Stratosphere-Troposphere Exchange and The General Circulation

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1 Introduction

Atmospheric circulation is important for mass exchange and mixing of chemicals between layers of the atmosphere. These processes are responsible for moving material vertically, such as ozone and water vapour, as well as to and from the poles. In this project, we explore, through simulations, the general circulation in our atmosphere, and the three-cell system.

1.1 Troposphere

The Troposphere is from the ground to anywhere between 8 - 18 km depending on the latitude (Mohanakumar, 2008). The troposphere is the densest part of the atmosphere containing about 85% of the atmosphere's mass and essentially all the water vapor in our atmosphere (Marshall and Plumb, 2016).

Figure 1 shows the atmospheric temperature profile based on the US Standard Atmosphere (NASA, 1976). In the troposphere, the temperature drops from a value of about 15°C at Earth's surface steadily with height till a minimum value of about -55°C to -60°C is reached at the tropopause (Saha, 2008). Tropopause occurs at a potential temperature of about 373 K, although other criteria are sometimes used (Holton et al., 1995). The tropopause is a region

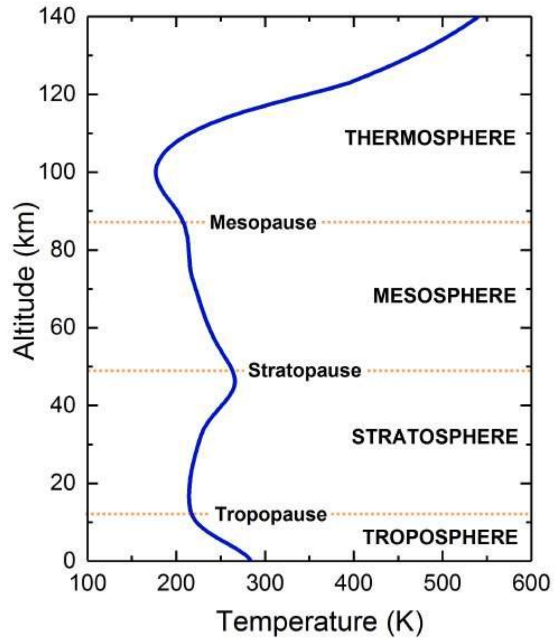

Figure 1: The atmospheric temperature profile based on the US Standard Atmosphere values.

in which the environmental lapse rate changes from positive in the troposphere to negative in the stratosphere. Due to this, as well as the high stability of the stratosphere the vertical mixing between the troposphere and the stratosphere is strongly inhibited.

1.2 Stratosphere

The stratosphere is between the tropopause and 50 km (Mohanakumar, 2008). In this layer the temperature increases gradually with altitude and reaches a temperature around 0°C near its upper boundary due to the presence of ozone which absorbs ultra-violet radiation from the Sun (Saha, 2008). The stratosphere is dynamically stable since warm air sits on top of the cooler air resulting in less convection and turbulence throughout this layer. However, the stratosphere is a region that has strong radiative, dynamical, and chemical interactions in which horizontal mixing much more rapid than vertical mixing.

2 Global Atmospheric Circulation

Global atmospheric circulation is the process of redistribution of thermal energy due to the difference of in temperature at the equator and the poles (Mohanakumar, 2008). In this global atmospheric circulation, air moves from areas of high pressure to areas of low-pressure creating winds across the planet. The structure of these planetary winds depends mainly on the latitudinal variation of atmospheric temperatures, the distribution of land and oceans, pressure belts, Coriolis effect of earth, etc (Mohanakumar, 2008). These atmospheric circulations affect the circulation of ocean currents as well, thus controlling the climate of our atmosphere.

Due to the difference between the surface temperatures hot air rises through convection and reaches the top of the troposphere up to an altitude of 14 km and moves towards the poles (Wallace and Hobbs, 2006). This accumulated air will eventually cool and descend towards the surface thus reaching the equator as easterlies. This type of circulation is referred to as cells. The circulation of our planet can be represented by a three-cell model. In the tropics this convective process creates Hadley cells that starts from the equator and reaches 30° latitude. In the midlatitudes the circulation is that of descending cold air that comes from the poles and the rising warm air that blows from the subtropical high giving rise to westerlies at the surface, and such circulations can be explained through Ferrel cell. Near the polar regions cold air sinks near the poles and blows towards middle latitudes as easterlies forming polar cells.

2.1 Hadley Cell

One of the very first attempts to account for the global circulation in terms of simple physical based models was proposed by George Hadley (Hadley, 1735). He proposed that trade winds were a part of a large-scale circulation that occurred due to latitudinal distribution of solar heating (Hadley, 1735).

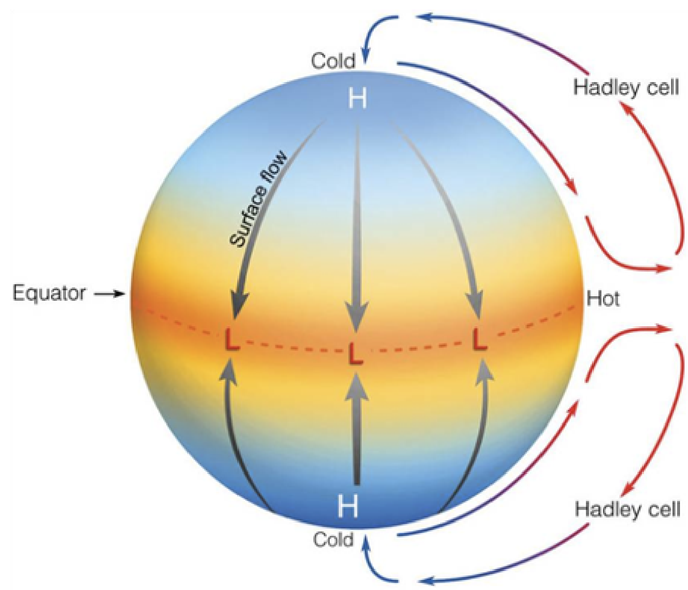

Figure 2: Schematic of the Hadley Cell. Warm air rises near the equator and flows poleward where it cools and descends back to the surface of Earth in the subtropics, and flows back towards the equator at the surface of Earth

Figure 2 shows a schematic sketch of a Hadley cell. As shown in the above figure, each hemisphere has a single wind system in which there is westward and equatorward flow near the surface and eastward and poleward flow at higher altitudes. Near the equator, the tropical regions receive more sunlight and therefore warm air rises near the equator. Once the rising air reaches the top of the troposphere, it flows poleward and loses heat to the cold air present near the poles. Finally, this cool and dense air drops down equatorward at low levels until it nears the Equator where it warms up and rises again thus continuing the cycle. One of the biggest shortcomings of the Hadley model was that it ignored the Coriolis effect of the Earth's rotation which has considerable effects on the general circulation. Because of this the Hadley model was unable provide explanations for the westerly winds (reversed circulation in comparison to Hadley cell) that was observed in the midlatitudes. One of the very first attempts to address the shortcomings of Hadley's theory was done by William Ferrel who proposed the Ferrel cell to account for the westerly winds observed in the midlatitudes.

2.2 Ferrel Cell

The Ferrel cell is a circulation pattern that was proposed by the American meteorologist William Ferrel (1817-1891) that accounted Earth's rotation in wind systems. He was able to mathematically provide explanations to the reverse circulation that was observed in the midlatitudes. He showed that the rotation of the planet could make winds move in circles thus resulting in cyclones that pull winds from warmer regions towards the polar front which drives the westerly winds (Ferrel, 2020). Unlike the other cells, the Ferrel cells are not driven by temperature. The Ferrel cell is largely driven by the energy given by the Hadley and the Polar cell. Ferrel cells flow in opposite directions compared to the Hadley and the polar cell giving rise to semi-permanent areas of high and low pressure in the atmosphere. In latitudes where air is rising it creates low pressure regions giving rise to high rainfall whereas in regions where air is descending it creates high pressure regions that leads to less rainfall. This is the reasons why we see more tropical forests towards the equator and more desert areas closer to 30° latitude.

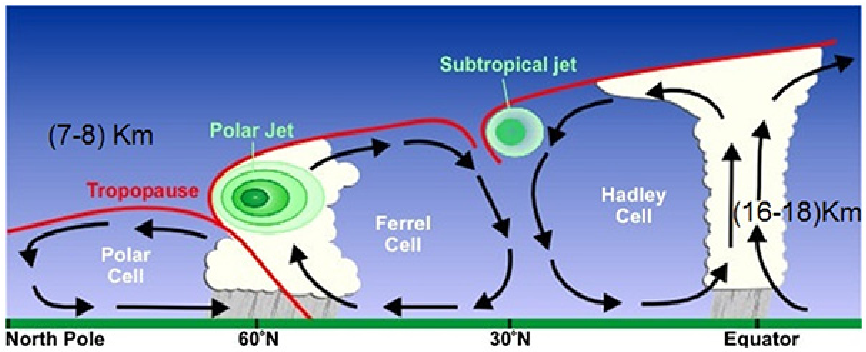

Figure 3: Schematic of the Earth's three cell structure. Hadley and Polar cell is driven by surface temperatures while Ferrel cell is largely driven by the energy given by the Hadley and the Polar cell

2.3 Polar Cell

The Polar cell is much like the Hadley cell where the circulation is driven by surface temperatures. It is the smallest and weakest cell extending between 60° and 70° latitude. Warm air rises around 60° latitude, and they move towards the pole where it cools down and descends creating dry high pressure area. When it reaches the polar surface, it is finally driven towards 60° latitude. Figure 3 summarizes all three cells observed in each hemisphere of the planet.

2.4 Coriolis Effect

The Coriolis Effect arises from the Earth's constant acceleration, through rotation, being a noninertial reference system (Marion, 2013). That is, experiments done on the surface of the Earth will appear like an inertial system, but with corrections through Centrifugal and Coriolis Forces. The acceleration due to the Coriolis effect is given by:

$$a = -2\omega v \sin\phi \tag{1}$$

where ω is the angular velocity of the Earth, and ϕ is the latitude, and v is the velocity vector of the object in question, such as an air parcel. The direction of the acceleration can be found by $\vec{\omega} \times \vec{v}$ (Marion, 2013).

From this, we can see that air parcels moving along the Earth's surface will be deflected into clockwise circles in the Northern hemisphere and counter-clockwise circles in the Southern hemisphere. The three-cell system exists as the natural consequences of the Earth's conditions, such as rotation speed, and land-water distribution (Dolman, 2019). Other planets, such as Jupiter, would show different numbers of cells.

3 Project

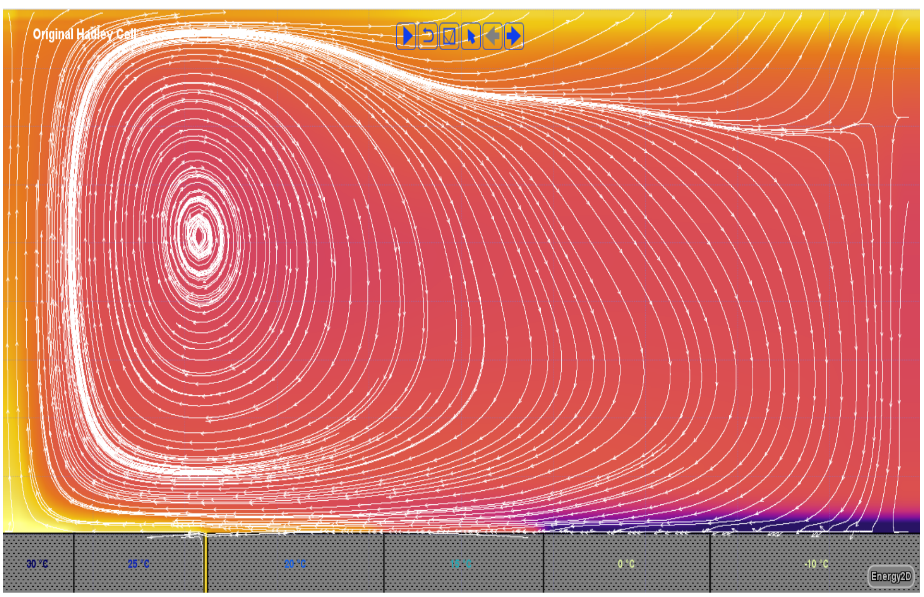

Figure 4: A simulation of the original Hadley cell which circulates air from the equator to the poles. This was created by setting a surface temperature gradient. The corresponding simulation file can be found in `Original_Hadley_Cell.e2d`

In this work, we use a two-dimensional heat transfer simulation `Energy2D`[1],

[1] https://energy.concord.org/energy2d/

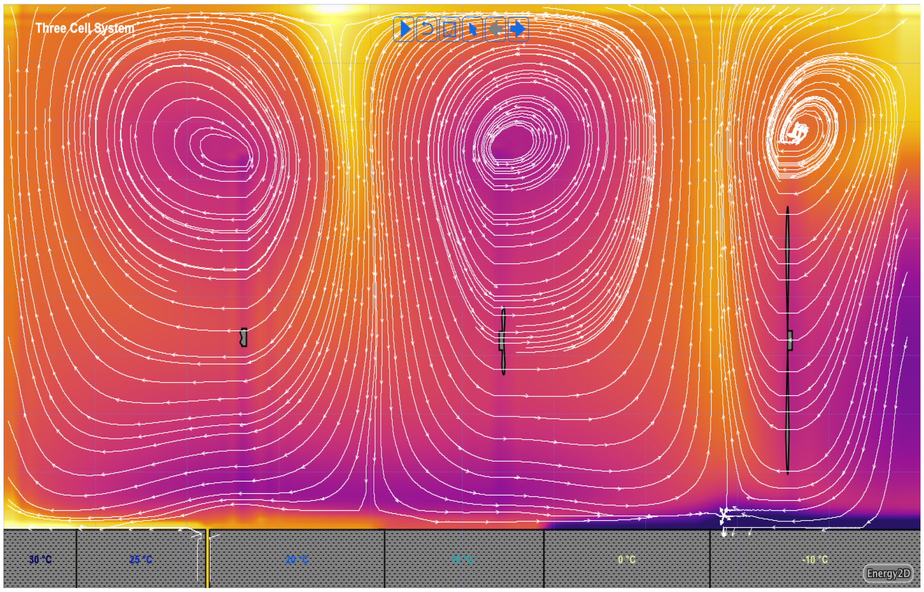

Figure 5: A simulation of the three-cell system including the Hadley, Ferrel, and Polar cells, shown from left to right. This was created by setting a surface temperature gradient, and atmospheric winds as fans which generate small winds to the left and right of the fan. Since the simulation is restricted to two dimensions, the Coriolis forces are instead represented as winds to the North or South, depending on latitude. The corresponding simulation file can be found in `3_cells.e2d`

which allows construction of convection, conduction, and radiative processes. `Energy2D` is packaged with examples, such as the Hadley cell example[2], which allows modelling of a simplified Hadley cell from differential heating of the surface alone. In this work, we modify this example within the constraints of `Energy2D` to produce the initially proposed Hadley cell shown in Figure 2, and the three cell system (with the Hadley, Ferrel, and Polar cells) with the addition of Coreolis forces.

After modifying the original example file, we aimed to build the original Hadley cell proposed by Hadley. To do this, we changed the surface temperatures to represent what they would be from the equator to the poles. Since we

[2] https://energy.concord.org/energy2d/hadley-cell.html

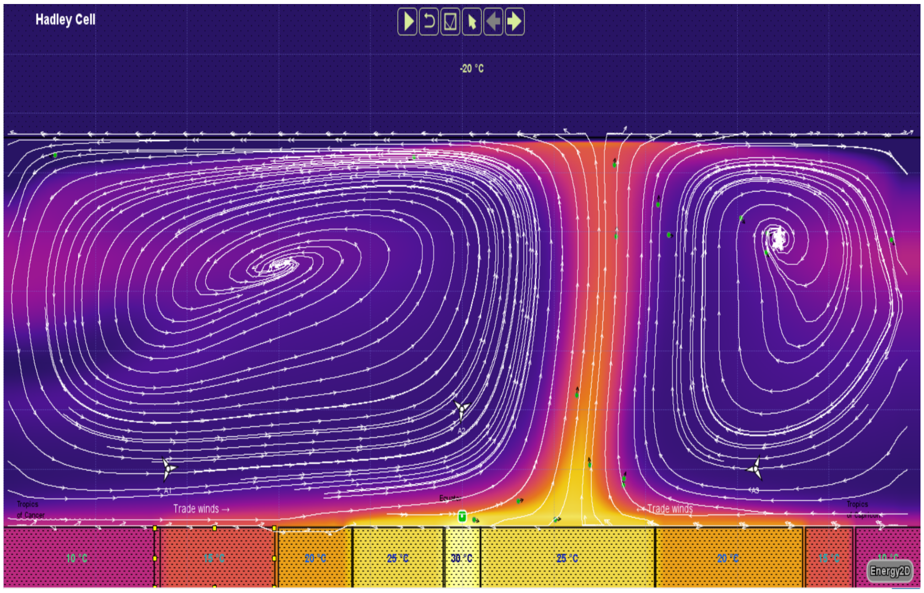

Figure 6: A similar simulation to the one shown in Figure 4, but with both hemispheres shown. The surface temperatures of the hemispheres are made different to represent differential heating on the surface based on the tilt of the Earth. Here, it is Summer in the Northern hemisphere. The corresponding simulation file can be found in `hadley-cell.e2d`

only want an approximate circular motion, and accurate values are not needed, approximations such as the flat geometry of the simulation, the estimates, and discrete nature of the temperatures were found to be acceptable, since they were given as acceptable in the original example. The original Hadley cell simulation is shown in Figure 4.

After modelling the original Hadley cell, we worked to model the three-cell system. Since `Energy2D` is restricted to two dimensions, adding the Coriolis force exactly was impossible. To solve this, we instead used the meridional component of the winds generated by the Coriolis effect, since winds could be added as "fan" objects in `Energy2D`. The Hadley cell has Trade Winds which point towards from the equator, the Ferrel cell has Westerlies which point away from the equator, and the Polar cell has Polar Easterlies which point toward the equator. For the purposes of this simulation, the Zonal component of these winds were ignored. The "fan" objects added to the simulation acted as areas of wind, where the fan graphic would be the center point of a region that would experience a user-determined wind. The direction of the "fan" graphic would indicate the direction of the wind, with the "blades" of the fan pointing in the direction the wind was heading. Running this simulation, shown in Figure 5, we observe circulation cells forming around the center points of the winds, which we claim is analogous to the Hadley, Ferral, and Polar cells. The regions of vertical lines between the cells are 30° N and 60° N from left to right.

Finally, we worked to show why plots of the circulation are typically one-sided. We found that this is because of different surface temperature conditions given by either land-water composition or seasonal differences between the hemispheres. We modified the example file for the Hadley cell, `hadley-cell.e2d`, to include a different surfact temperature profile for the Northern and Southern hemispheres. Figure 6 shows one possible configuration, where the Northern hemisphere is given generally warmer temperatures than the Southern hemisphere. In this case, the Hadley cell in the Southern hemisphere is much larger and faster than the one formed in the Northern hemisphere. Since this is a two-dimensional, simplified simulation, it is expected that when the surface temperatures Northern and Southern hemispheres are switched so that it is Winter in the Northern hemisphere, then the Hadley cells formed would also be switched.

4 Conclusion

From these simulations we see that general circulation is explained by differential heating of the Earth's surface. This circulation transports material from the stratosphere to the troposphere, and from the equator to the poles.

This explains how water vapour moves from the tropics to higher latitudes (Mohanakumar, 2008), and how CFCs from cities are able to destroy ozone in the stratosphere of the poles (Stohl et al., 2003). We found that the Coriolis forces (the winds added to the simulation) were able to explain the three-cell system.

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