The Monsoon and Its Variability
Prof. Sulochana Gadgil
Centre for Atmospheric & Oceanic Sciences
Indian Institute of Science - Bangalore

Lecture - 05
Rainfall and Clouds over the Tropics

So last lecture, we have talked about the some of the basic features of rotating fluids and so on which are relevant for understanding of clouds and rainfall. And today we will talk about Clouds and Rainfall.

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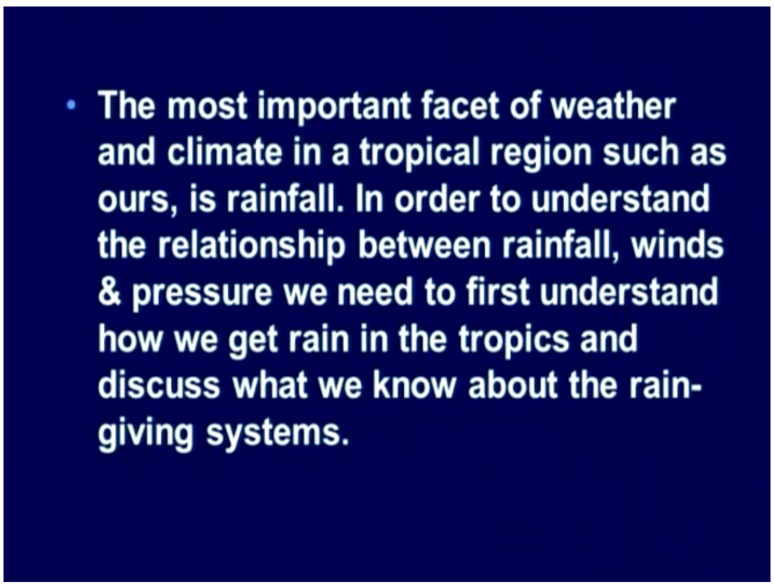

Because the most important facet of weather and climate in a tropical region such as ours, is of course a rainfall. In order to understand the relationship between rainfall, winds and pressure we need to first understand how we get in the rain in the tropics and discuss what we know about the rain living systems, so that is what I am planned to do in this lecture.

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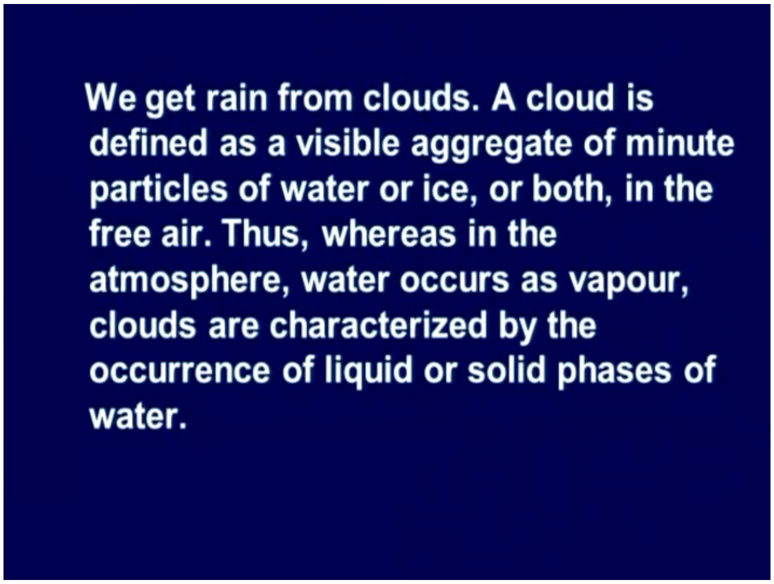

Now we all know that we get rain from clouds. What is the cloud? A cloud is defined as a visible aggregate of minute particles of water or ice, or both in the free air okay. Thus, whereas in the atmosphere water occurs as a vapour water vapour, clouds are characterized by the occurrence of liquid or solid phases of water.

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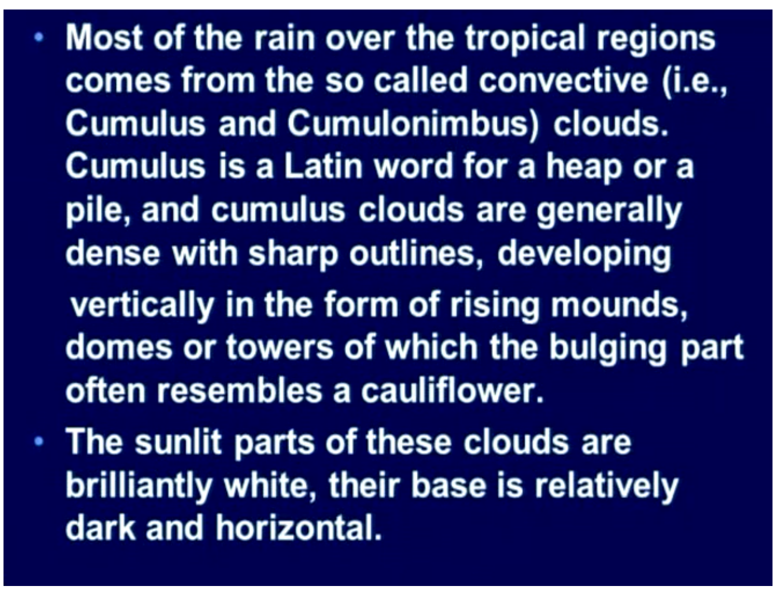

The most of the rain over the tropical regions comes from the so-called convective that is cumulus and cumulonimbus. Cumulus is a Latin word for heap or a pile, and cumulus clouds are generally dense with sharp outlines, developing vertically in the form of rising mounds, and we have seen all cumulus clouds domes or towers of which the bulging part often resembles a cauliflower.

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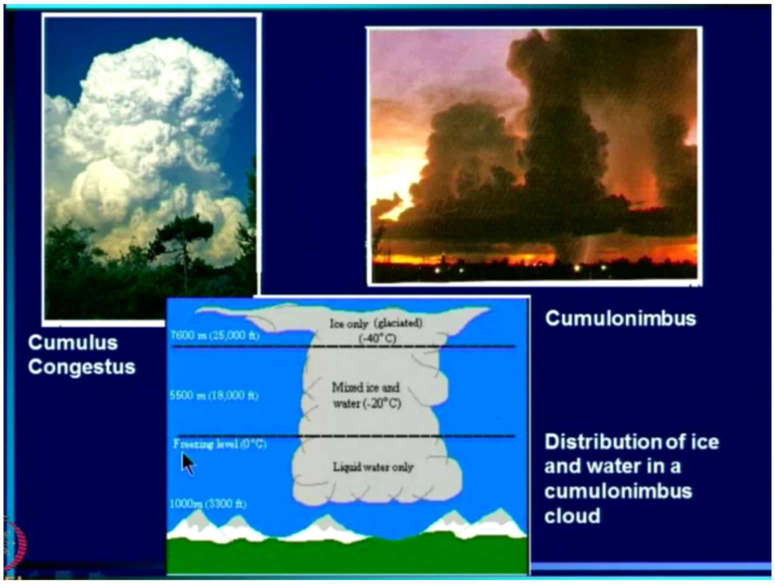

The sunlit parts of these clouds are brilliantly white and their base let me just show you a picture here, and then we will go back to, see this is cumulus cloud it is a cumulus congestus, and you can see that it does look like a cauliflower okay, so these are the cumulus clouds. And you already saw that the sunlit parts of these clouds are brilliantly white, and their base is relatively dark and horizontal.

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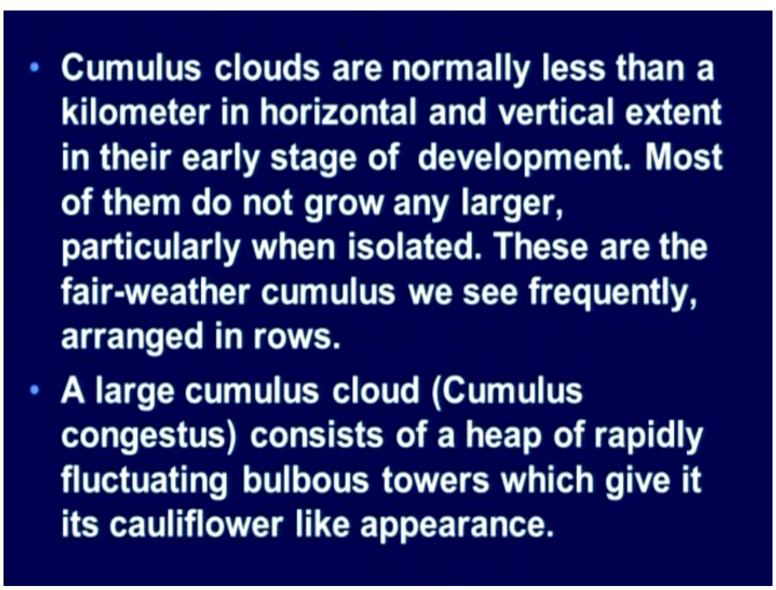

Now cumulus clouds are normally less than a kilometer in horizontal and vertical extent in early stage of development, when they are developing most of them do not grow any larger, particularly when isolated. These are the fair-weather cumulus we see frequently, arranged in rows, so when we fly often we see these clouds arranged in rows these are called fair-weather cumulus, because they do not give any rain.

A large cumulus clouds are called cumulus congestus consists of a heap of rapidly fluctuating bulbous towers which gave its cauliflower like appearance and we have seen that already, this is the cumulus congestus cloud with a cauliflower like appearance.

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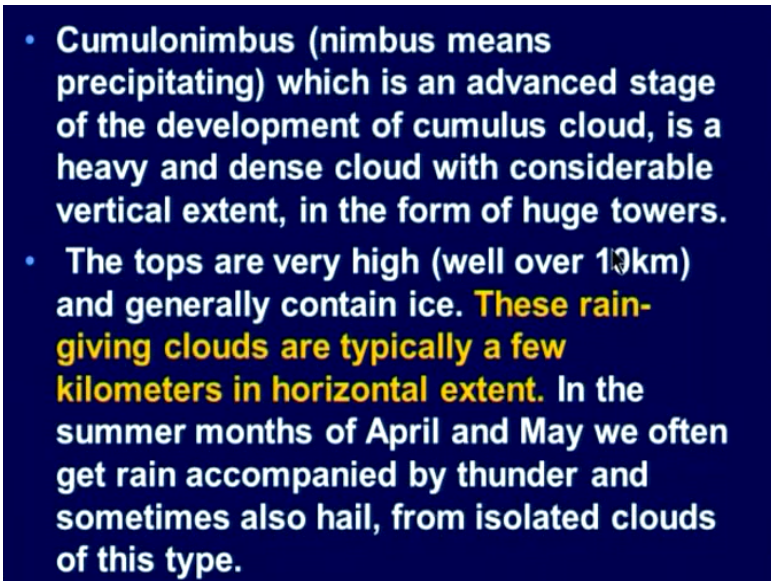

This is the cumulonimbus cloud, now nimbus means precipitating so cumulonimbus which is an advance stage of the development of cumulus cloud, it is a heavy dense cloud with considerable vertical extent in the form of huge towers, and this is what we see here this is the cumulonimbus cloud you see huge towers here, and our experience is that you know this is the photograph taken from high above where you see clouds has white.

But when we are below on the surface of the earth and huge clouds come in fact they cut out all the sunlight and what? It becomes very dark even in daytime, so this is the cumulonimbus cloud and cumulonimbus is so tall that actually not only does water vapour converted to water in here, but it also forms ice, and what you see here is that see this is the base of the cloud initially you having liquid water only and then mixed ice and water and finally ice only, okay.

So the tops of the cumulonimbus clouds are very high well over 10 km and generally contains ice, these rain giving clouds are typically a few kilometers in horizontal extent. In summer months of April and May we often get rain accompanied by thunder and sometimes also hail from isolated clouds of this type cumulonimbus clouds.

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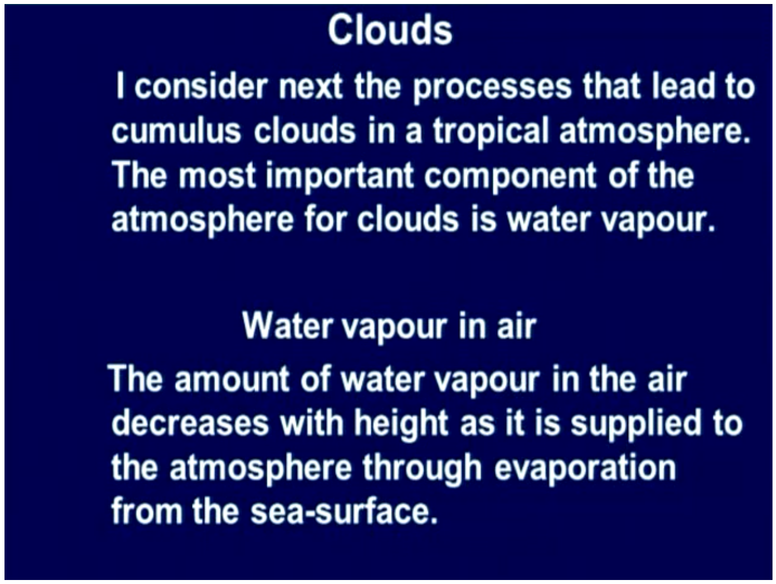

Now I consider processes that lead to cumulus clouds in a tropical atmosphere, the most important component of the atmosphere for clouds is of course water vapour, and we will have to define a few terms here. Water vapour in air, the amount of water vapour in the air decreases with height as it is supplied to the atmosphere through the evaporation from the sea surface, so the sources at the sea surface so obviously the distance from the source it is going to decrease okay.

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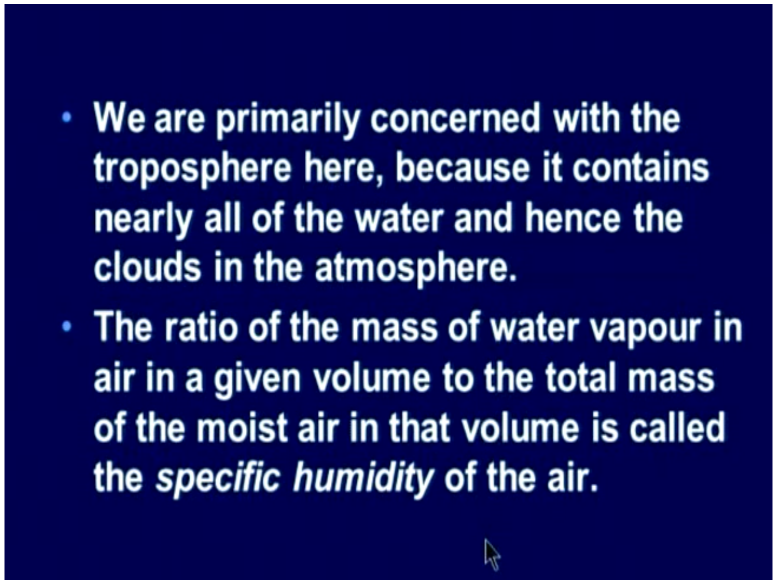

Now we are primarily concerned with the troposphere here, because it contains nearly all the water and hence the clouds in the atmosphere. The ratio of the mass of water vapour in air in a given volume to the total mass of the moist air in that volume is called the specific humidity of the air okay, so ratio of mass of water vapour to the total mass is called the specific humidity.

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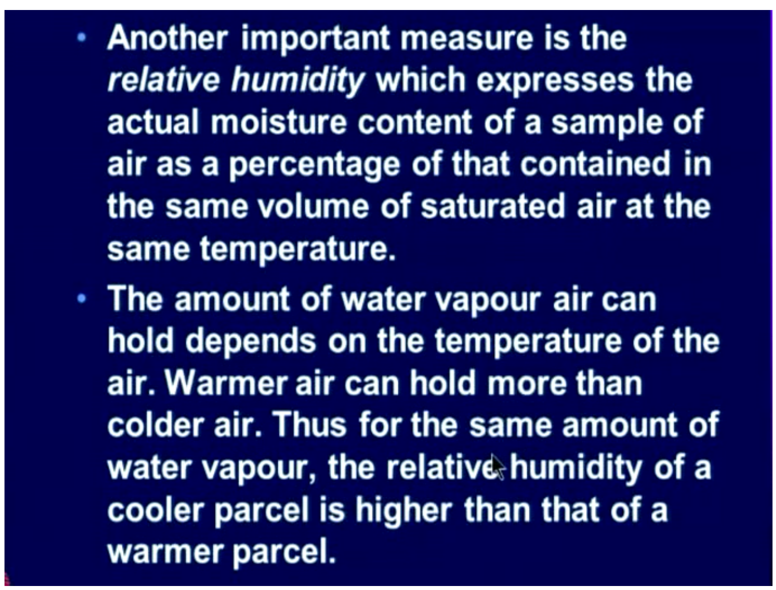

Another important measure is the relative humidity which expresses the actual moisture content of a sample of air as a percentage of that contained in the same volume of saturated of air at the same temperature, so when relative humidity is 100% that means the air is saturated, if it is 80% that means the air is not saturated, so relative humidity is very convenient a measure of humidity.

Now we all know that the amount of water vapour air can hold depends on the temperature of the air.

Warmer air can hold more water vapour than colder air, thus for the same amount of water vapour the relative humidity of a cooler parcel is higher than that of the warmer parcel. This is why if you place cold water in a glass of water you will see that air around the outer edges of the glass becomes cold, then it becomes saturated so the same amount of water vapour is there everywhere in the room but this air because it is colder gets saturated and water droplets appear outside the cold glass this is exactly what is happening here.

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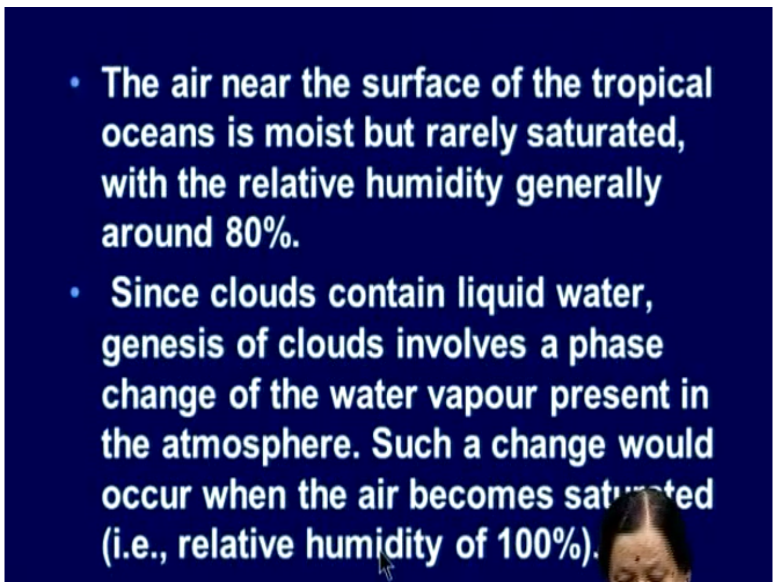

Now the air near the surface of the tropical oceans is moist but rarely saturated, with the relative humidity generally being around 80%. Now since clouds contain liquid water genesis of clouds involves a phase change of the water vapour present in the atmosphere, now as I mentioned in the example with a glass of cold water such a change would occur when the air becomes saturated that is relative humidity of 100%, for condensation of water vapour to water we have to get the relative humidity to increase to 100%.

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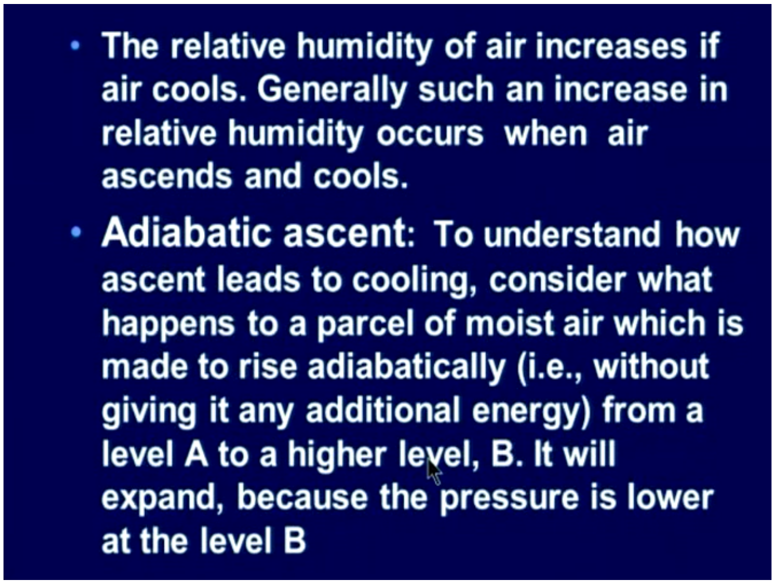

Now relative humidity of air increases if air cools, generally such an increase in relative humidity occurs when air ascends and cools. Now we have to understand how air cools during ascent? And what are the implications? So this is a very important components of clouds now adiabatic ascent. See to understand how ascent leads to cooling, consider what happens to a parcel of moist air which is made to rise adiabatically.

So you take up a parcel of moisture and let it go to a higher level without supplying any extra energy no additional energy is to be supplied the parcel has to be just lifted to another level okay from level A to a leve1 B.

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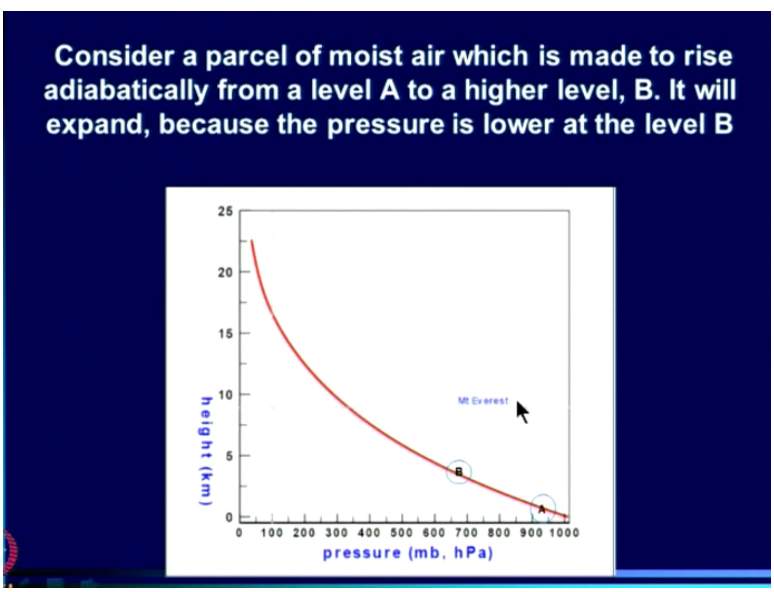

Now what will happen? So this is in fact the pressure that you have seen earlier with Mount Everest here, and we are taking a parcel of air A and we are lifting it adiabatically that is without giving any extra energy to it to 1eve1 B okay, then remember that the pressure at this level is lower than the pressure at this level right. Therefore, since the pressure at the higher level is lower the parcel will expand because the pressure is lower okay.

So because the pressure is lower when you take the parcel from A to B the parcel will expand.

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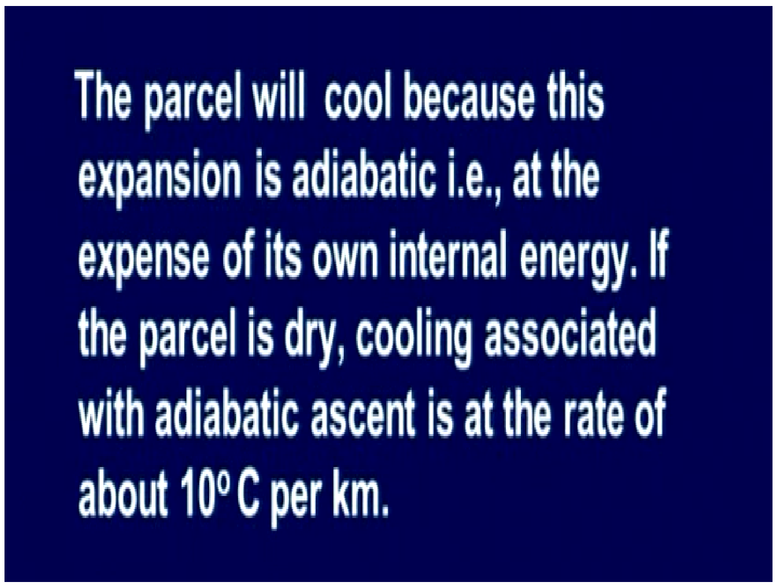

But we are not giving it any additional energy, so it will help to expand the energy that it needs will be at the expense of its own internal energy, so the expansion will occur at the expense of its own internal energy and therefore, the parcel will cool okay. So now we can actually calculate and as I promised I will not have too many equations in this course at this point I will not quote the equation.

But one calculate that if the parcel is dry cooling associated with adiabatic ascent is at the rate of about 10 degree centigrade per kilometer. See we can easily calculate how much it cools because of expansion to the pressure at the new level, so that is generally of the order of 10 degree centigrade per kilometer.

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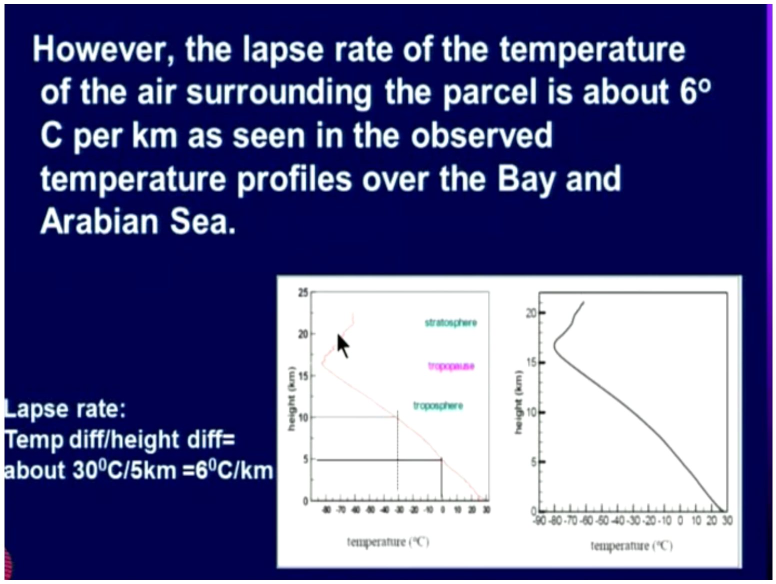

Now what is the observed lapse rate? Lapse rate is the rate at which the temperature decreases with height okay, so we already had remembered we had temperature profiles in the atmosphere over the Arabian Sea and over the Bay, and from these temperature profiles you can calculate as I have done here crudely what is the observed lapse rate of the air, and it comes to so for the temperature difference of about 30 degrees here okay is achieved in about 5 kilometers.

That is to say this is the rate of about 6 degree centigrade per kilometers, so the environmental temperature is increasing at 6 degrees per kilometer, but the parcel which we took from A to B actually decreased at 10 degrees per kilometer, so every time it ascends adiabatically it will find itself cooler than the environmental around.

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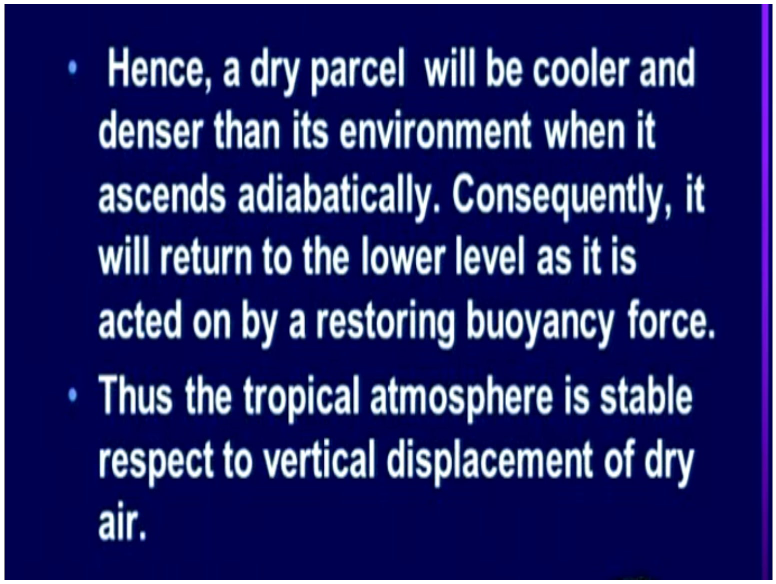

So I a dry parcel will be cooler and denser than its environment and because it is cooler and denser than its environment it will return to its lower level as it is acted on by restoring buoyancy force. So what happens to a dry parcel of air? Dry parcel of cools at the rate of 10 degree centigrade per kilometer the around it is only calling at the rate of 6 degrees centigrade per kilometer, so at the new level it is going to find itself colder and therefore denser than the surrounding air.

Therefore, because its density is higher it has to go down, so this is restoring buoyancy force will make it go down, now you remember definition of stability this means that the tropical atmosphere is stable with respect to vertical displacement of dry air, this is something we had seen before. That in fact if you have a dry parcel and you to it up without giving it additional energy it will come down.

And this shows that it is stable system because perturbation that you have given to the system by displacing the parcel vertically upward in fact decays with the time and the system goes back to its original state, so this system is a stable system. So what have we learnt here now? That in fact the tropical atmosphere is stable with respect to vertical displacements of dry air, now this dry air is important.

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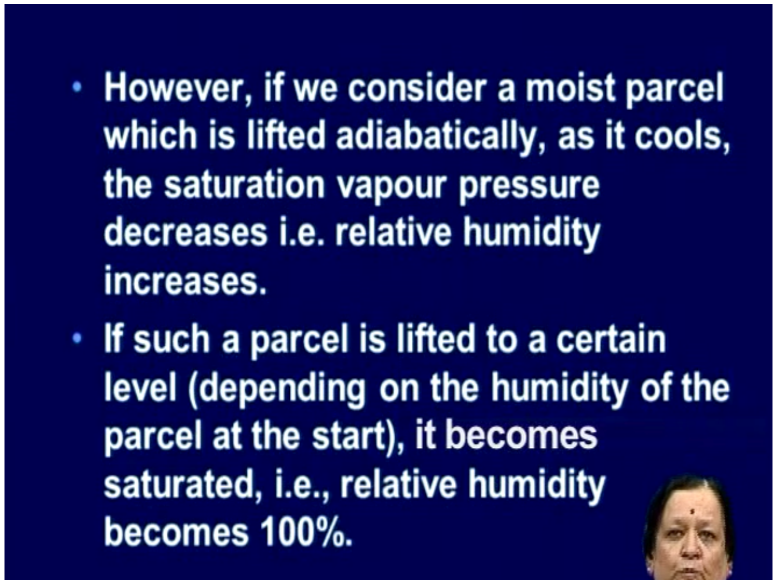

Now what if he took a moist parcel that is air which contains a water vapour and did the same thing, when that is lifted adiabatically initially it will cool at the same rate that 10 degree centigrade per km, but at a certain level this parcel will get saturated because when it cools its relative humidity will increase and so the parcel will get saturated, now this level is called level of lifting condensation. And at this level the relative humidity has become 100% and the parcel has become saturated.

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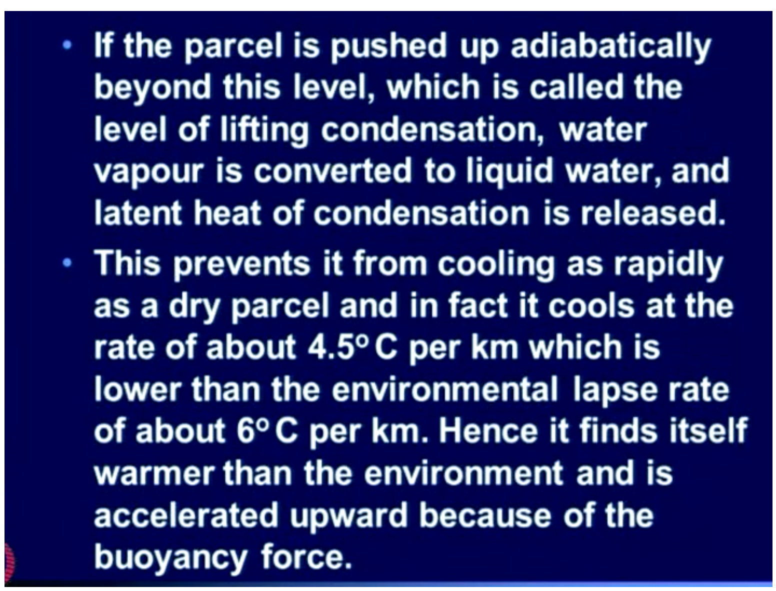

Now if the parcel is pushed up adiabatically beyond this level which is called the level of lifting condensation, then what happens? Then the air in the parcel already become saturated at this level, so beyond the leve1 it starts the water vapour starts condensing and water vapour is converted to liquid water, but what happens when the water vapour is converted to liquid water a large amount of heat is released, this is the so-called latent heat of condensation okay.

So when we have a parcel of moist air when will we lifted adiabatically initially it will call but if you can manage to lift it beyond the level at which it becomes saturated, then another process has come it starts getting warmer because of the latent heat of condensation that is released. Now because of this beyond its lifting condensation level the parcel when it goes up does not as rapidly as the dry parcel, in fact it cools at the rate of only about 4.5 per degrees per kilometer which is lower than the environmental lapse rate of 6 degrees per kilometer.

So this parcel when you have lifted it beyond the lifting condensation level in fact is warmer than the environment okay, the environment is cooling faster with height then this parcel is and therefore, it will find itself lighter than the environment so it will keep going up, you remember when we had a dry parcel it found itself in an environment related to which it was heavier, so it went back to its original position.

But once a moist parcel is lifted beyond level at which the condensation begins, because release of latent heat of condensation it becomes warm and it always find its a warmer than the air surrounding it, because the rate of its temperature decreases or its lapse rate is less than the lapse rate of the environment, environment is cooler faster than it is cooling faster with height then this parcel, so the parcel is buoyant relative to the environment and it will get accelerated upward.

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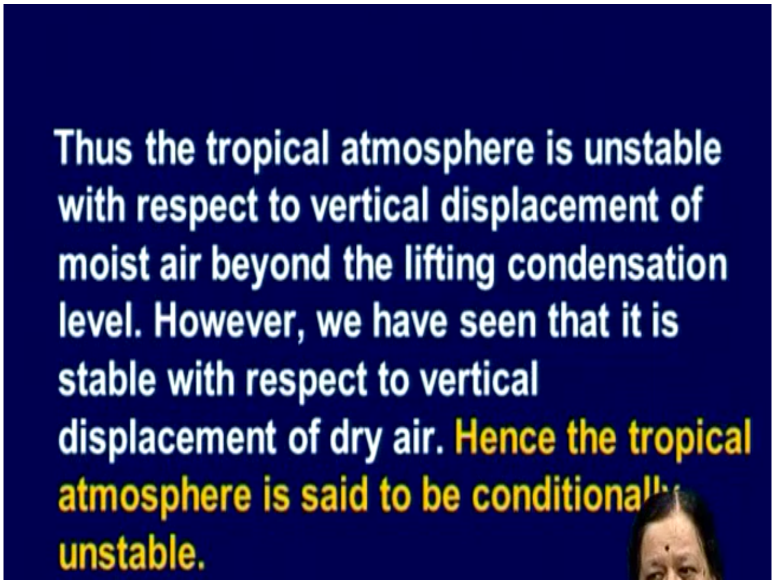

So this means that the situation is unstable right given a perturbation, the perturbation is growing given that you have pushed the parcel beyond this level it gives going up and up it never comes down again, so this means that the tropical atmosphere is unstable with respect to vertical displacement of moist air beyond the lifting condensation level, and it is stable with respect to dry air okay, so this is what is called conditional instability.

So tropical atmosphere is said to be conditionally unstable, why conditionally unstable? Because if there is dry it is stable, if there is moist it is unstable that is why it is called conditionally unstable.

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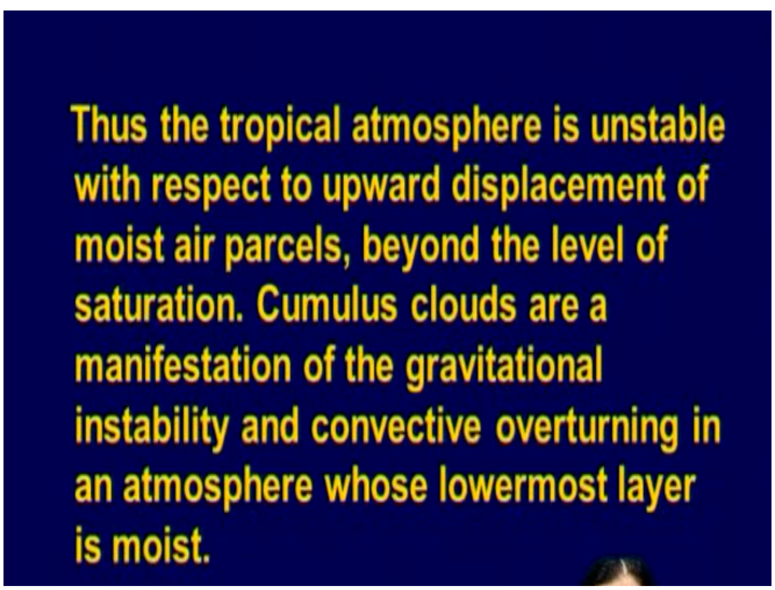

So the tropical atmosphere is unstable with respect to upward displacement of moist air parcel beyond the level of saturation. Cumulus clouds are a manifestation of the gravitational instability and convective over turning in an atmosphere whose lowermost layer is moist, so cumulus clouds are manifestation of this instability.

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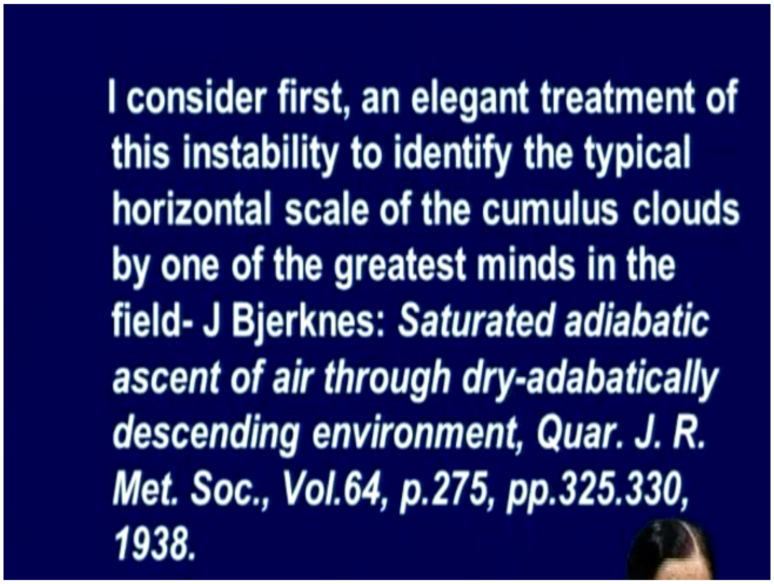

Now we have to ask the question, what happens in a conditional unstable atmosphere? How do cumulus clouds arise? Now first I consider an elegant treatment of this instability to identify the typical horizontal scale of the cumulus clouds by one of the greatest minds in this field Bjerknes and this is the paper that came out in 1938. I must tell you now, whenever we have an unstable system the approach is as follows, you would like to know how well the instability manifested?

What is typically the horizontal scale of the systems we will see as a result of the instability, to find that the game is played as follows? in fact what we do is perturb that unstable system with a perturbation of different spatial scales okay, you allow a different spatial scales perturbation in the system and then see which scale grows fastest in that unstable situation. And the idea is that means if you had all kinds of perturbation rather a perturbation compressing all scales.

Then that scale which grows the fastest will dominate and that is the scale that we will actually see as a manifestation of the instability, so this is how the game is played in stability problems and that is what exactly Bjerknes did.

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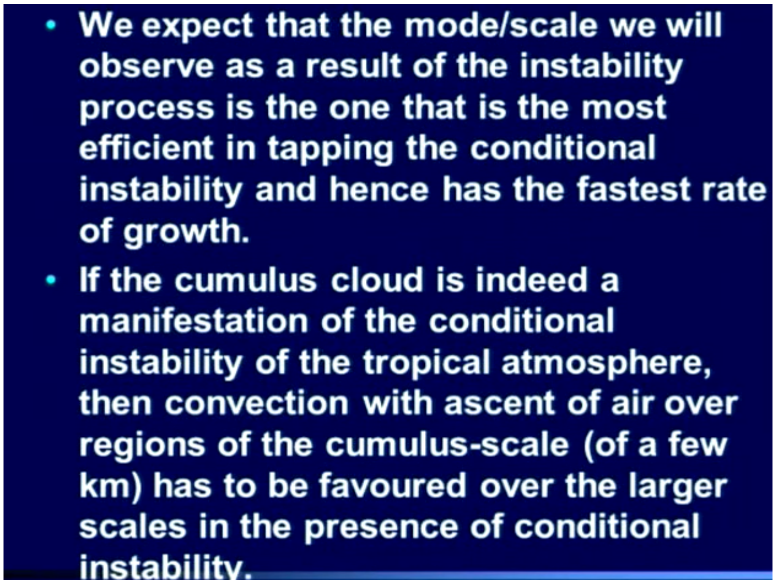

That we expect that the mode or scale we will observe as a result of the instability is the one that is the most efficient in tapping the conditional instability and hence has the fastest rate of growth, so you have a computational between modes of different spatial scales and the one that is growing fastest will in fact comes slowly to dominate that group and therefore, that is what we will see as the manifestation of the instability.

Now if the stimulus clouds are indeed a manifestation of the conditional instability of the tropical atmosphere, then convection with ascent of air over regions of the cumulus scale that is to say a few kilometers, we have already noted that the horizontal scale of raining cumulus clouds is of the order of few kilometers. So somehow this scale has to be selected over other scales in the presence of conditional instability.

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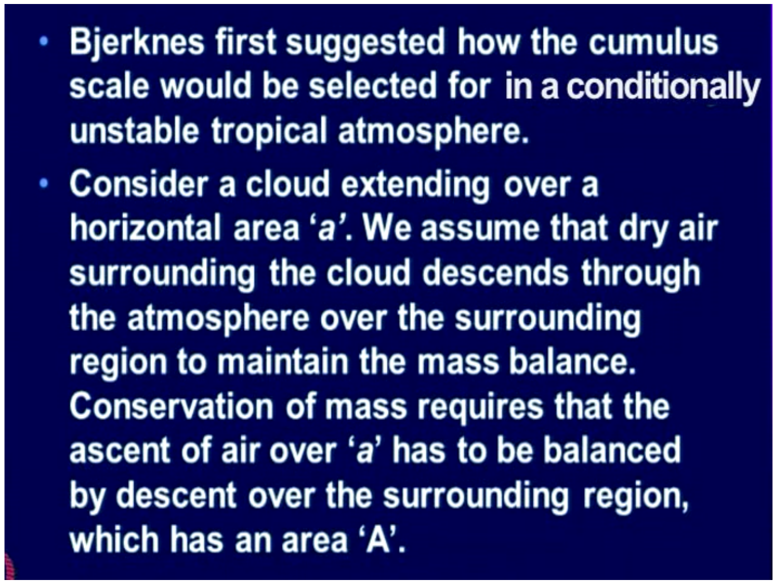

Now Bjerknes first suggested how the cumulus scale would be selected for a conditionally unstable tropical atmosphere.

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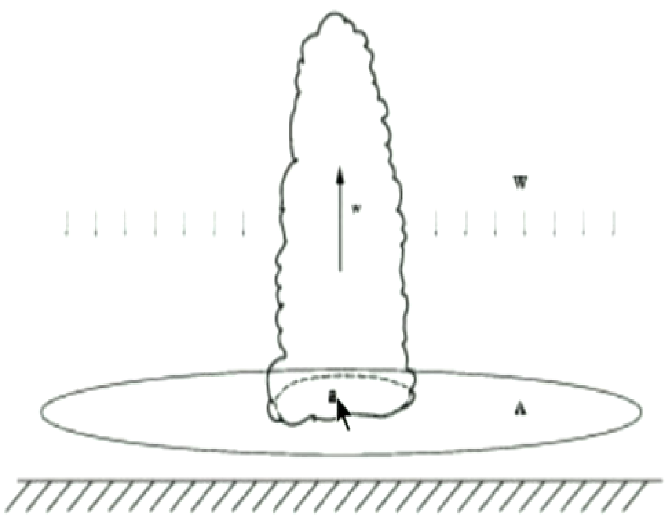

Now what we do is consider a cloud here, this is an idealized picture consider cloud which has a horizontal cross section of area a, and in the cloud we have already seen that for the cloud to form you should have an ascent of surface air to a level at which it becomes saturated and beyond that it will keep accelerating this is the ascending air in the cumulus cloud, and the air that goes up has to come down.

So around the cloud is the big area A here capital A in which there is descent taking place, so by conservation of mass or continuity or whatever you would like to call it, as much air that goes up as to come down, and if we have a smaller area a then the region of the descent, then the vertical velocity here will be higher than the velocity of descent here. So this is the system then the cloud air going up and this is the air finally returning to the surface, this is what Bjerknes looked at.

Consider a cloud extending over a horizontal area a, we assume that the dry air surrounding the cloud descends through this atmosphere over the surrounding region to maintain the mass balance. Conservation of mass requires that the ascent of air over a has to be balanced by the descent over the surrounding region.

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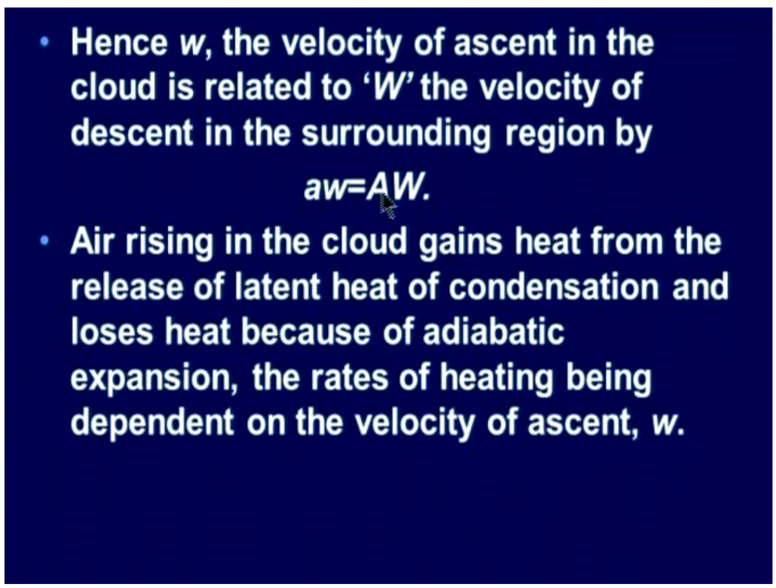

So that is to say small a*small w, w is the upward velocity has to be=big A*big W okay. So w is the velocity of ascent in the cloud, and capital W is the velocity of decent in the surrounding region, A is the area over which air is descending, little a is the area over which air is ascending in the cloud. So just by conservation of mass we have aw=capital A capital W. Now what is actually happening?

Air rising in the cloud gains heat from the release of latent heat of condensation and losses heat because of adiabatic expansion, the rates of heating being dependent on the velocity of ascent, w okay. So there are 2 processes going on inside the cloud, parcels are sending in the cloud are also expanding and therefore, cooling adiabatically. But a gaining heat through the latent heat of condensation, and how much they gain depends on how fast w is, how high w is.

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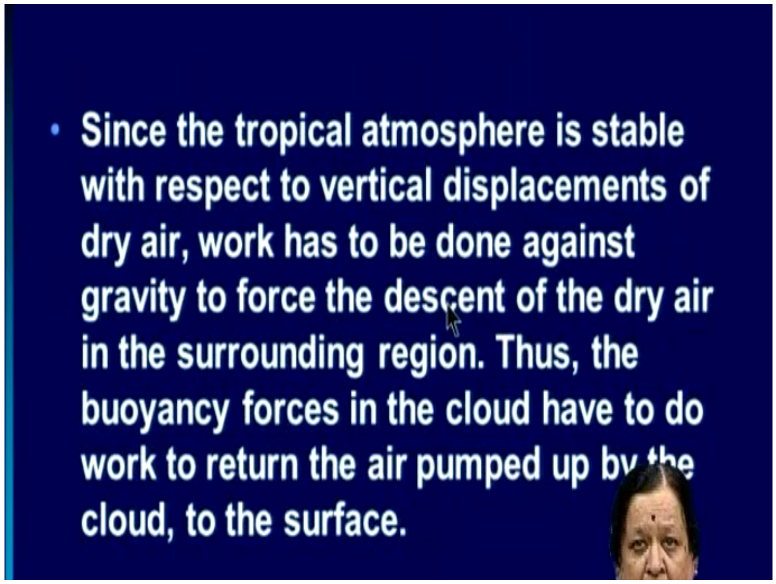

Now since the tropical atmosphere is stable with respect to vertical displacement of dry air, work has to be done against gravity to force the descent of dry air in the surrounding region, then this is what Bjerknes postulated which will come to examine this letter. So according to Bjerknes then cloud are doing the following, by the latent heat release the air is accelerating upward then it descents in this surrounding region.

But you know when it descents in the surrounding region the moisture has been rained out, so you have dry air descending in the surrounding region but dry air cannot simply decent in the surrounding region, because dry air is stable right tropical atmosphere is stable with respect to vertical displacement of dry air, so work has to be done to force the dry air to descent okay.

And this work to be done against gravity to force the descent of the dry air in the surrounding region is also done by the clouds, this is Bjerknes hypothesis. Thus, the buoyancy forces in the clouds have to do work to return the air pumped up by the cloud to the surface, this is a scenario that Bjerknes imagine.

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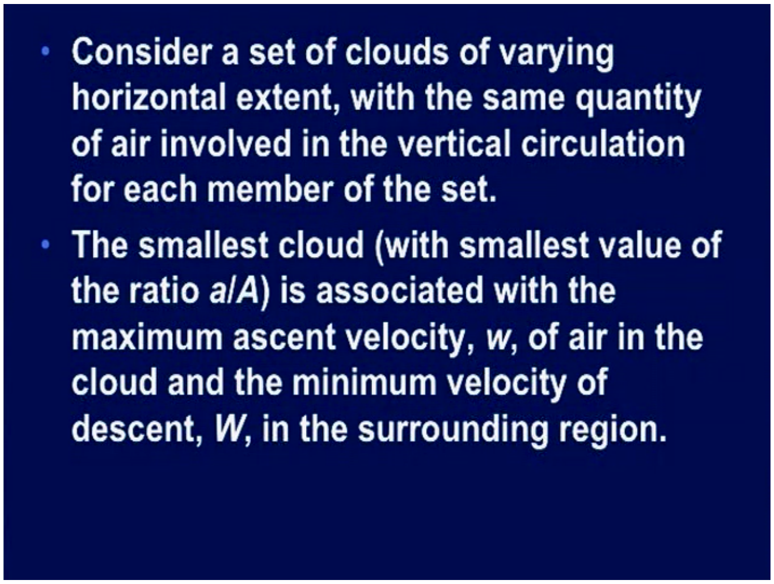

Now in this scenario, now consider a set of clouds of varying horizontal extent, with the same quantity of air involved in the vertical circulation for each member of the set okay, so to go back then what we are imagining is different clouds with different values of a and consistent with that approximate value of capital A. So you a have large number of clouds in which the horizontal extent varies okay.

Now the smallest cloud with the smallest value of ratio a/A is associated with the maximum ascent velocity w, of air in the cloud, now why is that? That is very simple because aw=AW, so if you have a small and large capital A, then this equation only holds if this is very large related to this. So if you have a small radial extent smallest cloud with the smallest value of the ratio a to capital A is associated with the maximum ascent velocity w, of air in the cloud and the minimum velocity of decent W, in the surrounding region.

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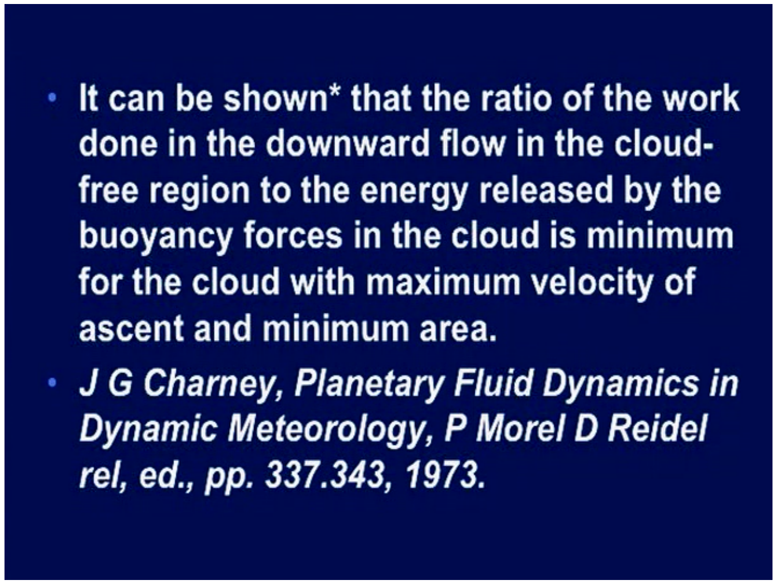

Now it can be shown and I am not going to get into details of this, but a very loose treatment by a lecture notes by Charney another greatest scientist in this area, he has shown that the ratio of the work done in the downward flow in the cloud-free region to the energy released by the buoyancy forces in the cloud is minimum for the cloud with maximum velocity of ascent and minimum area.

In other words, the thinner the cloud okay the ratio of the work done in the downward flow to the buoyancy forces is minimum that is to say the buoyancy force is have to do minimum work if the cloud is very thin okay. So it is thin clouds are associated with maximum velocity of ascent, for which the work done in downward flow in the cloud-free region is minimum okay.

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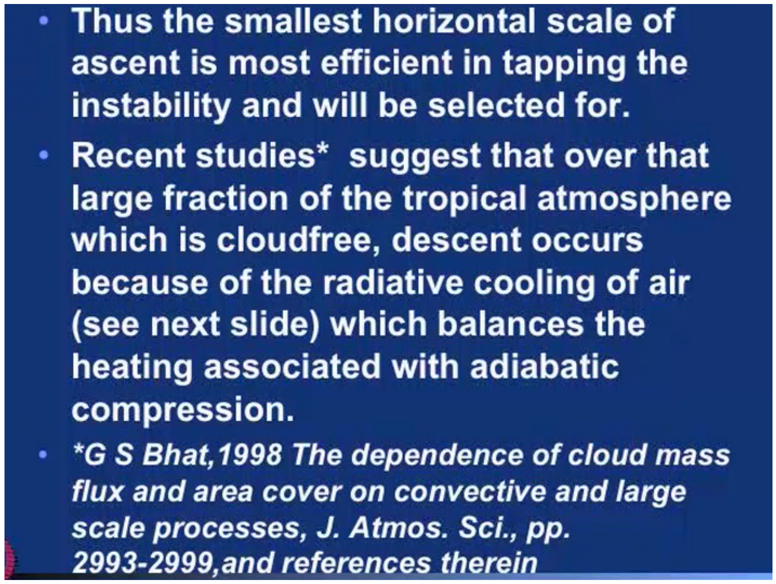

So what does this mean? This means the smallest horizontal scale of ascent is the most efficient in tapping the instability and will be selected for okay. So this is what Bjerknes showed that if we do an instability analysis of the conditionally unstable tropical atmosphere, we will get a selection for the smallest scale of ascent smallest cloud with the largest ascent velocity that is what is being selected for.

Now remember that a key point in this study was to see how much work has to be done by the cloud air, in pushing the air downward towards the surface around the clouds okay against the stability gradient. So this was part of the analysis here, but recent studies and there is a nice paper by my colleague who has discussed this, they show that the large fraction of the tropical atmosphere which is cloud-free in fact in that part descent occurs because of the radiative cooling of air which balances the heating associated with adiabatic compression.

So according to recent studies, the clouds really do not have to push the air down against the stability gradient, because as we noted earlier there is a radiative cooling going on and that radiative cooling can balance the heating that occurs due to adiabatic compression, so this is the development that happened after the Bjerknes.

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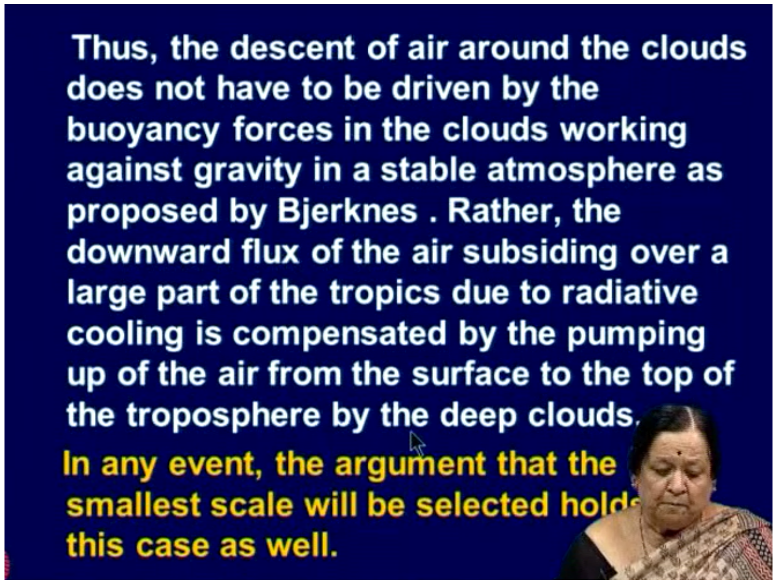

So the descent of air around the clouds does not have to be driven by buoyancy forces in the clouds working against gravity in a stable atmosphere has proposed by Bjerknes. Rather, the download flux of air subsiding over a large part of the tropics due to radiative cooling is compensated by the pumping up of the air from the surface to the top of the troposphere by the deep cloud okay.

So what is now happening is that everywhere almost everywhere in the troposphere you have air sinking because it is being cold radioactively, and it is only in this cloud chimneys where the air from the surface returns to the top of the troposphere from where it is descending okay, so this is another view to look at it. But in any event, the argument that the smallest scale will be selected holds in this case as well.

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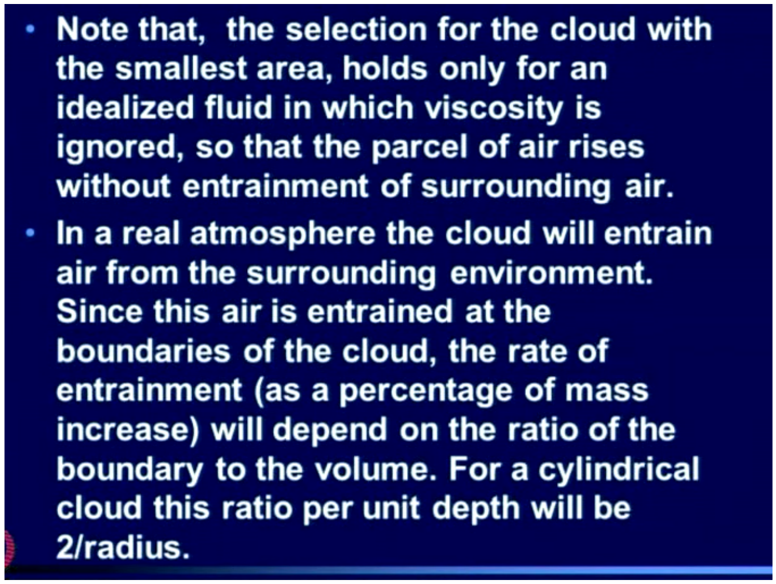

So now we have to look at one more point here, so far we have been looking more or less at an inviscid problem that is a problem in which we do not worry about friction okay. So selection for the cloud with the smallest area holds only for an idealized fluid in which viscosity is ignored, so that the parcel of air rises without any entrainment of surrounding air as the parcel of air is rising, because of the friction you expect the surrounding air to actually mix with that parcel and that is the effect that is not taken into account in this treatment.

Now in a real atmosphere the cloud will entrain air from the surrounding environment, since this air is entrained at the boundaries of the cloud the rate of entrainment as a percentage of mass increase will depend on the ratio of boundary to the volume right. If you imagine a cylinder then the boundary goes like 2 pi r the circle, and the area goes like r square okay. So the thinner the cylinder right then the larger the ratio of the circumference to the area.

So for a cylindrical cloud this ratio per unit depth will be of the order of 2/radius okay, so the thinner the cloud the larger the possibility of entrainment this is what it says.

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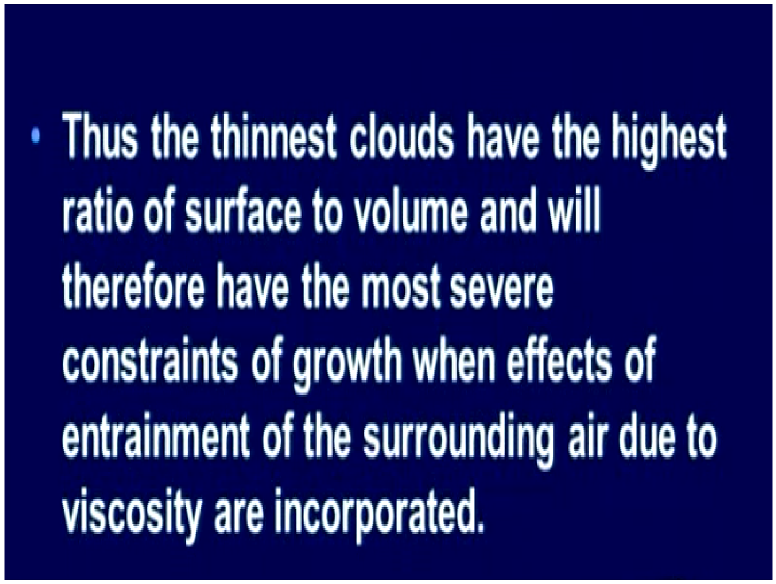

Thus, the thinnest clouds have the highest ratio of surface to volume and will therefore, have the most severe constraints of growth when effects of entrainment of the surrounding air due to viscosity are incorporated. Remember that entrainment is going to put a break on to the convection put a break on to a growing cloud, because entrained air is dry, whereas the cloud comprises liquid water.

So this mixing of dry air will decrease the humidity of the air and it is not good for condensation to occur. So having entrainment is going to hamper the cloud and the thinner the clouds the more the entrainment okay. So on the one hand if you look at the inviscid problem it is the thinnest clouds that will be selected, but when we consider the fact that in a real fluid there will be entrainment.

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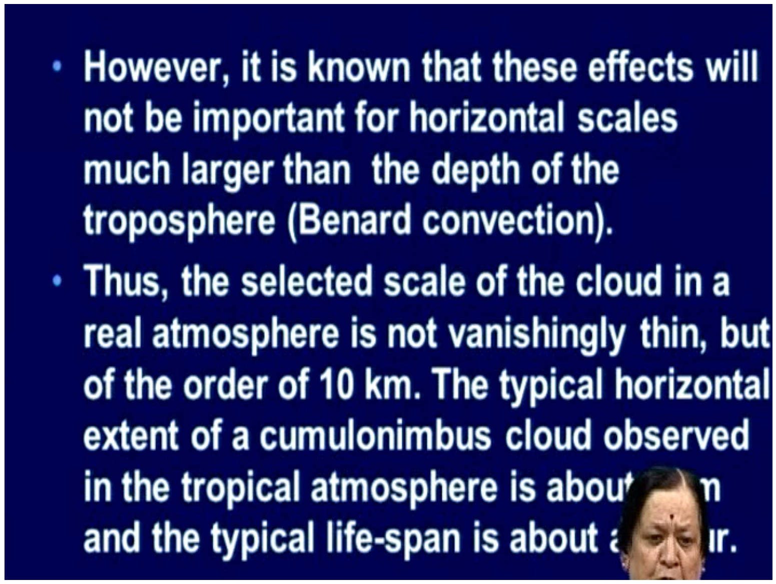

Then this entrainment will have the largest impact on the thinnest clouds, so this means not the thinnest but some scale larger than the thinnest for a real atmosphere. Now what is the scale that is going to be selected? It is known that these effects will not be important for horizontal scales much larger than the depth of the troposphere, now this is the result we know from the convection theories fluid convection theories, the classic problem of Benard convection of a fluid heated from below.

Again I am not going to go in to this, but taking the result of that it then is clear that the thinnest scale is not going to be selected for because they are going to be too much entrainment of dry air in the cloud, the selected scale of the cloud in the real atmosphere is not vanishingly thin but of the order of 10 km, because the troposphere is of the order of 10 km 10 to 15. So the typical horizontal extent of a cumulonimbus cloud will be of that order and it is in fact of the order of about 5 km, and I may have mentioned that the typical life-span is about an hour.

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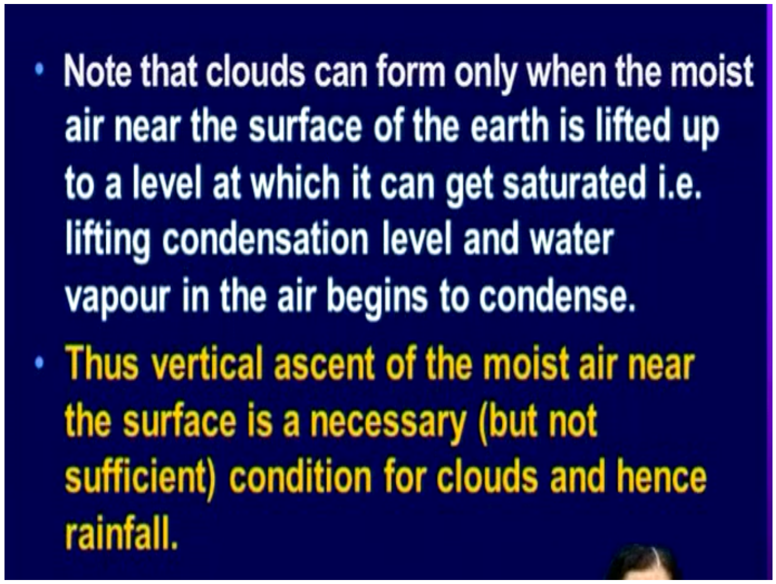

Now note the clouds can form only when the moist air near the surface of the earth is lifted up to a level at which it can get saturated that is lifting condensation level and water vapour in the air begins to condense. What is the critical feature required now for clouds to form? Vertical ascent of moist air near the surface is a necessary but not sufficient conditions for clouds and hence rainfall.

Because you may have vertical ascent it may not be strong enough to release enough latent heat of condensation for the cloud to grow, this is why it is necessary condition, but not sufficient condition that is to say you cannot have clouds unless you have an ascent of moist air from the surface, but merely having some ascent of moist air you know at some velocity does not guarantee that you will get clouds okay.

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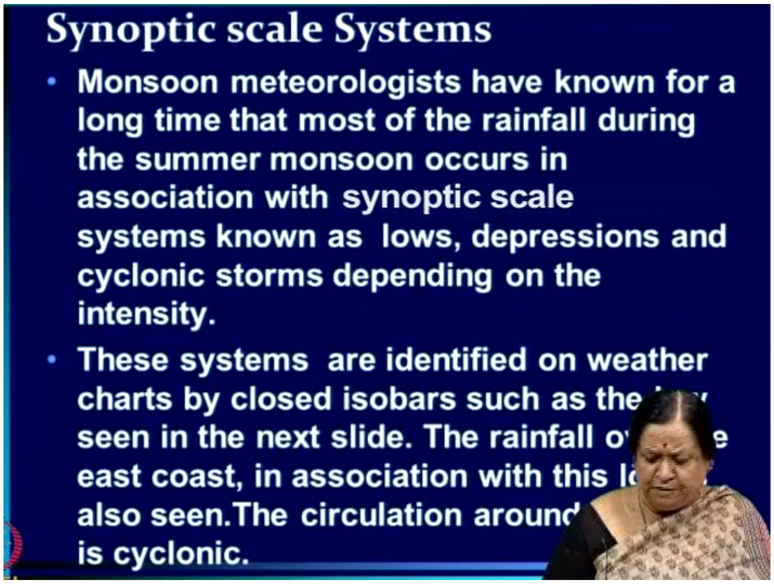

Now let us look systems that give us rain and there has been a lot of study of these systems for almost over 100 years using what meteorologist called weather maps okay, and synoptic scale system is what they identify them as these are systems that are associated with rainfall okay. And monsoon meteorologists have known for a long time that most of the rainfall during the summer monsoon occurs in association with synoptic scale systems known as lows, depressions, and cyclonic storms depending on their intensity.

Now you know before the satellites came and even now one of the major tools of the meteorologist is so called weather map, on which every day the observations, pressure, winds etc. have been allotted and often contours of equal pressure, equal wind, and so on are also drawn. So you have charts with isobars drawn and winds on them at different levels, so these systems are identified on weather charts.

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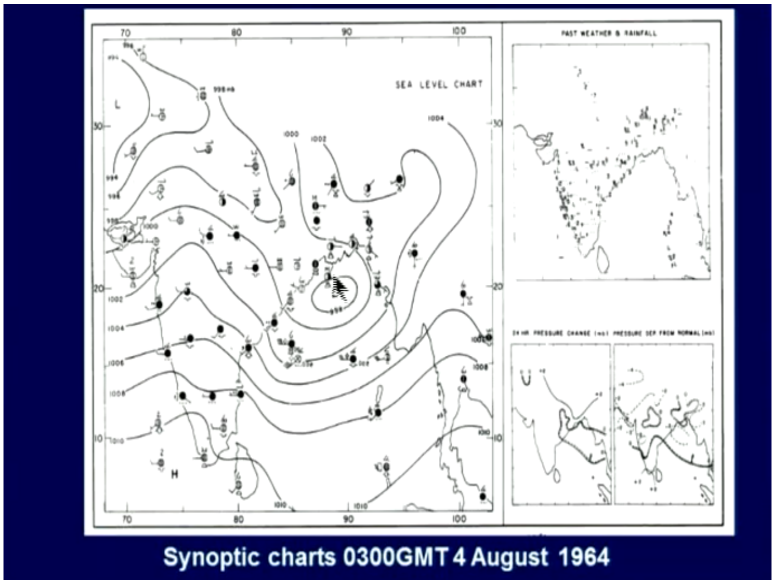

And I will give you some examples of the weather charts, a lot of these you can find in a very nice book by Y. P. Raw in Southwest monsoons this will all be in your recommended references, so this is the sea level chart that you see here, this is a sea level chart in a specific day. It is 3 GMT, 3 GMT 8:30 in the morning 4th of august 1964 and what you see here are isobars okay and there is one closed isobar, this is a low this is a low pressure here okay.

And corresponding to the low pressure you can see that there are of course westerly winds here and easterly here, and you can imagine that the geostrophic flow above where low also pursues will be counter-clockwise or cyclonic, so this is lower pressure system. And what you see here is the rainfall associated with it and it is by and large where the low is okay.

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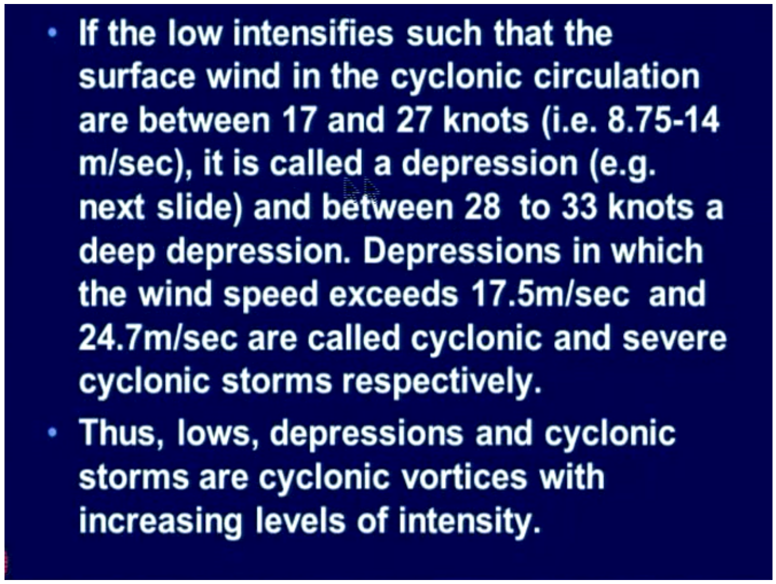

Now, so if the low intensifies such that the surface wind in the cyclonic circulation are between 17 and 27 knots, now this is what meteorologist usually used for winds, and this is what you see plotted on the weather charts, but for us who prefer metric units this correspond to about 9 to 14 meters per second. So the wind around the low has to be between 9 to 14 meters per second, then it is called a depression okay, a more intense low is all a depression.

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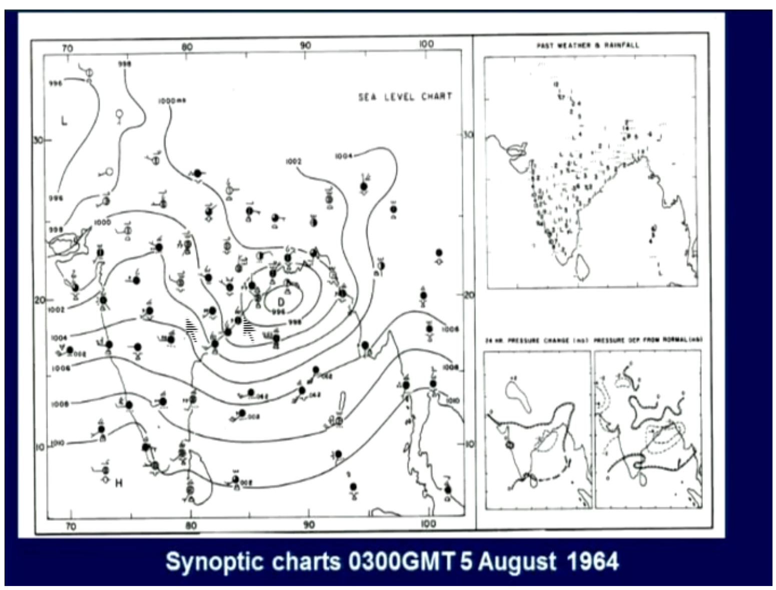

Synoptic charts 0300GMT 5 August 1964

And you will see an example in the next slide typically, you have more than one isobar around this and this is the depression, and this gives this kind of rainfall here. Now okay, so meteorologist have defined different systems depending on the intensity there all associated with cyclonic vorticity mind you, the lowest is low for which the velocity circulating velocity is less than about this 9 meters per second then comes depression where it is 9 and 14.

And then it is called if it is between 28 and 33 it is called deep depression okay, it is between 17 and 27 knots it is called depression, between 28 and 33 knots deep depression okay. So depressions in which the wind speed exceeds 17.5 meter per second and 24.7 meters per second are called cyclonic and severe cyclonic storms respectively, these names do not matter too much just remember that there are different kinds categories of cyclonic disturbances depending on the intensity.

And remember there all the cyclonic vortices with increasing levels of vorticity higher and higher vorticity associated, so this is the depression see this has now got more closed isobars this has become deeper.

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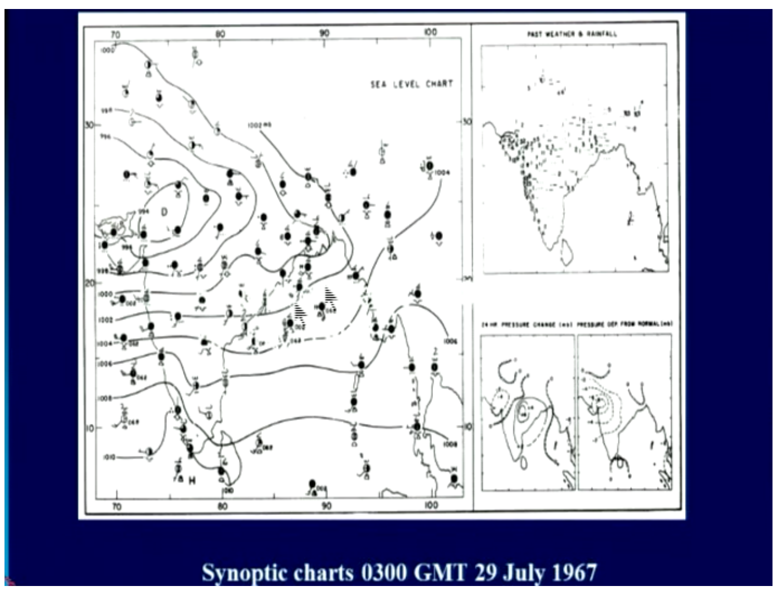

Synoptic charts 0300 GMT 29 July 1967

Now this is a depression on land and you can see here this is the rainfall here, and you can see that this is associated with high rainfall. And remember it is organized again over about a 1000 km or so in spatial extent.

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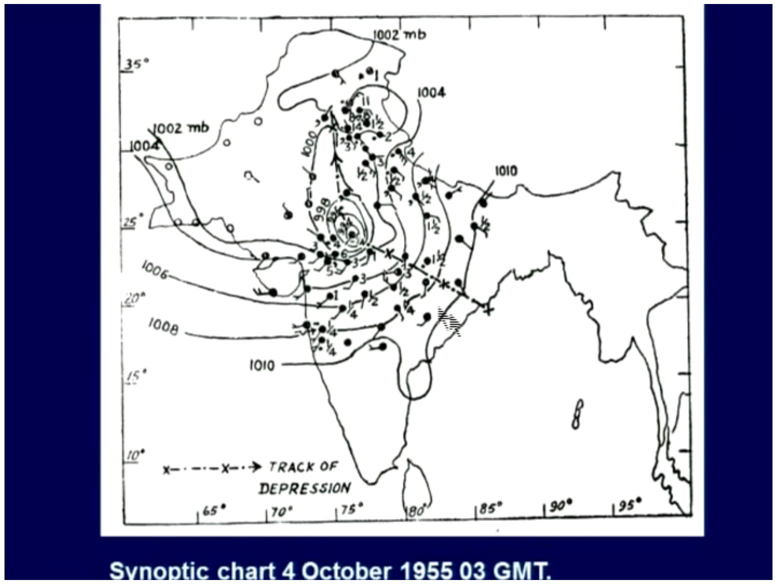

Synoptic chart 4 October 1955 03 GMT.

This is an example of a depression and just to give you a feel this is something that has moved from here to here okay, and now it is very intense depression centered on the land region of India, this is 4th of October 1955.

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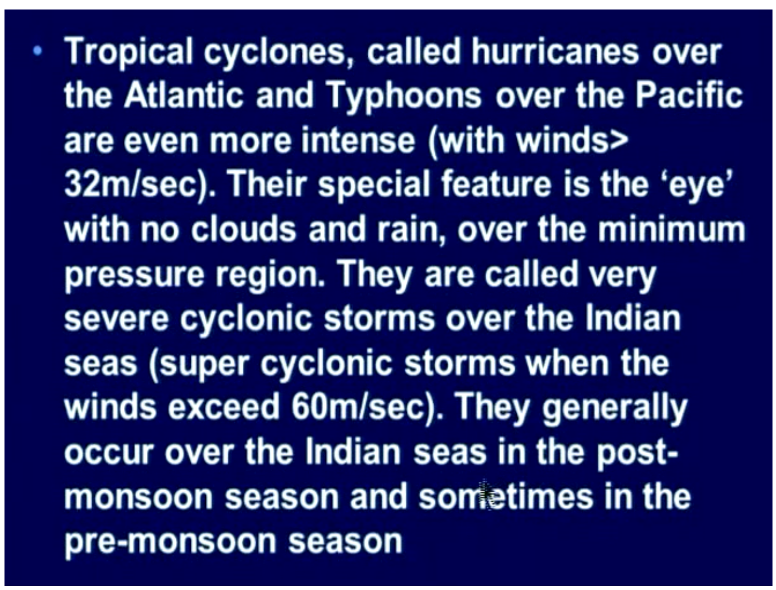

Now what happens when the system is even more intense than the severe cyclone, tropical cyclones which are called Hurricane over the Atlantic and Typhoons of the Pacific or even more intense, with winds about 32 meters per second. Now their spatial feature is the eye with no clouds and rain over the minimum pressure region okay, and they are called very severe cyclonic storms over the Indian seas.

Super cyclonic storms when wind exceeds 60 meter per second, and they generally occur over the Indian seas in the post-monsoon season and sometimes in the pre-monsoon season. So what are known as tropical cyclones or typhoons are seldom seen over the Indian seas during the summer monsoon, and why? I will explain when we come to it.

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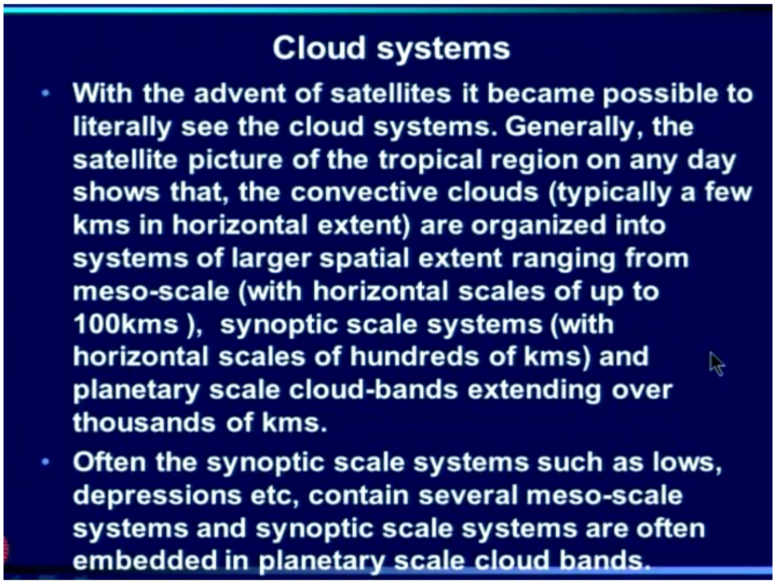

Now these are all systems which we are known well before the satellite era, but satellites give us and unique opportunity to see the clouds organization which is associated with this system. So with the advent of satellite it becomes possible literally see the cloud systems, so generally the satellite picture of the tropical region on any day shows that the convective clouds take look at this one.

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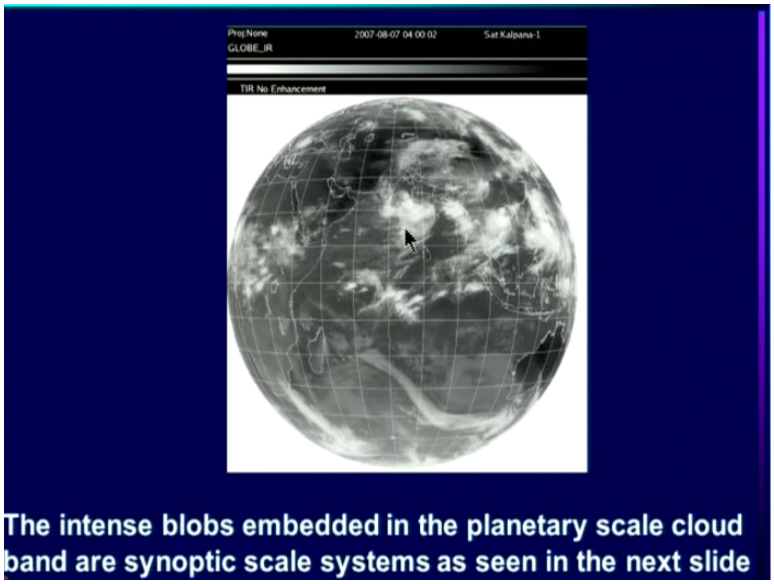

Now you can see that the convective clouds are organized over a very very large spatial scale, remember this is India here and so this itself is 2000 km, so you can see that this system is organized over 1000s of kilometers but within that there are some blobs which are bright and there are some regions which are not so bright. So you have on any single day in the tropics systems which are organized over different scales ranging from single systems synoptic scale systems to planetary scale systems.

So satellite picture of tropical region on any day shows that the convective clouds which are typically few kilometers in horizontal extent are organized into systems of larger spatial extent ranging from meso-scale to synoptic scale. Meso-scale is considered up to about 100 kilometers, synoptic scale is 100s of kilometers and planetary scales is extending over 1000s of kilometers. Often the synoptic scale systems are such as low depression etc. contains several meso-scale systems, and the synoptic scale systems are themselves embedded in cloud-bands.

So you see in this organized cloud-and which we can say is organized on a planetary scale, because it is extending over quarter of the earth here in terms of longitude, and in it are embedded disturbance which are synoptic scale disturbances of the kind lows, depressions and so on.

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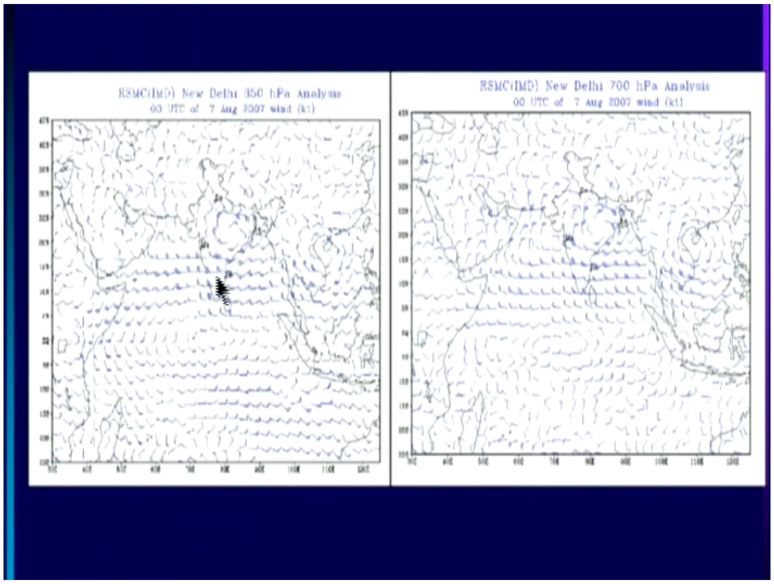

And this is this slide, which shows the wind pattern association with them, and at 2 levels, this is actually at 850 millibar that is just above the boundary line and you can see a very nice cyclonic vorticity here to the south of course it is westerly to the north it is easterly, and in this shear zone you have a very nice intense cyclonic vorticity. And this is a 700 millibar, 700 millibar are about 3 kilometers above the sea level is a level at which latent heat of condensation plays a big role.

So you get a low region here only when you have deep convective clouds at 3 kilometers, this is at 3 kilometers or so, and you see a very nice cyclonic circulation associated with it.

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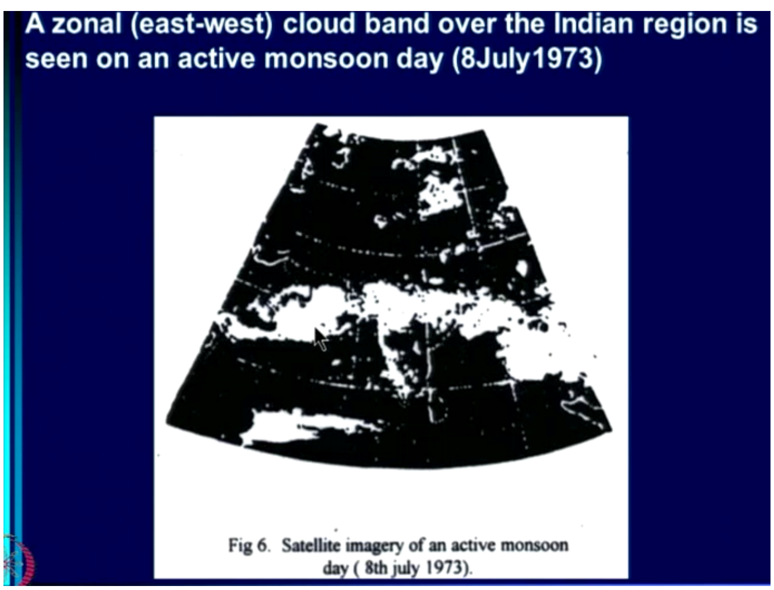

Now the first picture we saw of the zonal cloud-band also had you know this blobs embedded in it, it is not uniformly intense but rather there are cloud blobs embedded in it.

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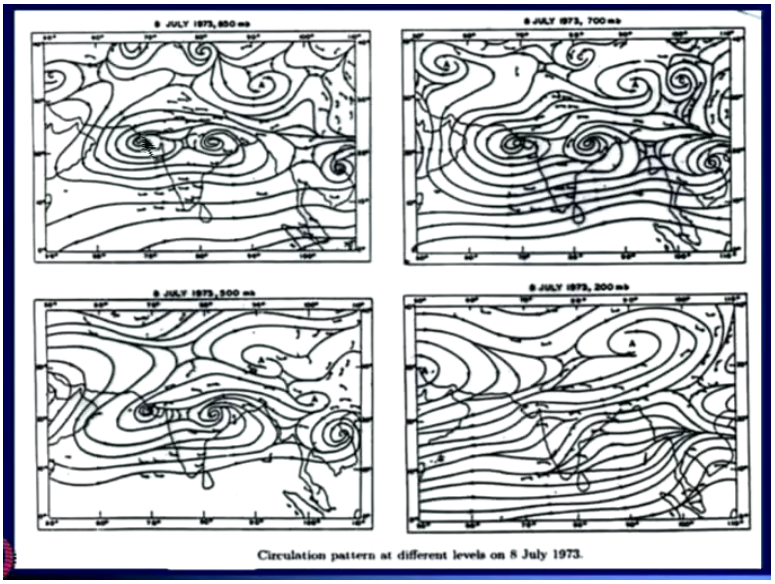

Circulation pattern at different levels on 8 July 1973.

And if we look at what is the kind of circulation for this cloud blobs, then you can see that there are all cyclonic vortices this is above the boundary layer this is again at 700 hpa and they are still intense you see that intense cyclonic vortices embedded in a general cyclonic vorticity region which is this whole region, embedded in it are strong cyclonic vortices which extend up to 500 millibar half the troposphere, and of course upper half the situation is different.

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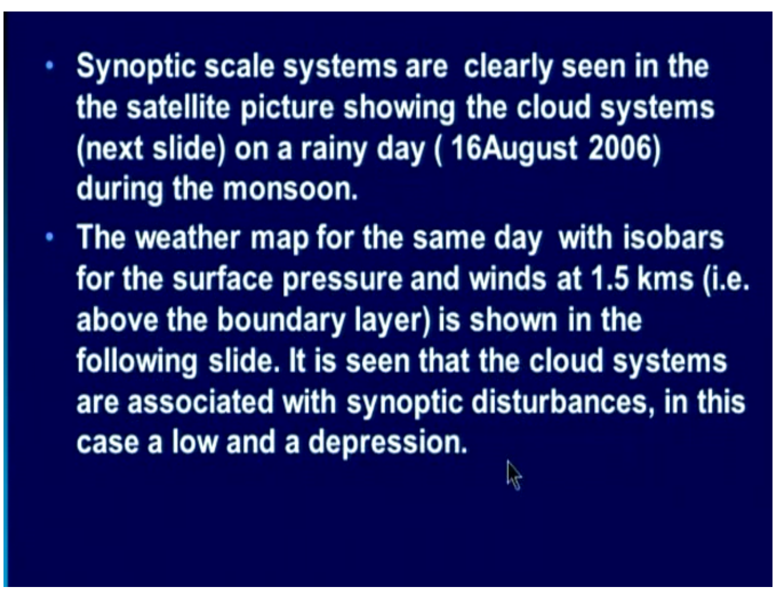

Here, now synoptic scale systems are clearly seen in the next picture also.

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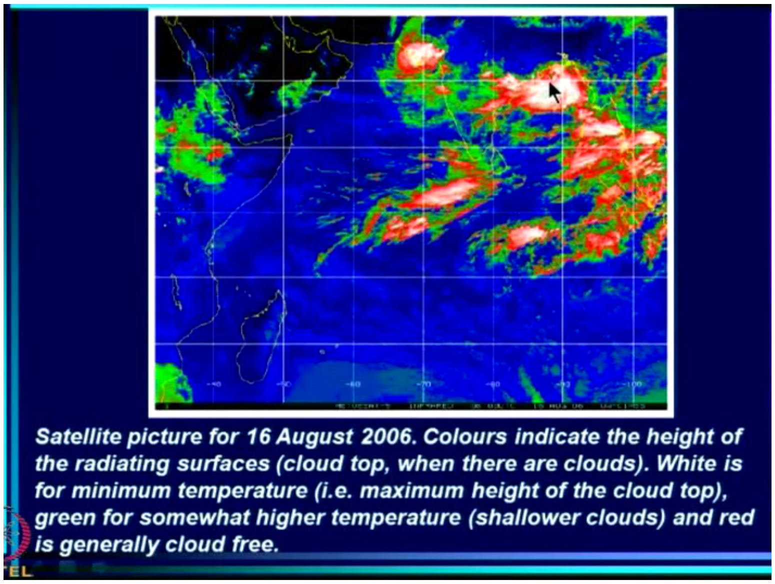

I just want to give you a feel for what the synoptic scale systems looks like, this is an infrared picture of meteor sat, and white means very deep cloud and red means deep clouds. And you see 2 distinct synoptic scale systems here, and there is another band of clouds here as well.

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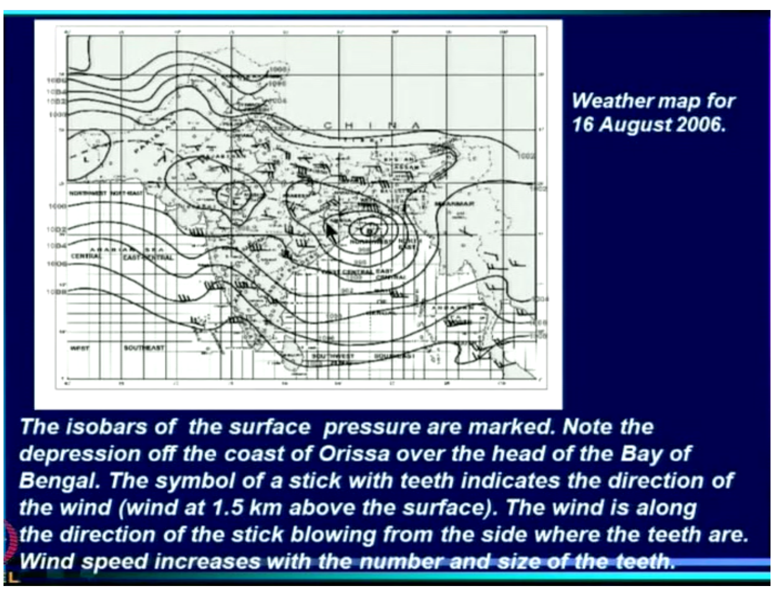

And for the same day this is how the weather map looks, you know this is lower and this is the depression, so you see that the cloud blobs of intense cloud that we see are invariably associated with cyclonic vorticity above the boundary layer okay.

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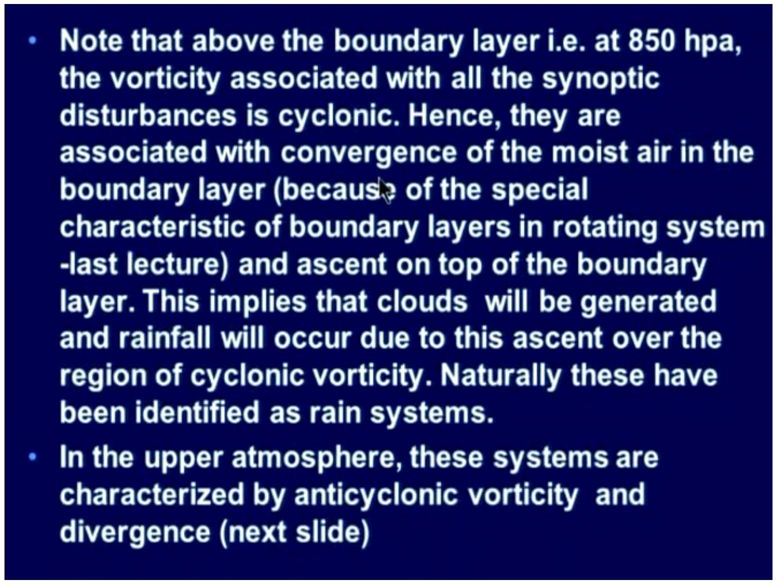

So all the synoptic disturbances all the systems what is the common future they have that above the boundary layer there is cyclonic vorticity, and hence what did we learn in the last lecture that if you have cyclonic vorticity above the boundary layer then you will have convergence in the boundary layer and remember the air converging in the boundary layer is moist air okay, so there is convergence of moist air in the boundary layer and ascent on the top of the boundary layer.

Why? Because in a rotating fluid, if you have cyclonic vorticity above the boundary layer you have convergence and you have an ascent of that air into the interior region. So what does this mean? This implies that clouds will be generated and rainfall will occur due to this ascent over the regions of cyclonic vorticity. So remember we said that unless the surface air is lifted up to and beyond the level at which the condensation takes place you cannot get clouds.

Now who is going to do the work of lifting? What happens is these disturbances as they are called monsoon disturbances the synoptic scale systems are often called monsoon disturbances in all these synoptic scale systems we have the distinguishing attribute of the synoptic scale systems is cyclonic vorticity above the boundary layer, and that cyclonic vorticity above the boundary layer is necessarily associated with convergence in the boundary layer and ascent.

So the synoptic scale systems then providing what the clouds need, and once they provide the ascent clouds will form, so in the upper atmosphere these systems are characterized by anticyclonic vorticity.

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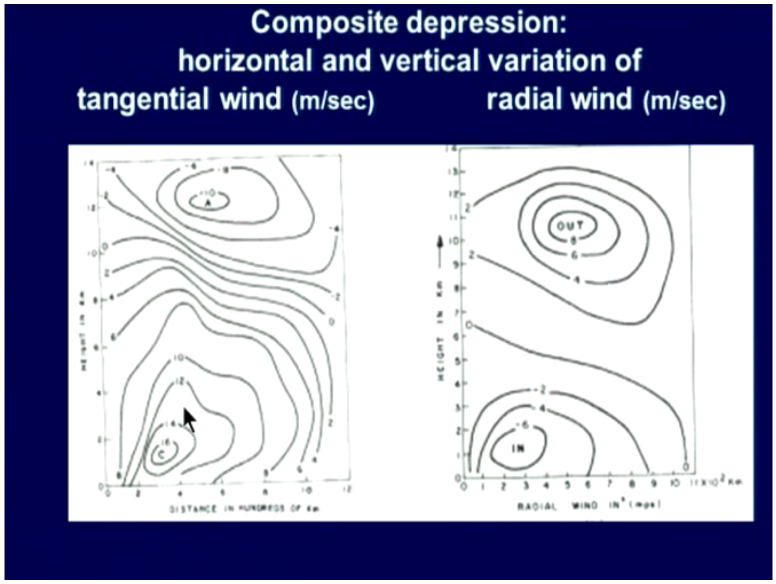

So now this is the composite remember I have shown you earlier a composite picture of the unset, now this is the composite picture of depression and what you see here is distance from the center of the depression, and this is the tangential wind okay and tangential wind is cyclonic up to a large part of the atmosphere and anticyclonic aloft. And the radial wind which is convergence, so it is converging moist air is controlling towards the center and once it rises then in the upper troposphere it divergence this is what you seen.

So this is the typical picture, vertical circulation then this is the radial component in and out and this is how the circulating component looks it cyclonic up to a high level in the atmosphere and in the upper levels it is anticyclonic.

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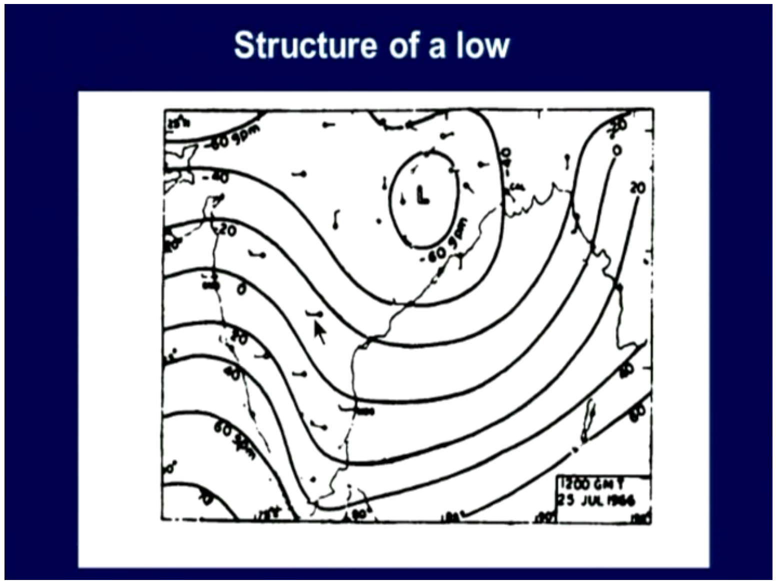

Now this is a structure of a low, and this is again another piece of work in which what they did is given all the kind of pressure and so on, they try to derive what is the vertical velocity by using equations.

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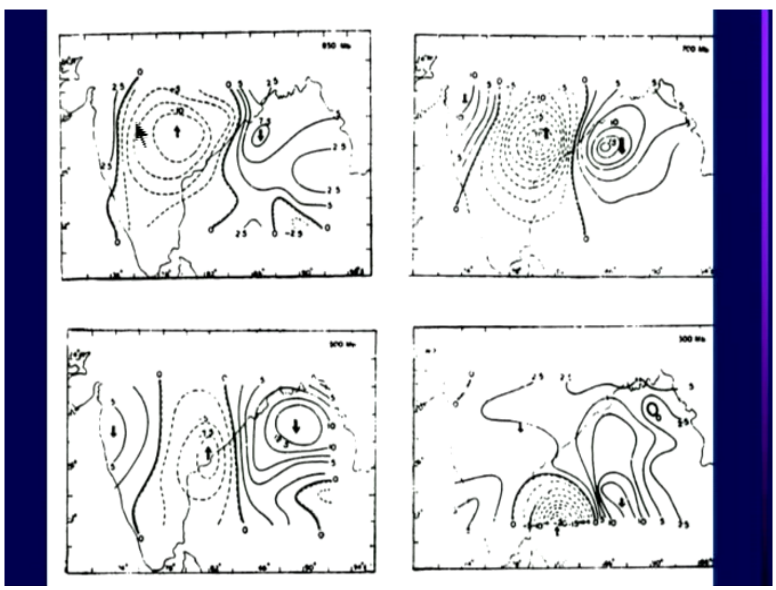

And what they find is see the velocity is upward over the Indian region and downward here, and it is also very much upward at 700 because it is lot of latent heat is being released, at 500 it has become weaker, and at higher level of course it is not there okay.

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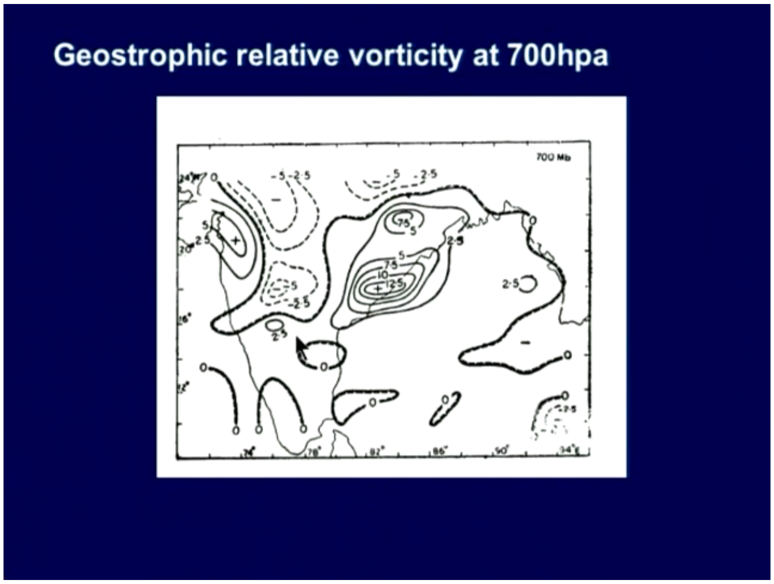

And they also calculated, what is the geostrophic vorticity, and they found that for the depression indeed the geographic vorticity is highly cyclonic, this is what we expected.

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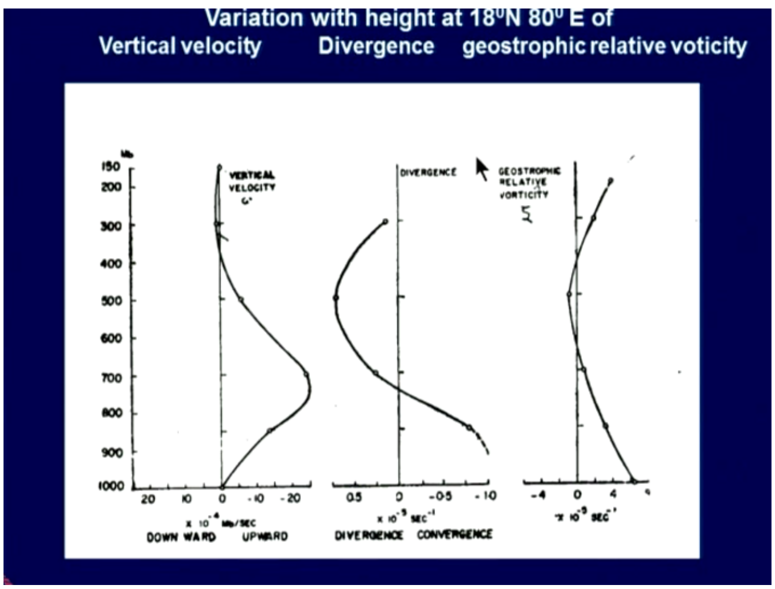

So what is the variation of height? For such a synoptic scale system variation with height, this is the vertical velocity, so you have vertical velocity increases up to about 700 and then it decreases, but it is ascending all the way up to 400 hpa okay, so air is ascending all the way here and then the descents starts in the upper troposphere. If you look at convergence and divergence of course in the boundary layer it is converging and it keeps converging up to almost 700 and then starts diverging.

And the geostrophic vorticity is cyclonic at the lower level and becomes anticyclonic.

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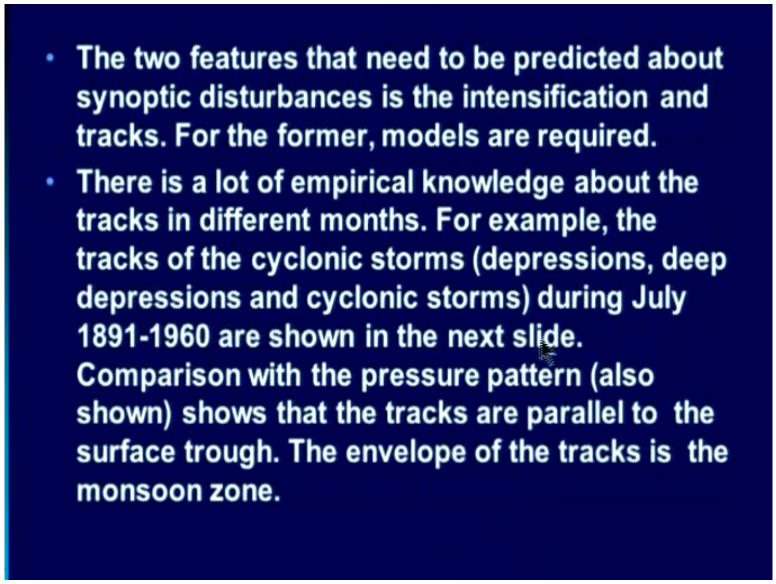

Now this is the situation about depressions that we had seen, and we have seen that there are associated with very well organized cloud systems. Now the 2 features that need to be predicted about synoptic disturbances is the intensification and tracks okay, will the load intensified to a depression, will the depression intensified to a deep depression and so on is one kind of prediction require.

And another prediction required is okay we have seen a cloud blob over the Bay of Bengal you know it is a depression where will it go? Where will it give rain? So both these are very important things, and there is a lot of empirical knowledge in our country about the tracks of these systems in different months because with weather maps people have been tracking them for a long, long time.

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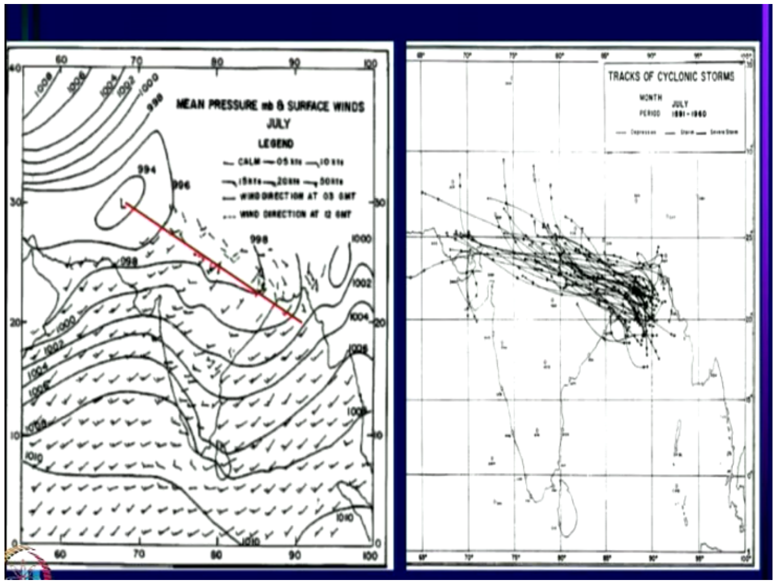

So let me just for you as an example, now these are the what you say on the right is tracks of all cyclonic storms for July over a very, very long period, in fact they are from 1891 to 1960. So these are tracks from 1891 to 1960 of all the systems that formed here there all formed around the head Bay and how did they move? They all moved here, and you can see that in fact this was the picture of July that we had and this is the trough zone, this is where the low pressure is.

And the envelope of this is exactly the monsoons zone of large-scale rain belt that we have seen earlier, so all the tracks tend to be this way.

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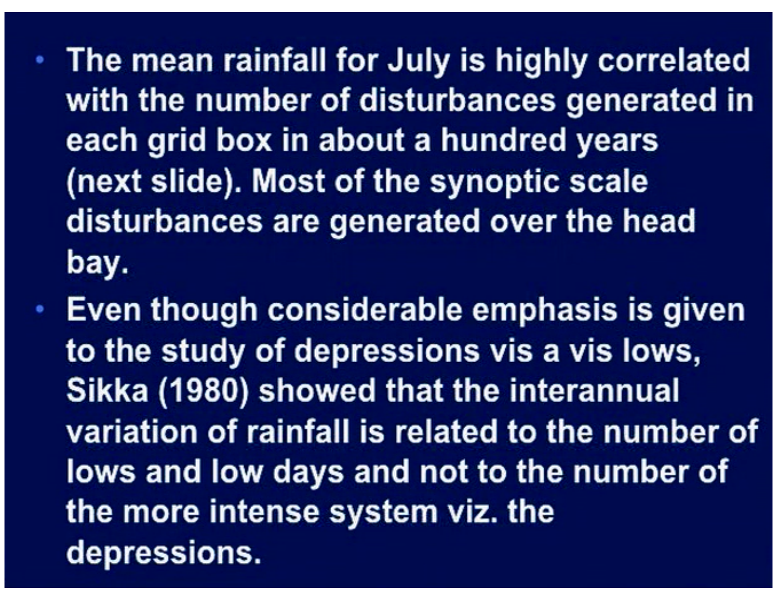

The mean rainfall for July is highly correlated with the number of disturbances is in each grid box in the next one.

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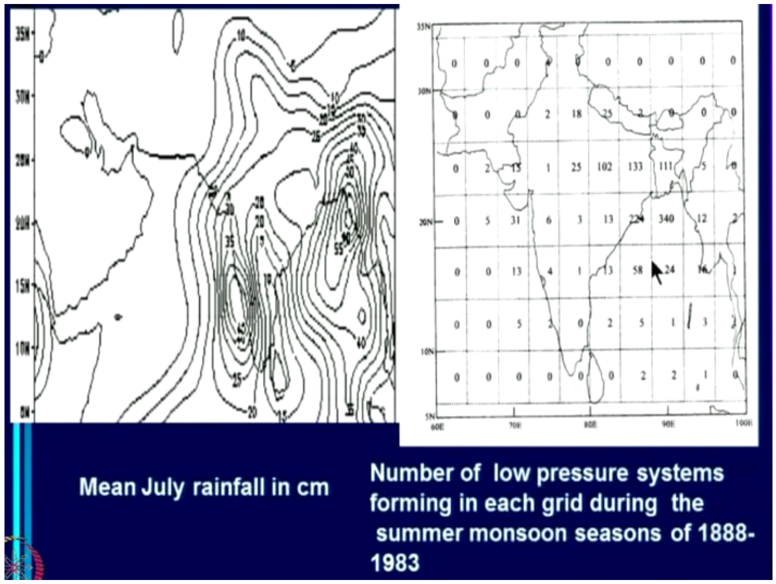

So what you see here, now let us look at this is the mean rainfall for July, and these are number of low pressure systems forming in each grid box from 1888 to 1983 again a large dataset, and what you see is high rainfall here large number of systems are generated, as you go here the rainfall decreases fewer and fewer systems generated, and same thing here rather large number of system generated here.

So most of the synoptic sale system disturbances as you can see are generated in the head Bay, and the rainfall in the month in fact seems to be related to the number of systems that are generated. Now I must mention here that, even though considerable emphasis is given to study of depression vis a vis lows, because depressions are more intense and more interesting. Sikka has shown that the interannual variation of rainfall is related to the number of lows and low days.

And how many days the lows were present over the Indian region rather than to the number of depression or depression days, so actually if you are worried about monsoon rainfall we should be concerned more about lows then about the more intense depressions.

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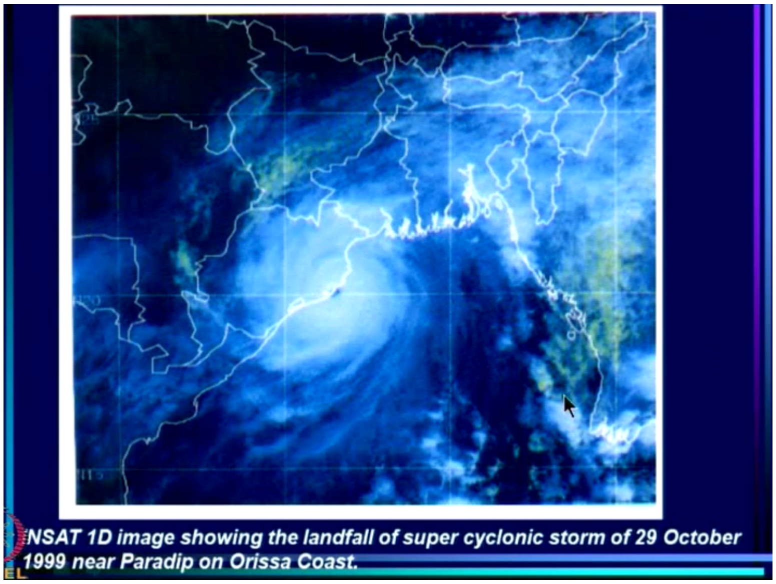

INSAT 1D image showing the landfall of super cyclonic storm of 29 October 1999 near Paradip on Orissa Coast.

Now I just want to talk very briefly about the most intense system and this is the picture of the super cyclonic storm on 29th of October 1999 near Paradip Orissa. And I wanted to show this picture because you see this eye here, this is the characteristic of a typhoon or a hurricane that right in the center of the system where the pressure is lowest there are no clouds, and that is the eye.

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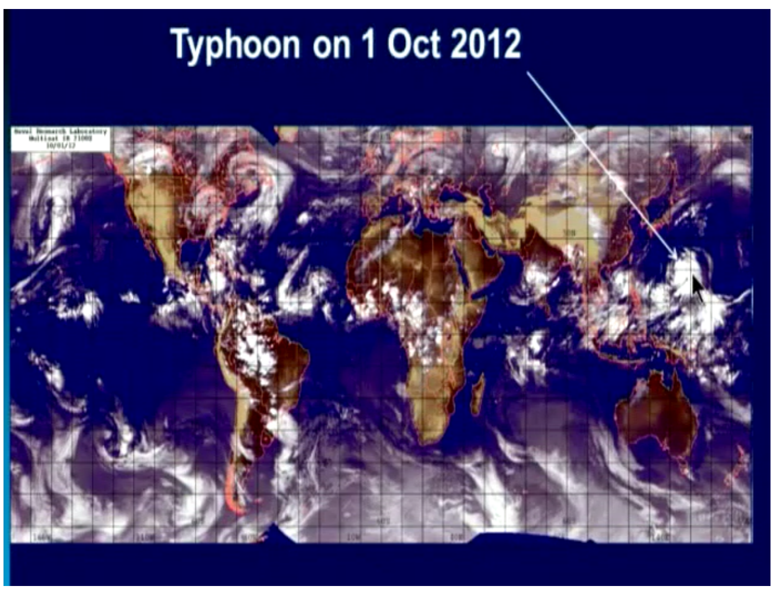

And in fact there was a typhoon here on 1st October very recently, and I think another is forming as I speak.

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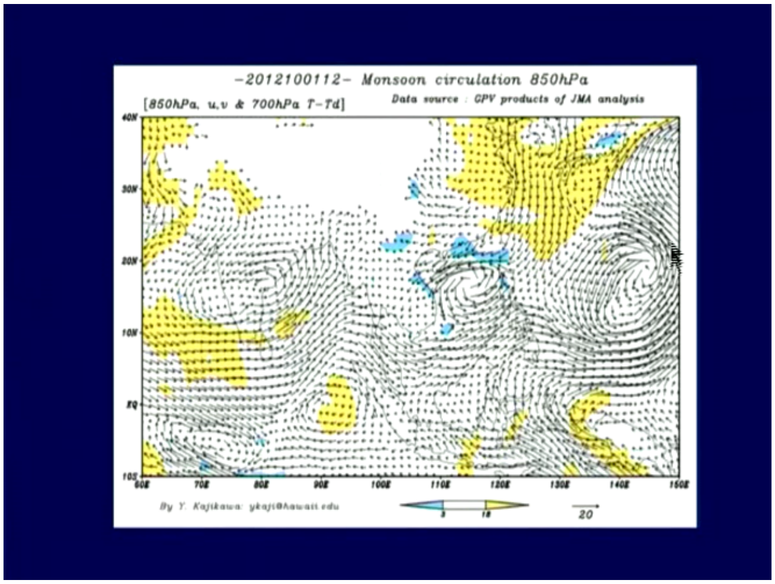

And you can see the kind of circulation that was associated with the typhoon, this is from the Japanese model they having interpolated the data and shown you what the circulation looks like. So what we have seen is, first of all how do clouds grow in conditionally unstable atmosphere, we have seen that the empirical evidence in the case that we get systems of reasonably large-scale from 100 to 1000 kilometers, with organized rainfall which are invariably associated with cyclonic vorticity above the boundary layer.

And in fact the monthly rainfall and large-scale rainfall is also related to the frequency of this so-called in synoptic scale disturbances. And in the next class we will look at how do clouds get organized over this large-scales, because remember the rain giving cloud is only few kilometers in horizontal extent, and yet these systems are 100s and 1000s of kilometers in extent. So how do these clouds get organized in what we called monsoon disturbances or synoptic scale systems or planetary scale cloud-bands or whatever?

So this is going to be the topic for the next time, thank you.