry upper tropospheric air. Many of the desert regions around the globe coincide with the sinking branch of the Hadley circulation.

1.2.2 Extra-tropical Circulation

Although the simple Hadley cell model depicted in Fig.4 describes the tropical regions quite well, it predicts little action in middle and high latitudes. There, the powerful constraints of rotation are dominant, and there can be no meridional circulation. The midlatitude atmosphere is full of *eddies*, which manifest themselves as traveling storm systems. Where do they come from? The observed state is *unstable* through a process known as *baroclinic instability*, which can be readily seen in our laboratory experiment. Through this instability, longitudinally asymmetric motions are generated, within which air parcels are exchanged along sloping surfaces.

The process of baroclinic instability is responsible for the genesis of the ubiquitous waviness of the midlatitude flow; these waves often form closed eddies, especially near the surface, where they are familiar as the high and low pressure systems that control most of our weather. In the process, they also effect the poleward heat transport required to balance the energy budget. The eddies "stir" the atmosphere, tending to minimize the equator-to-pole temperature contrast.

So, in cartoon form, our picture of the low- and high-latitude energy balance looks as shown in Fig.5. Together, these two components of the general circulation effect the poleward heat transport implied by the equator-to-pole radiative imbalance.

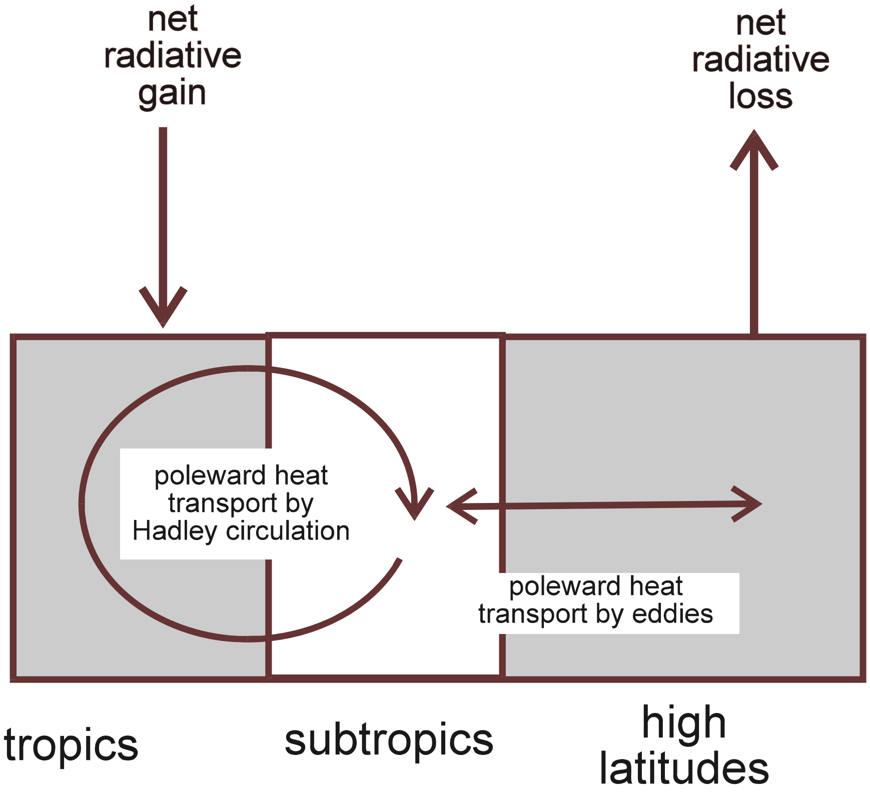


Figure 5: Schematic of tropical and extra-tropical circulation. transport occurs through the agency of the Hadley circulation in the Tropics and synoptic (weather) systems in middle latitudes.