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

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FUNDAMENTALS OF ATMOSPHERIC HUMIDITY AND WEATHER VARIABLES

Good morning class and welcome to our continuing lectures on climate dynamics variability and monitoring. In the previous class we completed our discussion on the important atmospheric or climatic variable of pressure. Today we look at an equally even if and almost as important a climatic variable which is atmospheric humidity. Now, what is atmospheric humidity? In simple words, it's the amount of water vapor that is present in air in a given location at a given temperature and pressure. So it is the measure of the amount of water vapour in air and it is an important climatic variable because not only it influences the amount of precipitation that a certain location will have, it has important impacts on comfort levels. If you remember, if you see hot and humid conditions are extremely discomforting for human life compared to drier conditions.

Furthermore, water vapor is a very strong greenhouse gas. So, there is something called a feedback cycle between the amount of CO_2 present in the atmosphere and the amount of water vapor that is present in the atmosphere as well. And this is a very important thing to know in terms of figuring out what is the extent of expected global warming due to an increase in the CO_2 emissions. We have to also include in that the change in the water vapor amount in air to understand the true extent of global warming due to anthropogenic emissions.

Now the amount of water vapour changes with location and with altitude and this is kind of intuitively obvious. So for example during the wet season like in June, July in India you will have extremely humid conditions prevailing in most of India. Whereas during summer or winter months the amount of humidity in the air decreases significantly. and it also changes with location. For example, arid regions like Rajasthan have much lower amount of water vapour present in air compared to humid regions like Assam or coastal regions like Chennai etc.

It also changes with altitude you will see that as we increase in altitude the ability of air to hold water vapor decreases. Which is why you have condensation and cloud formation at higher altitudes, because the water vapor that is being transported through convection cells from near the sea level get condensed out to form clouds at the higher altitudes and we will see why that is as well. Now in general air has some amount of water vapor but not a lot. So, the percentage of water vapor present in air is usually quite low. So, if you remember the atmospheric composition amounts.

Here, in the water vapor, while the fraction is variable, depends on location, the approximate amount is 1.7×10^{19} grams, while the total atmosphere is 5×10^{21}grams. So, the percentages are even lower than argon, which is around 0.9 percent. So, it will be a very mean amount of water vapor present will be around 0.4 percent, 0.1 percent or 0.2 percent like that, if you compare it with argon. The amount of water vapor concentration in air is quite low. As a result, you can assume water vapor to behave like an ideal gas at these low concentration values.

So, this is an important thing to remember that when it's in air, water vapor usually behaves like an ideal gas. So, the $p\forall = nRT$ relationship holds for water vapor as well. So, it behaves just like any other gas constituent in the atmosphere. Like CO_2, like oxygen, like N_2. When we were discussing the partial volumes, partial pressures, mole fractions, mass fractions, all of those relationships also hold for water vapor as well.

As a result, you can assume that the total pressure of moist air can be considered to be the sum of pressure of dry air and the pressure of water vapor. So, if you remember, the total pressure is the summation of the partial pressures of the individual components. Now, unlike other components the concentration of water vapor is highly variable with location, time, seasons etc. Whereas all the other components do not change as significantly with time location etc. They are well mixed whereas water vapor can evaporate into or condense out of air so it has a highly variable concentration. So, it is a standard practice to consider the total pressure of moist air as the partial pressure of dry air which we call P_{air}.

So, this is dry air containing oxygen, nitrogen, CO_2, argon, CO, ozone, etc. Plus the partial pressure of water vapor which we denote by the variable e. This is basically partial pressure of water vapor only. We are calling it by the variable e here which is standard practice in many climatology course textbooks. So e is the partial pressure of water vapor in air and it is often also called the vapor pressure.

So, when you are hearing the term vapor pressure you should remember that what we are talking about is the partial pressure of water vapor in the atmosphere at a certain location. Now, the idea here is at any given temperature and pressure, air can only hold a certain amount of water vapor and if the concentration of water vapor increases beyond that value, water vapor starts to condense, that is get converted into liquid, ok. So, if you see that in normal circumstances in cold winter days. In early morning, when the ground air becomes very cold, the ability of air to hold water vapor decreases significantly and hence a lot of the vapor condenses out and form fog, dew, et cetera. So, this is what is the unique thing about water vapor that unlike other constituents of the atmosphere.

The water vapor can evaporate into the system at certain conditions and condense out of the system at certain other conditions. And for a given temperature and pressure, there is a maximum partial pressure of vapor that air can hold. And this maximum ceiling pressure, partial pressure of vapor is called the saturation vapor pressure e_s. So, what it means is if you know what the saturation vapour pressure e_s is for atmosphere at a given condition then you are assured that the actual vapour pressure will always be less than e_s. So, this term E will always be lower than the saturation vapour pressure e_s.

At best it can equal e_s and beyond which time the water will condense out. So, the pressure will remain stable, vapour pressure will remain stable at e_s only. Okay, so water begins to condense out of air and become liquid once the vapor pressure begins to exceed the saturation vapor pressure. Air is said to be saturated with vapor pressure. So, saturated air means, air whose vapor pressure has become equal to e_s.

So, air is said to be saturated with water vapor when the vapor pressure becomes equal to the saturation vapor pressure for the given temperature. So, we have learned a few things that the partial pressure of water vapor is called e and it is called the vapor pressure. Air has a maximum amount up to which it can carry water vapor and the corresponding maximum partial pressure is the saturation vapor pressure e_s. Beyond this point water will start to condense out of air. Air is said to be saturated with water vapor when the vapor pressure becomes equal to the saturation vapor pressure for the given temperature.

Based on this, we can define a very important weather variable that you hear a lot in weather stations. It is the relative humidity RH. It is the ratio of the actual vapor pressure of air to the saturation vapor pressure at that given air temperature. So, the ratio $\frac{e}{e_s}$ is basically our relative humidity. It's the ratio of the actual vapor pressure of air at that given location by the saturation vapor pressure of that air at that location.

So, $\frac{e}{e_s}$, this represents how much maximum vapor the air at that condition can hold and E represents how much vapor it is actually holding. So, that is $\frac{e}{e_s}$ which is given as relative humidity. And obviously relative humidity can be between 0 and 1. It can be expressed in percentage terms as 0% to 100% as well. So, when in weather reports you hear relative humidity of 60%, you know that the vapor pressure of air at that location is 0.

6 times the saturation vapor pressure at that given condition. Okay. Now how do we evaluate this saturation vapor pressure? So, there is a quite a well-developed theory in thermodynamics which can help us evaluate the saturation vapor pressure for any temperature of the atmosphere. We will not look at the theory in detail, we will just look at the results. So, this is an approximate solution of what is called the Clausius-Clapeyron equation.

$$e_s \cong 611\exp\left[\frac{L_v M_w}{R_u}\left(\frac{1}{273} - \frac{1}{T}\right)\right]$$

From which the solution is coming. This holds relatively well near the sea level. So, it will not hold very well at very high altitudes, but this is a reasonable expression that can work. So, here the saturation vapor pressure at a given temperature T of air is almost equals to 611 into exponential of this term here. So let us explain this term clearly. L_V is the latent heat of vaporization. It's the amount of heat that is required to evaporate 1 kg of liquid water into water vapor. This is the latent heat of vaporization and this L_V term is around 2.5 into 10 to the power 6 joules per kg.

So, you require 2.5 mega joules of heat to evaporate 1 kg of liquid water into water vapor. That is your latent heat of vaporization. The molecular weight of water is M_w.

It is 0.018 kgs per mole. So it's around, so molecular weight of water is around 18 grams per mole. So it's around 0.018 kg per mole. Okay.

So the units are very important. This is in joules per kg. This is in kgs per mole. So you have to remember the units. R_u is the universal gas constant, which is joules per mole Kelvin.

Okay. Again, you are expressing it in this format, joules per mole Kelvin, universal gas constant. Okay. This is 273, basically it's the 0 degree centigrade, okay. And this is the temperature of air in Kelvins. So, if the temperature of air is 20 degree centigrade, in Kelvins it's 20 plus 273.15, right. So, that is approximately 273, okay. So 20 plus 273 is 293 Kelvin. So you will put 293 here. So obviously 273 represents 0 degree centigrade in this context. And this entire expression, the total unit is Pascals.

Which is Newton per meter square. So if you keep these units, then the expression inside will be unitless and you will get Pascals as the total unit. And what is 611? It's the saturation vapor pressure of air at 273 kelvins. So at 273 kelvins, the saturation vapor pressure is 611 Pascals and this is what is given here. And you can see this is the fact, if you set temperature T as 273 here, then exponential this term becomes 0, e to the power 0 is 1, so e_s at 273 Kelvin is 611, so that is what we are putting here. And note that this expression is strictly valid at sea level because that is where the atmospheric pressure is 1 atmosphere.

In general, this terminology will also be dependent on the pressure of air. So, this is near or close to sea level. It is reasonably okay if you use it at somewhat higher altitudes, but not at very high levels of the atmosphere. Note that this is basically coming from an integration of this expression, the general Clausius-Clapeyron equation at sea level, which is,

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

If you integrate this at sea level, you are getting this expression here.

All right. This is just for information. This is the expression we will be using most of the times. All right. So suppose we plot this expression against pressure for various temperatures of air. What kind of an expression we are getting? So this red line is the plot for e_s using this expression here.

All right. Here at the bottom temperature is given in terms of degree centigrade. So, remember this is 273, 283 kelvins, 293 kelvins, 303 kelvins, this is 263 kelvins, etc. Here it is plotted in terms of degree centigrade for easier understanding. And the y axis is the vapor pressure in millibars. Remember 1 millibar is 100 pascals, so it is the same as hectopascals, ok.

So this is basically 3000 pascals, this is 1000 pascals, this is 500 pascals like that. We have measured, usually it is measured in either hectopascals or millibars, so this is the unit that has been used. And this is the plot of e_s. So how can we use this graphical plot if we want to use this, ok. Firstly, we note that as the temperature increases, e_s is rising exponentially.

So, the saturation vapor pressure is rising in an exponential fashion with increasing air temperature. So, this is the reason why air at higher temperatures can hold significantly more water vapor than air at lower temperatures. And we will discuss this further during the class. So colder air has less capacity to hold water as compared to hot air. Now suppose you take a certain temperature say 10 degrees centigrade.

Now if you move up at 10 degrees, it is around how much? Around between 15 to 16 millibars, for example. Exact expression you can identify using the expression itself. Suppose it is around 16 millibars. So, the maximum vapor pressure that air can have at 10 degree centigrade is 16 millibars of vapor pressure. If the actual vapour pressure is lower, say suppose it is 10 millibars at 10 degrees, then the relative humidity is 10 by 16, whatever that expression is going to be.

So, the area below this curve is where the actual vapour pressures of air can reside. This side is air cannot hold vapor pressure values beyond the saturation vapor line. So this region, there is no actual values that exist in this region. All the variable values that vapor pressure of air can have lies to the lower, at the below this saturation vapor line. So this part of the curve is unphysical, this part of the curve is physical.

Any state of air below this line you have relative humidity less than 1. So, it is called unsaturated air, it is called the unsaturated region. While this line gives the points or the state of air which are saturated air where relative humidity is 100 percent. So, for example, at 20 degrees if you go up it is around say 24 millibars. So, saturated air state is 24 millibars, but if the actual air vapour pressure is 20 millibars say, it is in the unsaturated region.

So, this line is the saturated zone and this area here is the unsaturated air region. So, let us see how to use this plot. Consider this point A here, which is in the unsaturated domain. And the T_A is 20 degree centigrade and E_A which you can see here is around 12 millibars. So if you drop a horizontal line here you will get around 12 millibars.

12 or 13 millibars it does not matter, and remember 12 millibars is 1200 pascals. So this is the actual vapor pressure and this gives the state A of a certain moist air person. At this point the saturation vapor pressure is 24 millibars and is given by point C. So, e_s at the temperature T_A which is 20 degree centigrade is equal to E at point C which is 24 millibars.

Then the relative humidity is the vapor pressure at point A divided by the vapor pressure given by point C, which is 12 by 24 or 0.5.

This is the relative humidity of a parcel of air at state A. Now, suppose this air is cooling down. Suppose day has come into night and the air parcel is beginning to cool down due to radiation into the space. And as it cools, Remember, the temperature of the air is decreasing. So the cooling process can be written as this line AB. So air is cooling down and its temperature is decreasing from 20 degrees down, down, down, down till it hits the point B which is on the saturation vapor pressure line.

This point B, the temperature is 9 degrees centigrade. So this is 9 degrees centigrade. At this point, this parcel of air has become saturated because it has hit the saturation vapour pressure line. So, suppose you take a parcel of air with a certain amount of water vapour, the temperature at which this parcel of air becomes saturated if it is cooled is called the dew point temperature. So, this point, the temperature corresponding to point B, 9 degree centigrade is the dew point temperature of the air parcel at state A. Because if the air parcel were cooled up to 9 degree centigrade, it would hit the saturation vapor line and it would become saturated.

So, at this point, Remember, there is no loss of water vapor from the parcel of air because it is still in the unsaturated region. So, the partial pressure of water vapor remains the same. So, A and B is horizontal. So, it remains 12 millibars. What is happening is the state B at 9 degree centigrade, 12 millibars is the saturation vapor pressure.

So, E_B is equal to E_A equal to 14 millibars. This is 12 millibars, sorry about that. E_B equals to E_A equals to 12 millibars, all right. with T_B as 9 degree centigrade. So at state B, the relative humidity is 1 and air has become fully saturated. This temperature B is called the dew point temperature corresponding to the vapor pressure of 12 millibars.

All right. Now, what would happen if the vapor is cooled further down? See, remember anything beyond this curve is unphysical. So what will happen is vapor will start to condense out of your parcel of air. Okay. And what will happen in this condition is that further cooling the state of air will move along this curve.

Okay. So suppose we cool this further to 0 degree centigrade. Okay. To certain points D here which is at 0 degree centigrade. Okay. So what is happening is water vapor is condensing into liquid and that liquid is coming out of the air parcel consistently. So, this is the condensation process.

You see refrigerators, fog formation and etc. And hence the partial pressure or the vapor pressure falls and it is falling along this curve. So, at 0 degree centigrade, it remains saturated at all times during this cooling process. So, once it hits the saturation vapor pressure, further cooling will always cause the line to go along this saturation vapor pressure curve. So, at 0 degrees, if you see, you are reaching again at 6.1 millibars, which is the saturation vapor pressure at 0 degree centigrade. So, the rest of water vapor has condensed out of the air parcel so that the partial pressure of vapor is 6.1 millibars at 0 degree centigrade. So, any further cooling will cause water to start condensing out of air in the form of dew, mist, fog or cloud water droplets and the process part will be along the saturation vapor pressure line. So, this is how we can interpret this sort of a curve. So, now we will discuss something called the humidity ratio or the mixing ratio omega.

It is sometimes called humidity ratio, it is sometimes called the mixing ratio and the variable is omega. It's the ratio of the mass of water vapor present in a parcel of moist air divided by the mass of dry air in that given parcel of moisture.

Okay. So if you take say 100 kgs of moist air parcel somewhere. Okay. How many kgs of it is water vapour? How many kgs of it is everything else that is dry air? That ratio is called the humidity ratio or the mixing ratio. And we can also express this in terms of the partial pressures. So this is equal to 0.622 into the partial vapour pressure divided by the partial pressure of dry air.

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

Remember the total pressure is partial pressure of dry air plus vapor pressure. And here you are getting the vapor pressure by the partial pressure of dry air into 0.622. Now this 0.622 is nothing but the ratio of the molecular weights of dry air and water vapor.

$$\omega_s = 0.622\frac{e_s}{P_{air}}$$

We will see this in the later section in the next class. So, the ratio of the mass of water to the mass of dry air is proportional to the partial pressure of water vapor by the partial pressure of dry air multiplied by this conversion constant 0.622. Suppose we have a saturated parcel of air. For that saturated parcel this e becomes equal to e_s and this is called the saturation humidity ratio omega s. The mass of water that that the maximum mass of water that a certain parcel of air can hold is the mass of water under saturation conditions that is M_W at saturation condition by the mass of dry air.

That gives the saturation humidity ratio omega s which is given by 0.622 into e_s by the partial pressure of dry air. So, you have this omega and this omega s is the saturation humidity ratio. The ratio of these two assuming that the mass of dry air remains constant is the relative humidity $\frac{e}{e_s}$. So, what that means is clearly that you can evaluate the fraction, the amount of water vapor present in a certain parcel of air using the variables E and e_s that we have introduced in the previous section.

So, we will continue discussion in the next lecture. So, thank you for today and see you in the next class.