Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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Week- 03

Lecture- 16

TEMPERATURE GRADIENT OF DRY AND SATURATED AIR PARCEL, EARTH SUN RELATIONSHIP

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate monitoring. in the last few classes we had been discussing the concept of dry and moist adiabatic lapse rates, the concept of potential temperature for dry air and saturated air and used those concepts to understand what are the conditions that would ensure an unconditionally stable atmosphere where there won't be significant convection currents and associated weather disturbances. An unconditionally unstable atmosphere, where you will have convection currents and strong weather disturbances precipitation propensity etc and a conditionally stable atmosphere which when the atmosphere is dry and stable, and when it reaches saturation conditions becomes unstable all of these conditions and the associated expressions and derivations we have done in the last few classes. Here we will wrap up our discussion on atmospheric stability by comparing how a parcel of air temperature changes with altitude as it is moving up in an adiabatic process and we will compare between the case of a parcel of dry air and the case for a parcel of moist air ok and we will see the impact at different latitude value. So, this figure here kind of shows this impact Here, what we are seeing here is a parcel of air which at different temperatures near the surface. So, we have on the left hand side, the significantly cold parcels of air which begins at an initial temperature of 0 degree centigrade, 10 degree centigrade or minus 10 degree centigrade, some things that we will encounter in the high latitude versus hotter parcels of air like air parcels that are starting at 20 degree centigrade or 30 degree centigrade near the ground as could be typically encountered in lower latitudes like near the equator.

Secondly, we are comparing the rate of change of temperature of these parcels of air with as they rise adiabatically with altitude between two cases. In one case, the parcel of air is dry, so there is no water vapor in it. In another case, the parcel of air is saturated with water vapor. What we saw is the moist adiabatic lapse rate is smaller than the dry adiabatic lapse rate so a dry parcel of air will cool much faster than a moist parcel of air.

Here the dry parcel of air temperature plots are given by the dotted lines and you can see and the moist parcel of air temperature profile with altitude is shown by the solid line and we can see for warmer air parcel the differences quickly become very significant. So, consider a case where we have a dry parcel of air that is starting at 30 degree centigrade at the sea level versus a saturated parcel of air that is also starting at 30 degree centigrade at sea level. As it rises, because the saturation adiabatic lapse rate is much smaller than the dry adiabatic lapse rate, the dry air cools much faster. So, by 2 kilometer altitude, the dry parcel of air temperature has decreased from 30 degree centigrade to say about 18 degree centigrade, whereas the moist parcel of air temperature has barely decreased by say 3 degree centigrade to about 36 or 35 degree centigrade, 26 or 25 degree centigrade, ok. So, we are already seeing more than 7 degrees difference in temperature with a rise of 2 Km, Aad this difference continues as we go up and up.

So, at 8 kilometers, which is near the top of the troposphere near the equator at least 8 to 12 kilometers. So, near the 8 kilometer region that same parcel of air has now cooled to more than minus 50 degree centigrade, whereas the moist parcel of air has cooled to only 10 degree centigrade. So, a 40 degree centigrade temperature difference has accumulated between the dry parcel of air and the moist parcel of air by the time they reach near the top of the troposphere or top of the convection cell. So, you can see that there are large differences in temperature between the dry parcel of air rising up and a moist parcel of air rising up, and hence the extent of water vapor that is present near the surface, especially in the hotter regions of the earth, matters a lot in determining what is the temperature of the convection cells at the top of the troposphere. If it is a extremely dry region like in a desert, you will have extremely cold temperatures near the top of the troposphere, whereas if it is a moist region like over the ocean in the equator, you will have significantly warmer air current rising to the top of the troposphere, ok.

That is one point. Another point is the difference between the fate of parcels of air that are rising from much lower temperature conditions. So, suppose you are near the higher latitudes. So, say 60 degrees or 70 degree north latitude, where it is quite cold and say the parcel of air's initial ground temperature is 0 degree centigrade. And now we are looking at the dry parcel of air which is the dotted line and the moist parcel of air which is the solid line, and here we can see the temperature difference between these two remains quite small at this cold temperature condition.

And the reason is because the air parcel is already quite cold, its ability to hold water vapour is much lower at this low temperature. It's exponentially less based on the Clausius-Clapeyron equation. What this means is there isn't much water vapour to begin with which can condense and release latent heat which is heating up that parcel of air and decreasing the saturation adiabatic lapse rate compared to the unsaturated adiabatic lapse rate. So, the temperature differences are small because the difference in Γ_s and Γ_d are also quite small. So, you can see this point if you look at the expression for Γ_s.

$$\Gamma_s = \frac{\Gamma_d}{1 + \frac{L_v}{c_p}\frac{dq_s}{dT}}$$

So, this is the expression for Γ_s in one condition. We have also given an alternative expression in the previous case also. And here what we see here is that a important point here is the rate of change of the Ws or qs term, the relative humidity or the specific humidity term with dT, rate of change of temperature, and if you start at extremely low temperature, this gradient is much lower. So, that is an important point that needs to be kept in mind that if you are starting at very low temperatures, then the difference between the moist parcel temperature and the dry parcel temperature is not that much. Now, what happens then typically is that air parcels rising near the equator are much hotter than the air parcels rising near the high altitude like 60 degrees or 70 degrees.

Therefore, the temperature difference between an air parcel at the equator and the air parcel may be say 30 degrees near the ground. So, this is say 30 degrees and this is 0 degrees. So, this is at 60 degree north latitude and this is 0 degree latitude. The initial temperature difference is 30 degrees. By the time you reach 7 kilometers ok, this air parcel even if it is moist has attained a temperature of minus 6 degree centigrade, whereas the moist air parcel starting from the equator has cooled slightly and has reached a temperature of nearly 15 degree centigrade at the same condition 15 degree or 10 degree centigrade at the same condition.

So, what started as a temperature difference of only 30 degree centigrade has gone into a temperature difference of 70 degree centigrade between the air parcel at 7 kilometers above the surface at 60 degree north latitude and a similar air parcel rising from the equator ok. So, the temperature gradient at high altitudes between the equatorial region and the arctic region is much increases as you increase in altitude. So, near surface if the air temperature difference is certain delta T it may become 2 times or 3 times that delta T as you go up in altitude. These considerations have an important impact in determining the temperature gradients in the upper atmosphere as well as the associated wind patterns in the upper atmosphere ok. So, these are some of the ideas that come up because of these differences in the adiabatic lapse rate Now, how does this impact, how does these things change because of global warming? So, what we can see is increased surface temperature and increased evaporation from warmer oceans will result in hotter and more humid air at the surface.

So, the air will become hot and more humid near the surface compared to what it was before the anthropogenic global warming kicked in, ok. Thus, conditionally unstable regions will have a greater tendency to tip from a stable to unstable region, because air pulses are likely to be holding more water vapor and hence likely to tip from a stable dry system to a unstable saturated system much more easily. So, you are likely to get much significant weather instabilities and precipitation events due to the rising temperature, especially in regions where it was stable before ok. So, that is one of the key insights that you are getting from this discussion that as the global temperature increases, the amount of humidity in near surface air also increases because of increased water evaporation rates because of higher temperatures. This can keep the balance in a conditionally stable region from a stable to an unstable condition and you are likely to get more weather disturbances, more intense precipitation.

Also, the gradients are much larger between regions of low temperature and regions of high temperature as you increase the temperature of a parcel of air. So, temperature gradients at high altitudes are also going to get exacerbated because of the increase in the amount of moisture and heat which is present in the parcels of air. So, those are the two main take out points on how global warming will part of this kind of stability or instability. So, next chapter that we will discuss is what we call the earth sun relationship. It's a very important part of what determines the weather and the climate of the world.

So, earth sun relationships include those parameters like latitude, longitude, earth rotation, earth revolution, axial tilt, eccentricity and parallelism. We will define all of these terms sequentially that impact the average solar radiation energy flux in watt per meter square that is being received by a location on earth at any given time during the year. So, every location on earth is getting certain solar energy in terms of energy per unit surface area watt per meter square energy per second per unit surface area, okay. This is called the average solar radiation flux. All the primarily geometric and astronomical parameters that impact this average solar radiation flux per unit area that we are getting at a given location on the earth is a part of earth sun relationship.

They include the latitude of that location, the longitude of the location, the nature of earth rotation and the revolution, the axial tilt of the earth and things like eccentricity and parallelism which we will discuss. These are very important because almost the entirety of the energy in the atmosphere and the oceans is coming from solar energy that is being absorbed by the surface, by the air and by the water. Thus, the extent and variation of this solar energy flux with time of day or seasons or years or even decades has a significant impact on the prevailing climate and seasons in a region, this is kind of obvious. So, we will quickly go over certain basic things that you may have already learned in your school in terms of geography, we will just go over these, so that we can have the discussion on on those terms, so we will define some of the terms. The first term that we will be defining is what is called the solar irradiance.

This is primarily the amount of energy that is coming to earth from the sun averaged over the entire surface of the earth. So, there are several ways to explain this. First is, What is sun? The sun is an average star whose mass is around 1.99×10^{30} kgs and whose total radiation energy it is emitting per second is 3.9×10^{26} watts joules per second. So, this is the total amount of energy that the sun is emitting per second.

It is a huge number, ok. And the surface of earth is around 6000 kelvins in temperature. Now the mean distance between the sun and the earth is around 1.496×10^{11} meters, so around 1.5×10^{11} meters which is the mean distance between sun and the earth. And this mean distance basically controls the amount of solar energy that the earth receives per unit time per unit area which is called the solar irradiance.

This is the amount of solar energy which is arriving at the top of the earth's atmosphere. Because the atmosphere also absorbs some of it, not all of this irradiance is actually hitting the surface of the earth. So, we will discuss that in later classes. Now, if you look at this picture, somewhere here is the sun, far far away. And the sun is so far away that all the light rays are more or less parallel when it comes to earth.

The earth is a sphere, but it is projecting a circle when the sun is seeing it. So when we see the sun, it looks like a disc. It is a circular projection of the spherical sun, right. Similarly, when the sun looks at us, for example, if you think of it that way, then the earth also looks like a circular disc, which is this circular projection, and all the sun's light is going through this circular disc. So, what we see here is that the total energy of the sun which is 3.9×10^{26} watts divided by the total surface area at the earth sun distance. So, there is a spherical surface area you can think enclosing the sun at the earth sun distance. So, if you divide that you will get the solar energy per unit area at the earth sun distance. Then we multiply it by this circular projection that the earth is projecting towards the sun, the total area and that will give you basically the flux in watts. Now the average solar irradiance received by earth on the top of its atmosphere is 1360 watt per meter square.

So, this circular projection area is receiving solar energy at the rate of 1360 watt per meter square. However, this energy is basically distributed over this circular area which is basically pi r square, r is the radius of the earth. n which is the pi r square where r is the radius of the earth. However, this energy has to be distributed over the entire spherical surface of the earth. In general, of course only the lighted half, one hemisphere is receiving the sun's rays, but if you average over the entire 24 hour period where the earth is rotating, and then do the per unit area measurement, then the total earth surface is $4\pi r^2$, r is the radius of the earth and the surface area of it is here, so it is $4\pi r^2$ and this solar irradiance of 1360 watt per meter square is being is distributed over this area, ok.

So, the total energy the earth receives is 1360 into πr^2 divided by $4\pi r^2$ which means 1360 by 4 which is 340 watt per meter square it may change a little bit from decade to decade so in some decades this is a little bit higher in some decades a little bit lower because the earth sun distance is not really fixed, it can change a little bit okay over long periods of time. Anyways, this is the average solar into insulation at the top of the atmosphere when we are dividing it over the entire spherical surface four pi r square of the earth so earth on average at the top of the atmosphere receives 340 watt per meter square of solar energy flux So, this is the average this will have a significant variation depending on the location on which that flux is falling. So, to understand that variation we have to understand the parameters on which that variation depends namely primarily latitude and then other parameters like longitude etcetera are also important ok. So, what is latitude ok? Now since the earth is spherical and it is rotating around an axis, this axis is the north south axis, north pole and the south pole and the straight line through this is the axis of the earth around which it is rotating. Now, we consider a plane which is perpendicular to the axis and divide this axis into two halves ok.

So, the distance between the north pole and this point here is the same as distance between the south pole and this point here. So, we are imagining an imaginary plane perpendicular to the axis which is bisecting the axis. This imaginary plane is called the equatorial plane and where it hits the surface of the earth, it creates a circle and that circle is the equatorial circle or the equator. So, we have defined the north pole, the south pole and the equator, alright. Now, you can also generate other planes which are perpendicular to the axis.

At equal distances along the axis line. So, you can create a plane here, you can create a plane here, you can create more parallel planes which themselves will subtend circles on the earth, on the earth surface and all of these planes are parallel to each other and perpendicular to the north pole south pole axis. These are all called latitudinal planes and the circles they subscribe on the surface of the earth are called latitudes. So, we have the equator we have the latitude, okay. Now, how do we define this latitude so suppose you have a latitudinal plane like this, it is there is a circle that is generated on the surface of the earth because of this latitudinal plane, now any point on this circle you connect with the center of the earth okay.

And, you connect any point on the equator with the center of the earth okay. The angle between these two lines, the line connecting any point on the latitude circle with the center of the earth and the line connecting the equatorial circle with the center of the earth the angle between them will be a constant value regardless of which point you choose and this constant value helps us to define that corresponding latitude so here that angle is 45 degrees. And the angle is going in the anticlockwise fashion so it's called 45 degree north. Similarly, this angle here is 30 degrees and the angle is going in the clockwise fashion from the equator to the latitude and so this is 30 degrees south. So, every latitude has a unique angle from 0 to 90 degree north and 0 to 90 degree south and based on that we are defining the latitude circle value.

Now because the earth rotates around the axis during a rotation any point will only lie within its own latitudinal circle. So, suppose here is a point it is rotate earth is rotating in the east west direction then as it rotates this point will move along this latitude circle so all geographical points only ever move along its latitude circle during the rotation of the earth The direction along a latitude circle is positive in the east to west direction. So, if you move from east to west that direction is considered positive and is called the zonal direction. So, east going towards west is called the zonal direction along a latitude and it is a positive if east to west, if it is west to east it is negative ok.

Next we will discuss longitudes. So, longitudes are nothing but a series of half circles on the surface of the earth whose center is the center of the earth. So, you take the center of the earth, you draw half circles from the north pole to the south pole. And these lines are called longitudes. The longitudinal half circles are also called meridians or meridional lines. They are oriented perpendicular to the latitudes.

So, this line and if you have draw a latitude line, they are oriented perpendicular to 0. That is where they intersect that angle will be 90 degrees. One latitude half circle is taken as a reference and it is called the prime meridian, and it runs through the Greenwich in London and it is given 0 degree as the default value. Just as equator is given 0 degree as the default value. Other meridional half circles are defined in terms of the angle they sustained at the center of the earth with respect to the prime meridian.

So, here basically suppose this is 0, you take an a point here, you draw a perpendicular on the north south axis, you draw another perpendicular from your preferred meridians say 90 degrees west to the north south axis at the same point and the angle between them is the longitude angle if it is in the east to west direction or if it is in the west to east direction it is negative ok. Now, the meridians are hence defined in terms of 180 degrees west and 180 degree east in terms of the prime meridian. So, this is the 0 degree meridian you can move this way and you make this angle here. So, this is 90 degrees west, If you go in this direction east of it and you subtend an angle with the center of the earth, this is the 30 degrees east. So, this way you can go from 180 degrees west to 180 degrees east with respect to the prime meridian.

All points along a longitude are in the same time zone. So, all points along the longitude are in the same local time zone. That is, all of these points experience the noon at the same instant of time. And all of these points experience things like sunrise and sunset simultaneously.

This simultaneity is important. For all of the points across a meridian, noon happens simultaneously, morning and evening happens simultaneously, midnight happens simultaneously. Now the direction along a latitude, so this direction along this latitude is called the north-south direction and is the meridional direction. So direction along a longitude circle is the east-west direction, it is called the zonal direction. The direction around the longitude circle, the north-south direction is the meridional direction. The intersection of any latitude circle with any longitude half circle is always orthogonal and hence the longitudes and latitudes create an orthogonal coordinate system by which any point within the earth surface can be located, ok

So, we will stop here. We have defined longitudes and latitudes. We will see how they are used in determining the several climatic parameters and the corresponding effects in temperature in the next class. Thank you for listening. See you again in the next class. Goodbye.