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

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ADVANCED ATMOSPHERIC HUMIDITY CONCEPTS CONTOURS AND KEY RELATIONSHIPS

Good morning class and welcome to our continuing lectures on climate, dynamics, variability and monitoring. So in the previous class, we started our discussion on atmospheric humidity, and we discussed important concepts like vapor pressure E, which is the partial pressure of water vapor in the atmosphere, the saturation vapor pressure Es, which is the maximum vapor pressure that water vapor can have in air at a given temperature and pressure, the relative humidity, which is the ratio of the vapor pressure to saturation vapor pressure. How to evaluate the saturation vapor pressure Es as a function of temperature for pressures near the sea level in terms of the latent heat of vaporization of water, the molecular weight of water, the ideal gas constant and the temperature of air in kelvins and how this Es varies graphically with temperature and how you can use that to figure out important weather variables like the dew point temperature or the saturation vapor pressure. We also started our discussion on humidity ratio or mixing ratio omega, which is the ratio of the mass of water vapor by the mass of dry air in a parcel of moist air, which we saw is proportional to the vapor pressure to the partial pressure of dry air. We also discussed the saturation humidity ratio which is the ratio of the maximum mass of water vapor that a certain air parcel can hold the certain temperature and pressure by the mass of dry air and this is proportional to the ratio of the saturation vapor pressure to the partial pressure of dry air. Now, Es which is the saturation vapor pressure depends on temperature through the Clausius Clapeyron equation.

$$d(\ln e_s) = \frac{L_v M_w}{R_u}\frac{dT}{T^2}$$

This equation here, alright. Or if you want the differential form this is the equation. Depends on the temperature

So, as atmospheric pressure increases or decreases the partial pressure of dry air also increases or decreases. So, we can evaluate omega s contours, the values of omega s with temperature for a given parcel of air. So, here is the temperature of air in terms of degree centigrade, this is the pressure in hectopascals and the contours are in omega s values the saturation humidity ratio or the saturation mixing ratio which is units of grams of water vapour per kg of dry air. So, remember there is a very little amount of water vapor present in dry air usually. So, the proper units is expressed in grams. How many grams of water vapor present in how many kgs of dry air? That is the unit grams per kg. Here it is written as mu s because it is from a different textbook. Here we will use the omega s term. So, these are the omega s contours at different pressures. So, this is 1000 hectopascals, this is the sea level pressure and this is 200 hectopascals, so high up in altitude. 0.2 times the atmospheric pressure. And this is the temperature values of air parcel at these pressures from minus 30 degree centigrade to plus 30 degree centigrade. So, if you look, for example, at 1000 hectopascals, and at say 20 degree centigrade, if you go up, this 1000 hectopascal 20 grams of water vapor are present per kg of dry air at around 25 degree centigrade. So, if you look at a moist air parcel at 25 degree centigrade at sea level then the maximum amount of water vapor it can hold is around 20 grams per kg of dry air. Similarly, if you decrease the temperature, so the maximum amount of water vapor that an air parcel can hold becomes 10 grams at 100,000 hectomascals at one atmosphere at around 12 degree centigrade.

So, as the temperature of air falls, the maximum amount of water vapor that a parcel of air can hold is decreasing from 20 to 10 to 5. So, 5 is around 5 degree centigrade, 2 is around minus 8 degree centigrade and just 1 gram per kg at around minus 15 degree centigrade. So, hotter the temperature of air, greater is the amount of water vapor that a saturated parcel of air can hold. So, that is one point. Another point is if you decrease the pressure, the total pressure, so if you move up in altitude, the air, total air pressure is also decreasing.

Suppose you have moved up in altitude certain kilometers and the pressure has decreased to 600 hectopascals. So, now you see that at 600 hectopascals 20 grams of moisture air can be held at around 18 degree centigrade. So, as you are decreasing the pressure, these curves are moving backwards. All right. So, at lower temperatures, the same amount of water vapor grams can be held.

Okay. So, if you look at the expression here, omega S equals to Es by P air. Okay. If P air is decreasing, the total pressure is decreasing, alright. So, the P air is also decreasing while at the same temperature. So, suppose I keep the temperature same, 20 degree centigrade, okay.

$$\omega = \frac{m_w}{m_{air}} = 0.622\frac{e}{P_{air}}$$

At 20 degree centigrade, air can hold 20 grams of water vapor per kg of dry air at around 900 hectopascals, oka

As temperature decreases, the carrying capacity is decreasing. But as pressure is decreasing at the same temper

So, the specific humidity is the ratio of the mass of water vapor by the mass of the total parcel of moisture. Whereas, humidity ratio is the mass of water vapor by the mass of dry air only. So, if that is omega, then it is the ratio of humidity ratio by 1 plus humidity ratio.

And the saturation specific humidity Qs is omega s by 1 plus omega s. So the saturation humidity ratio by 1 plus the saturation humidity ratio.

Now, usually these omega values are much, much lower than 1. Remember, this is grams per kg. So, if you do kg per kg, this becomes 20 into 10 to the power minus 3, 10 into 10 to the power minus 3. So, these are around 0.002, 0.001, 0.01, etc. So, these are the ratios we are looking at. So, one plus omega is or omega is almost equal to omega. So, under most conditions the specific humidity ratio and the mixing ratio are more or less the same and these two can be used interchangeably. So, once again because this omega value is much much less than 1, 1 plus omega is almost equals to 1.

$$q = \frac{m_w}{m_{air} + m_w} = \frac{\omega}{1 + \omega}$$

So, the specific humidity ratio is almost equal to the humidity ratio and this is also true for Qs is almost equals to omega s. So, sometimes it is also expressed in terms of specific humidity that can also be done. Now, if you look at the vapour pressure expression, it is the relative humidity into the saturation vapour pressure, correct.

$$RH = \frac{e}{e_s}$$

So, here in this plot, what we are looking at is the pressure in terms of altitude, and this normalized pressure, so pressure at sea level, 1 atmosphere pressure is taken as 1. Now as we move up the air pressure decreases very rapidly and we saw that in the hydrostatic balance relation the air pressure is decreasing at an exponential rate with altitude.

So the total pressure is decreasing. Now the total pressure is equal to the pressure of dry air plus the vapor pressure. What you will also see is two aspects. As the total pressure is decreasing, the vapor pressure is decreasing, but another aspect is the temperature of air is also falling very rapidly, at least in the troposphere. So, this is mostly within the tropospheric region.

So, if you remember in the troposphere, you go up a little bit, temperature is falling from 300 kelvins to around 200 kelvins. So, 300 kelvins is around 30 degree centigrade and 200 kelvins is around minus 80 degree centigrade. So, the fall is from 30 degrees to minus 80 degrees and if you see, the curve for saturation vapor pressure, it decreases close to zero by minus 10 degree centigrade. So, if you start at 30 degrees, the saturation vapor pressure is here and by minus 10 degrees it's here and minus 20 degrees it's close to two millibars only. So, the saturation vapor pressure has decreased very quickly from around 40 millibars to around 2 millibars, okay, between 30 degrees and minus 20 degree centigrade.

Now, the actual vapor pressure will always be lower than the saturation vapor pressure correct; so, what you are seeing here is that the actual vapor pressure is declining also very quickly compared to its normal value, standardized value at sea level. So, if the sea level vapor pressure is say 1, then by altitude of 5 kilometers it has gone to 0.1 because of the rapid decrease in temperature in the tropospheric region and it goes close to 0 by 10 kilometers. So the vapor pressure falls to 50% of its surface value by 2 kilometers above the sea level.

So, this we can see here. 50% of its surface value by 2 kilometers above the sea level and falls merely to 10% by 5 kilometer altitude. In addition, the water content also falls with increasing latitude. So this is one part. The second part is, if you change the latitude, then also the water content, the specific humidity or the humidity ratio falls very significantly. Because at high latitudes, the temperature is falling very quickly.

So, at equator, if the mean temperature is around 25 degree centigrade, near the poles, the mean temperature is minus 10, minus 20 degree centigrade. So, as you move up to higher and higher latitudes, you are getting lesser and lesser specific humidity which is also a function of the vapor pressure, correct. So, this is the pressure in hectopascals and this is the specific humidity in grams per kg. So, this is sea level, this is 200 hectopascals, so high up in the troposphere. This is 9 degree north latitude and 9 degree south latitude, so within the tropical belt.

So, if you look at the latitude, equator is 0 degrees, then 9 degree north and 9 degree south, so close to the equator. Close to the equator, near the sea level, the specific humidity is around 16 grams per kg. Okay, so you can see from here This is the humidity ratio, saturation humidity ratio, but specific humidity will be close to this. So, 16 grams per kg is around this point here and the temperature is around 20 degrees. So, this is more or less what you would expect that at one atmosphere conditions when the mean temperature is around 15 to 18 degrees, you expect the temperature the specific humidity ratio to be close to the saturation humidity ratio of around 16 grams per kg and this is what you are getting here, 16 grams per kg of water present in one parcel of moist air.

Now as the pressure declines the specific humidity declines very quickly. So here there are two aspects. Firstly, at high altitude the temperature is decreasing very quickly. So that is why your vapor pressure is decreasing very quickly.

Also, the total pressure is declining. So in that context per kg of dry air actually the carrying capacity of water vapor is increasing slightly. So, these two effects are working together but the overall effect is a rapid decrease because the temperature effect overwhelms the pressure effect. So, you are getting a rapid decrease in the amount of water vapor present per kg of air as we move high up in the altitudes. It starts very high and falls very quickly as we move high up in altitude. Now, if you look at a 30 degree north, 30 degree south, so subtropical region.

Here the temperature is lower and also near the surface subtropical regions are more arid. So, you are getting lower relative humidity and hence lower specific humidity values. So, you are starting at around 9 grams per kg and again falling off quickly at high altitudes. Similarly, if you go at even higher latitudes, 45 degree north, 45 degree south.

So, this is the temperate zone. Your mean temperature is lower near the sea level. As a result, you are starting off with a very low specific humidity, because the saturation vapor pressure is low and hence the actual vapor pressure is also lower at these low temperatures. So, it starts at only 5 grams per kg and the decrease is slightly slower because the temperature gradient is slightly lower in the high latitudes. If you remember near the equator the temperature gradient del T del Z is much steeper than near the poles, right? So, this effect we are again seeing here because the temperature decay is lower, the slopes are less steep compared to the equatorial regions. And as you go at very high latitudes, 66 degree north and 66 degree south, Arctic and Antarctic circles, you start up at very low specific humidities and it slowly decreases at high altitudes.

So, very high humidities near the equator, moderate humidities near the mid latitudes, lower amount of water vapor carrying capacity near the poles. And the steep slope, the rate of decrease of water vapor content is much steeper near the equator compared to near the poles. So, these are the main take backs from here. You can also hence plot the specific humidity contours, the mean specific humidity contours with pressure and with latitude. So, this is equator, this is 90 degree south, so south pole, 90 degree north which is north pole.

This is pressure from 100,000 hectopascal to 200 hectopascal, so top of the troposphere. These contours are isocontours of specific humidity. So, this region here is 16 grams per kg. This region here is 14 to 16 grams per kg. Then this is 12 grams, 10 grams per kg, 8 grams per kg. This is 0.5 grams per kg. So, you can see, firstly, at high latitude, high altitudes, specific humidity declines very quickly. Okay, so the gradients are very steep near the equator. It starts from 16, goes very quickly to 0.5 at around 300 hectopascals. Alright. As you move away from the equator, the starting specific humidity declines very quickly as well. So, there is a steep gradient of specific humidity from the equator towards the poles from 16 grams to 0.5 grams at 75 degree south and 75 degree north. In the north, the specific humidity is slightly higher because in the north you have land masses which are slightly hotter. So you get 2 grams per kg or 1 grams per kg even up to 90 degree north latitude, okay.

But overall the trend is a steep decline both with altitude and with higher latitudes from equator onwards at higher latitudes the specific humidity starts low and the gradient is less steep. Because the temperature gradients are also lower okay. So, this you can see here, so this is how therefore the contours of specific humidity look. So, here is a very important point here, we will touch on this point today. We will see that water vapor is a very strong greenhouse gas, alright.

So, the concentration of water vapor in the atmosphere actively helps to trap heat in the lower atmosphere. However, we see that in the higher latitudes, the amount of water vapor present in air is much lower than in lower latitudes. So, that means the heat trapping ability of water vapor is more strongly present in the equatorial and the subtropical regions compared to the temperate and polar regions. So, more heat is getting trapped due to this water vapor greenhouse effect near the equator and the subtropics than near the high latitudes like the poles, and this also helps to cool the poles much more than the equatorial region. Because it has low water vapor content, it can lose heat more effectively when sunlight is not present during nights or during the long winters and hence the poles can get extremely cold.

Whereas, the equator, because of the heat trapping ability of water vapor and high concentrations, heat is not lost to a significant extent even at night times and that is why equatorial nights remain relatively warm and hot. And you will feel this in the local weather as well. So, if you go to an arid region like Rajasthan, like the deserts, you will see very hot days and quite cold nights. There is a lot of heat coming from the direct sunlight because there is no cloud cover during the day. But most of the heat is escaping very quickly because the water vapor content in the arid regions are quite low and so the heat dropping effect is much lower.

So, that is why the deserts can cool off very quickly at night times and they have very cold winters and cold nights compared to a coastal region which has relatively constant temperatures in daytime and night. This is also true for the seas. So, if you travel in the seas, you will see very little difference between daytime temperature and nighttime temperatures, and this is because over the seas, there is a lot of water vapor, especially in the subtropical and the equatorial regions. Which is why coastal nights are hot and sultry whereas arid nights in the deserts are usually cold and dry, okay. Now this effect has an important point in the greenhouse gas effect also as the earth warms up the amount of water vapor that air can hold is also increasing because the air temperature is rising.

Okay. And if you see that the specific humidity here or the humidity ratio is directly proportional to E and this E is exponentially increasing with temperature, correct? So, as temperature increases slightly, you expect a very large increase in the amount of water vapor that air can hold, okay? As a result, small changes in global temperature can create large changes in the amount of water vapor content in the atmosphere and which can result in increasing the greenhouse effect, and this is especially true near the polar regions where water vapor content is low. So, in the polar regions, the water vapor content in general is extremely low. But a small change in temperature can increase the water vapor content significantly and increases the heat trapping effect of water vapor in the poles to a much more significant extent. Near the equator it's almost saturated anyways, okay. Here you have a much significant increase in the heat trapping ability near the poles due to a small rise in the water vapor content compared to equator which already has a significant greenhouse effect due to water vapor and this is why you will see in the climate models at least this is one of the reasons why in the climate modelue to the increase in the greenhouse gases, the poles are seeing a much higher rise in temperature compared to the equators.

Because the water vapor over the poles is increasing and that effect is much more greater near the poles because of its initially low water vapor content compared to equatorial regions. So, this is one of the reasons and I am saying this qualitatively right now. We will see some examples later in the class, of how there are complex feedback loops between CO2 emissions, surface temperature rise and water vapor distribution that impacts the regional rise in temperature and the overall rise in temperature that the earth is currently suffering from. Now, a rough expression for the variation of saturation humidity with temperature based on the Clausius-Clapeyron equation can be given. So, this is the change in specific humidity, delta Qs by the original specific humidity, saturation specific humidity Qs.

$$\frac{\Delta q_s}{q_s} \cong 20\frac{\Delta T}{T}$$

This is almost equals to 20 times delta T by T. Okay. So, the relative change in saturation specific humidity is 20 times the relative change in temperature. So, if the mean temperature is increasing by say, suppose this is 300 kelvins and the mean temperature is increased by 3 kelvins.

So, this is 3 by 300 so 1 by 100 so 0.01. This is 0.01×20. Right. So this becomes 0.2. Okay. So, for a 1% increase in the global mean temperature, we are getting a 20% increase in the carrying capacity of water in the atmosphere.

All right. That is the magnifying effect that is present due to the exponential relationship between vapor pressure and temperature. So, it shows that if the mean temperature of earth increases, the specific humidity of air is also likely to increase and hence air will carry more amount of water vapor. And since water vapor is a heat trapping gas like CO_2, increasing water vapor content of warmer air serves as a positive feedback loop that tends to increase the effects of global warming.

So, on that note, we will stop in today's class. We will discuss another important concept called virtual temperature and then look at an example of how to use these kinds of relationships that we learned in an actual solved problem. Thank you for listening and see you in the next class.