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

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ATMOSPHERIC LAYERS; TROPOSPHERE; TEMPERATURE LAPSE RATE

Good morning class and welcome to our continuing lectures on atmospheric dynamics variability and monitoring course. In the last class we started on our discussion of the first and perhaps the most important climatic variable which is atmospheric temperature. And we saw that while the mean atmospheric temperature today is around 15 degree centigrade, there is large variation in the atmospheric temperature that is recorded at different locations of the planet based on its latitude, its altitude, the season in which it is being recorded and whether that location is far from the oceans or near the continental interiors. So we saw that in winters of a hemisphere, we are seeing significantly colder temperatures, particularly in the continental interiors, especially in the high latitudes, and significantly hotter temperatures are recorded in summers, again in the continental interiors and usually in the subtropical belt. And if you look carefully, then while the July to January temperature deviations are almost non-existent in the oceans and close to the coasts, they are extremely large in the continental interiors. So, we will look at the reasons for these differences as we go along in the class.

But first we also want to note that these temperatures are usually temperatures of the surface air, so the air mass just above the surface, the temperature of air at that location. However, atmosphere extends from the surface to very high altitudes in space. So another aspect of atmosphere which is very important in determining the climate dynamics of the world is the variability of temperature as you move up from the surface upwards towards space. So with rising altitude.

The variation of mean atmospheric temperature with altitude is an important feature and it helps us identify distinct layers of the atmosphere as well. So here this figure shows the mean distribution of air temperature from the surface upwards towards the near the boundary of the atmosphere where the earth's atmosphere meets space and this is recorded near the equatorial region so near the equator the surface temperature is around 300 kelvins so which is around 28 27 degree centigrade and as you move up in altitude so the y-axis if you can see is in kilometers okay so the atmosphere firstly extends from zero kilometers which is near the surface to 120 kilometers above the surface so in contrast for example even the largest mountains are much much lower and if you see for the first 20 kilometers of the atmosphere we see that the temperature drops nearly linearly with increasing altitude. And this region of the atmosphere is called the troposphere. This is the most important region of atmosphere that determines the weather of the world as most weather related phenomena like winds, cloud formation, convection currents, etc. are occurring in the troposphere.

Around 18 to 20 kilometers from the surface this linearly decreasing trend of air temperature begins to reverse itself and we have an inflection point which is called the tropopause. Beyond this we see a reversal of the trend and air temperature starts to rise as we move up in altitude. And this region above the troposphere where the air temperature rises with altitude is called the stratosphere, which is the second layer of the atmosphere. This trend also reaches an inflection point at around 50 kilometers above the Earth's surface at the stratopause. There again, we return back to the trend of the air temperature decreasing with altitude

And this region is called the mesosphere, which is the third region of the atmosphere. Here the air temperature steadily drops until we reach around 85 to 90 kilometers, where we again get a broad inflection point. And beyond that, we see a steep rise in air temperature, which is the thermosphere. So what we see is air temperature with altitude follows a kind of a zigzag pattern, and this pattern helps us to differentiate different layers of air. The lowest layer, troposphere, where air temperature linearly decreases with altitude, The next layer stratosphere where air temperature linearly increases with altitude

The third layer mesosphere where air temperature again linearly decreases with altitude. And the fourth layer thermosphere where air temperature increases with altitude. And the inflection points are called tropopause, stratopause and mesopause respectively. So we will just briefly describe these regions and we will focus on troposphere for most of our discussion because that is where most of the weather and climate is related. So the troposphere is the lower 10 to 15 kilometers of the atmosphere. It is the densest region of the atmosphere and you will see when we do some problems later in the class that more than 80% of the total mass of air is located in the troposphere itself. Remember, air is a compressible gas. The density of air is actually highest in the surface. And as we go up in altitude, the density of air decreases. And we say that air has become thin. This is the reason why mountaineers have a difficulty breathing and have to carry oxygen cylinders because the air has become so thin light so less dense with altitude that not enough oxygen gets into our lungs at those high altitudes because it's a densest layer that is why troposphere even though it's the smallest region in terms of total length it is the densest and the thickest part of the atmosphere containing most of its mass

Here the temperature is observed to linearly decrease with altitude z and this rate of linear decrease is called the lapse rate Γ.

$$\Gamma \equiv -\frac{\partial T}{\partial z}\ (\frac{K}{km}).$$

And the mean lapse rate of the troposphere is around 6.5 kelvins per kilometer. So every kilometer increase in altitude, the mean air temperature decreases by 6.5 kelvins or 6.5 degree centigrade. Now why does the temperature decrease? So we will explain this in further and further detail as we go along in our class.but primarily it is determined by the energy balance between the convective radiative heat transfer from the surface and the radiative cooling of the air layers into space. So in this troposphere, suppose you take a small air block of air here somewhere. This air block is absorbing radiation coming from the earth. So we will see that atmosphere absorbs radiation that is being radiated by the earth primarily. It is mostly transparent to solar radiation.

It absorbs heat radiation coming from the earth and hence heats up. Another way it heats up is through convection currents that moves the hot air near the surface to upper regions. So in this way heat transfer occurs in a certain altitude from the bottom. However the air is also losing heat to space through radiation. So the air itself is radiating to the space outside which is extremely cold.

It's close to 3 or 4 kelvins. So there is a lot of radiation of heat from the hot air to the space outside. And this balance of the incoming heat flux from convection and radiation and the outgoing heat flux through radiation to space is determining the temperature of a certain mass of air within the troposphere. And as a result, when we do this calculation, we will see this linear decrease in temperature of air layers as we move further and further away from the surface. As we said, the troposphere is the region where most of the weather and climate related phenomena occur, including winds, cloud formation, precipitation, etc.

And most of our discussion regarding the atmosphere will concentrate on the physics of the troposphere. Now, this figure kind of seems to show that this is kind of a uniform figure for all over the planet. That is not true. This figure is primarily near the equator. If you change the latitude and even change the seasons in different parts of the latitude, then this figure will change to some extent

So, for example, here we have the mean temperature profile from the surface up in altitude at the equator, which is the red line, 45 degree north latitude, which is this green dotted line. and 80 degree knot latitude which is the blue dashed line. Two points. Firstly, the temperature of air at the surface is decreasing as we go higher up in latitude as we would expect. The mean temperature of high latitudes is significantly lower than the mean temperature at the equator.

So, at 80 degree north, for example, the temperature starts minus 10 degrees. At 45, it is 10 degrees. At equator, it is 25 degrees. we can also see another interesting point the tropopause is happening at much shallower altitudes at high latitudes so both at 40 degree north the tropopause starts at around 12 kilometers at 80 degrees north the tropopause starts at around 8 to 9 kilometers whereas the equator it starts at around 16 17 kilometers and because the tropopause is so far higher in the equator because of the lapse rate which remains more or less the same, you are getting much colder temperatures at the tropopause at the equator compared to the poles. So interestingly because so the troposphere itself is thinner at high latitudes compared to the equator. as a result the tropopause temperature is higher at high latitudes compared to the equator because the tropopause is lower down near the high latitudes and it's higher up at the equator so in equator the troposphere starts hot and ends much colder whereas at high latitude it starts cold and does not decrease in temperature to that extent okay Also we see that the tropopause is much more broader at high latitudes compared to the equator. So in equator the stratospheric heating effect reversing the trend line of temperature starts almost immediately. So the tropopause is just a line. Whereas in the high latitudes, 45 degree north as well as 80 degree north, you are seeing that the heating effect is significantly lower and you are getting more or less same temperature up to 25 kilometers. There will be heating effects afterwards, but you will have a broad tropopause

Another important aspect that you are seeing observationally and we will try to explain these in this class or in the next as time allows is that with seasons also this lapse rate and the temperature profiles change. So this is 80 degree north, the blue is January, the green is April, the red is July and the brown is October. April and October will be more or less same as we can see here some differences we will concentrate on January and July 80 degree north July is summer so you are having a hotter surface temperature and then it's decreasing till the tropopause is hit and then you are getting the broad tropopause where the temperature is more or less constant In January, of course, the land temperature is significantly colder at around minus 25 degrees centigrade. And you are seeing, if you look closely, a temperature inversion. So as you move above, for the first one or two kilometers, the air temperature is hotter than the land temperature

And hence, as you move up, the air progressively becomes warmer. in the troposphere itself. So, between 0 to 2 kilometers or 0 to 1 kilometer mostly As you move up at these high latitudes, especially in winter, the air is warmer, becomes progressively warmer till you reach a maximum here and then the traditional decrease in air temperature starts. So this temperature inversion near the surface in northern hemisphere winters at high latitudes is a very interesting and unique feature of these regions.

Okay. Now, why does these things happen? So, we will discuss the stratospheric effect and why you are having a big stratopause, a big tropopause later. This temperature inversion is happening because at high latitudes in winter, there is very little sun. daylight is less than 2-3 hours and often it's 24 hours of night so the surface which is a very good radiator of heat cools rapidly and because it has no sunlight it is very very cold it is radiating to space over a 24 hour period so it becomes very cold the air above it is not stationary it is coming from lower latitudes as well so it is transporting heat to these colder regions and hence the air above it is slightly warmer than the surface In general because the surface is so warm most of the heat of the air above it is coming from absorption from surface radiation and surface convection. But especially in the high latitudes in winter the surface is so cold that there is no heat absorption from the air. Air is getting heat primarily from wind currents, air currents that are moving transporting heat from low latitudes to these high latitudes and hence air is warmer than the surface and it becomes progressively warmer for the first one kilometer and then the general heat budget kicks in and you are getting a decrease.

then you have the much milder gradients of the troposphere and lower stratosphere at these regions. So what this kind of shows is that temperature, while there is an idea of mean layerings and mean temperature gradients, there are significant variability in terms of geography as well as seasons, which is one of the themes of our course. That there are significant variabilities in our climate depending on the type of region we are looking at and what season we are looking at. now one other interesting fact here is why is the troposphere so thick in the equator and so dense in the poles or thin okay so one of the reasons is the equator is hotter so the air above the equatorial region is also warmer and hence less dense warm air has lower density the same mass of air occupies a larger space and hence a larger height so near the equator because of the warmer temperatures there occupies a higher altitude for the same mass and hence in general the troposphere is warmer and lighter and hence more higher up with respect to the poles where the air is much colder and hence much denser from the star. The other issue is the high heat that is being absorbed by the surface and hence radiated to the surface air creates large convection currents where the warm air near the surface convects upwards to create large convection cells.

These are called the Hadley cells. We will discuss these Hadley cells later in the class in more detail. And these convection cells kind of mix the troposphere and the effect of this convection cells extend much higher up in altitude compared to the convection cells, much weaker convection cells that lie in the polar and the subarctic regions. So the big thermally driven convection cells and the overall heat of air making it light causes the troposphere to be well mixed and and higher on average near the equator compared to the poles. So, this basic explanation has been shown here itself. So, a more finer understanding of the temperature gradients with latitude can be shown from these figures here.

So here if you can see at the x axis is the latitude value. So equator 30 degree north, 60 degree north, 90 degree north. So the northern hemisphere 30 degree south, 60 degree south, 90 degree south which is the southern hemisphere. And this is the altitude in kilometers. So, 0, 5 kilometers up to 45 kilometers. Remember the troposphere is around

15 kilometers to 8 kilometers like that, right. If you see for the equatorial region, it is around 18 kilometers. In the sub-arctic region, it is around 8 kilometers. So, this is 15 to 8 kilometers.

This is where the troposphere is. this region tropopause is, so up to this point is the troposphere, above that is the stratosphere, all right. This is December, January, February, so winter in the northern hemisphere, June, July, August, which is summer in the northern hemisphere, all right. This color map is the temperature contour. So, red is 300 kelvins, 290 kelvins, 280 kelvins, so hot. Cold is 190 kelvins, 200 kelvins, 210 kelvins, which is cold.

White is in between 240 to 250 kelvins. Remember, 273 kelvins is 0 degrees. So, 0 degrees here. So, everything here is sub-zero, everything here is above zero. All right. Now, if you take a look at how these contours look like, you will see here, this is the equator.

So, if you go from the equator upwards, you see the high temperature slowly decreasing. So, here you are starting at around 300 kelvins, slowly decreasing and you reach the coldest temperature which is the tropopause at the equator. So, if you remember here, the coldest temperature is the tropopause region where the inversion is happening. So, the tropopause is shown by the area within this contour above the equator which is below 200 kelvins, alright. Then above we are getting the stratopause where you are getting the slow heating of the stratosphere where the temperature is rising again.

At this point if you see the polar regions so 80 degrees north and 80 degrees south you see two different aspects. In winter the northern hemisphere does not receive a lot of sunlight at all. Alright, and you see the temperature at the surface is already quite cold as we have seen and we see a steady decrease in temperature but then you are seeing nearly isothermal conditions here. So, the temperature contours become broader and broader.

So, you can see this here. 80 degree north in January you see the temperature contours become broader so the decrease temperature gradients become far more mild and you see a slow decrease in temperature very slow decrease in temperature and here the minimum temperature occurs at around 20 to 25 degree centigrade but this entire region where the temperature contours are temperatures is decreasing very slowly is kind of an extended tropopause region where your temperature is decreasing very slowly with altitude. So, you see here, this is 210 kelvins, this is 220 kelvins. Over 15 to 20 kilometers in altitude has been gained with just 10 kelvins decrease in temperature. Beyond this, you are seeing this slow increase back as the stratospheric trends come into the picture. In the southern hemisphere in contrast, in the December, January, February is basically summer there. Here you will see that the minima is around 10 kilometers. So the tropopause basically is very close to the surface. So it's lower than the equator. It's happening at 10 kilometers

Then you see a steady rise in temperature. So you can see here in July you see this condition and after 25 you will see a rise in temperature. So, here this is 25 degree here and see here a steady rise in temperature is happening. So, here the temperature inversion and then the temperature increase in the stratosphere is happening much earlier than in the winter side higher latitudes. Why this is the case? Because the southern hemisphere in December, January, February receiving a lot of sunlight and the stratospheric heating is caused by the UV radiation based heating of the ozone layer.

We will discuss this in detail. So if there is a lot of sunlight, then you will get a lot of heating. If there is not enough sunlight, you won't get a lot of heating in the stratosphere. so this heating effect is largest in the high latitudes in the southern hemisphere winter because you are getting nearly 24 hours of sunlight okay and you see this trend the minimum temperature in the equator here minimum temperature of northern hemisphere here minimum temperature southern hemisphere here being reversed in june july august so when it's northern hemisphere summer the minimum temperature in the Northern hemisphere near the Arctic is happening again close to 10 degree, 10 kilometers above the altitude, just like here. And this zone has gone to the southern hemisphere. Because of the absence of sunlight, there is very little stratospheric heating and you are getting a broad region of nearly constant slow cooling that is happening over the Antarctic.

Whereas the equator remains more or less fixed. You are getting very similar trends in the equator which gets relatively same amount of sunlight throughout them. So what this kind of means is how the temperature gradients look, where the stratosphere and the troposphere boundaries are, and what are the heating rates and the lapse rates for the troposphere and the stratosphere depend very much on what season you are looking at, what latitude you are looking at, and these two are very important factors over and above the mean trends that we have discussed so far. So, these lapse rate and its variations has a very important influence in weather events as we will discuss later in the course. So, we are stopping here today. In the next class, we will start with stratosphere and we will discuss further as we go along.

Thank you for listening and we will see you in the next class.