Lecture 3 Atmospheric Stability and General Circulation

In Lecture 2 we saw that we could describe how the temperature of an ideal gas responds to a change in pressure. This is important in the atmosphere because it will help us describe vertical motions of air – in particular convection – based on observed vertical temperature profiles. We will call this "atmospheric stability" (or instability, in the case of a vertical profile that is subject to overturning due to buoyancy of the air below).

In this set of slides, we will consider what might happen to a parcel of air in an atmosphere with a given temperature profile. We will assume that the vertical motion of that parcel happens fast enough so that no material is exchanged, nor any heat transferred, between the parcel and its surroundings. This allows us to assume that the parcel would move adiabatically in accordance with the relationship in the previous lecture. Let's consider what might happen in an atmosphere with the following vertical temperature profile:

-10 °K km⁻¹ (dry adiabatic lapse rate) Neutrally buoyant

Near the surface, the actual temperature of the atmosphere falls off at a rate of about 10 degrees per km. Under these conditions, an air parcel from the surface can rise, and it will have the same density as the surroundings – so it may or may not continue to rise, depending on factors other than buoyancy (e.g., winds over topography, etc.)

surface

Т (К)

Let's consider what might happen in an atmosphere with the following vertical temperature profile:

-10 °K km⁻¹ (dry adiabatic lapse rate)

<u>Stable</u>

In the middle of the profile, and above the surface, T of the atmosphere falls off more slowly than the adiabatic lapse rate (that is, - dT/dz < 10 °K/km). Under these conditions, if an air parcel were to start to rise adibatically, it would always be cooler than surrounding air, so it would sink back down. We call this kind of vertical temperature profile "stable," because under these conditions, there is no way for a parcel to rise without somehow being heated. Let's consider what might happen in an atmosphere with the following vertical temperature profile:

-10 °K km⁻¹ (dry adiabatic lapse rate) In this example, we see that in a narrow region near the top of the profile – dT/dt ~10 °K km⁻¹, and once again under such conditions, if an air parcel were to rise (or fall) adiabatically, the temperature would be the same as the surroundings – neutrally buoyant. Note that this is only a very narrow layer, above which the profile again becomes stable with respect to vertical motion of a dry parcel of air.

Is this same vertical temperature profile stable with respect to vertical motion of a 'wet' parcel of air?

-6 °K km⁻¹ (wet adiabatic lapse rate)

Vertical motion would

<u>Unstable</u>

A parcel that is wet (i.e, in which water can condense) has $-dT/dz \sim 4-6 \, {}^{\circ}\text{K km}^{-1}$. Such a parcel, if it were to start rising would find itself warmer than the surrounding air due to the release of latent heat from the condensing water. This would cause the parcel to be less dense than the cooler air surrounding it, so it would continue to rise until it reached an altitude where its temperature once again matched that of its surroundings.

A wet parcel could rise

Is this same vertical temperature profile stable with respect to vertical motion of a 'wet' parcel of air?



What would an example of an unstable temperature profile look like?

Altitude (km)

Under these conditions, note that there is nothing to stop a dry parcel of air from rising. Once it starts, it is always warmer than its surroundings, so always less dense, so it continues to rise. The same would be true of a wet parcel of air.

> -10 °K km⁻¹ - (dry adiabatic lapse rate)

What would an example of an unstable temperature profile look like?

Altitude (km)

Over time, the air that has risen would mix with air aloft, warming that air. Similarly, cooler air aloft would sink (because it is more dense than air below it), and the vertical temperature profile would change – air aloft becoming warmer, air below becoming cooler. This would act to 'mix' the air so that the vertical profile would eventually look like the adiabatic profile.

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> Therefore, whenever you see the atmospheric temperature falling off at a rate of 10 °K km⁻¹, you can assume that vertical transport is occurring. If water is condensing, we can definitely see that vertical motion in the form of cumulus clouds.

Altitude (km)

T (K)

One more definition – when we have a condition in which the temperature profile is stable with respect to motion of a dry parcel of air, but unstable with respect to motion of a wet parcel of air, we call this 'conditional stability' – that is, the stability depends on the condition of the air. If a relatively warm and humid parcel of air were to start rising in this situation, it would reach a point where it becomes very buoyant, and it would rise faster. This is essentially what happens in a thunderstorm.

See the following web site for a good summary of atmospheric stability.

http://www.forestencyclopedia.net/p/p426

Outgoing infrared radiation (70) Reflected solar radiation (30) Reflected by atmosphere (25) (4)Emitted by (25)atmosphere (12)(66)Incoming solar (29) radiation Absorbed by (100)atmosphere (25)(100)Gases 101 Greenhouse Thermals (5) 111 effect (88) Radiated by surface (104) Reflected by Evaporation (24) surface (5) Absorbed by mm surface (45) Copyright © 2004 Pearson Prentice Hall, Inc.

Earth is heated by sunlight (mostly visible and near infrared) incident on the surface. This warms the surface, creating a situation where the air there is less dense than the air above, which is not heated significantly by sunlight. This creates an instability, such that the warm air at the surface will convect (i.e., rise). This is an important mechanism for removing heat from the surface. Note in the figure that rising air carries 29 units of heat away from the surface, when only 45 units of heat from the sun were originally absorbed by the surface. That's nearly 2/3 of the total energy incident on the surface. This is what drives the weather.

Why is all of this important?

In addition, we note that the temperature in the lower atmosphere (the troposphere – the part that is relatively well mixed by weather systems) falls off at a rate of approximately 80 degrees Kelvin per 16 km – that's about 6 degrees per km. This is not too different from the wet adiabatic lapse rate. What this tells us is that vertical motions in the atmosphere must be important, and that they also must be carrying a lot of water, that has evaporated from the surface and is condensing aloft. The release of latent heat is a major part of the heat budget of the atmosphere and also very important for the movement of water from the relatively wet tropics to the cooler, and relatively dry midlatitudes.





We now have pretty much most of what we need to describe the main features of Earth's General Circulation



4. In the polar regions in winter, air becomes very cold, and it sinks in a region called the 'polar high.' Because descending air does not condense water, the polar and subtropical highs are very dry. 1. Air rises in the tropics where the surface is heated most strongly by direct incidence of solar radiation

2. Air can only rise until it bumps up against the warmer air in the stratosphere (which is warmed by absorption of ultraviolet radiation by ozone). Thus it turns poleward, carrying the heat that it acquired at the surface (and also acquired from latent heat of condensation of water in tropical storms).

3. As air moves poleward, it finds itself in a cooler environment, and it radiates some of its energy to space as infrared. The air cools, and becomes more dense, and descends in the subtropics.

There are few more things we need to know about atmospheric dynamics in order to complete the picture for the transport of pollution around the planet. We don't really have time to go into much detail in this class (this is done in ATOC 1050 and 3600, among others). What is important to note is that because the earth is rotating, air that is traveling poleward from the equator will experience a pseudo-force (called the Coriolis Effect) that will deflected it at right angles to that poleward motion. Because the earth appears to rotate counterclockwise when looking down on the North Pole, this 'deflection' makes the air turn in an eastward (called "westerly", or "from the west") direction when viewed from a point of view that is stationary with respect to Earth's surface.



The physical basis for this can be illustrated in the figure at left. Air at the equator is literally travelling faster than air at mid latitudes, thanks to the curvature of the earth. Thus, as this air moves northward, it finds itself surrounded by "slower" air, so it appears to speed up relative to that slower air. Consequently, the equator-to-pole flow (and return flow from pole-to-equator) doesn't exactly occur with a pure North/South direction. The coriolis effect, in combination with the pressure gradient forces that are established by rising (surface low pressure) and sinking (surface high pressure), acts to turn air that is converging at the equator to the west (northeasterly trade winds).

Similarly, air that is traveling in a northward direction is deflected to the east (westerlies). This 'zonal' flow pattern acts to disperse pollutants emitted at a surface in the east west direction faster than it does in the north south direction. Thus, pollution from China ends up in the US in a week's time. Pollution from the US ends up in Europe, etc. The air will eventually mix throughout the northern hemisphere on a timescale of a few months. When it reaches the equator, convection lifts the air, where about half of it returns to the northern hemisphere – the other half end up in the southern hemisphere. Thus, it takes a few years for air that is released in the NH to mix fully into the SH.

