The Monsoon and Its Variability
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Lecture - 06
Organization of Clouds over Meso-scale, Synoptic Scale and Planetary Scales

So last time, we have discussed how clouds get generated in an atmosphere which is conditionally unstable that is to say which is stable to vertical displacement of dry air but unstable with respect to vertical displacement of moist air. Now today we are going to talk about organization of these individual clouds over different scales meso-scale, synoptic scale and the planetary scales.

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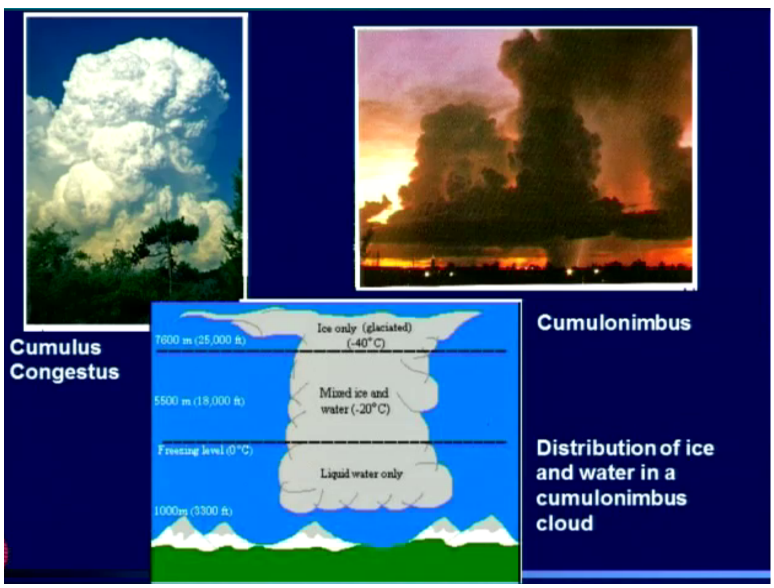

Now these are the clouds we talked about, these are individual clouds cumulus congestus being a rain giving cloud, cumulonimbus being a rain cloud and so on and so forth.

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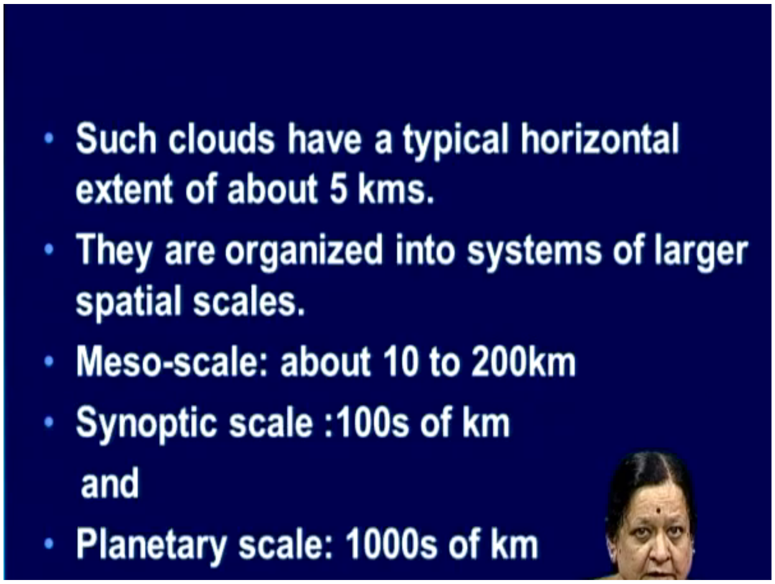

Now such clouds have a typical horizontal extent of about 5 kilometers, they are organized into systems of larger spatial scales, now these important scales are meso-scale which is about 10 to 200 kilometers, so which we will have several clouds of extent of 5 kilometer. Then synoptic scale which is 100s of kilometers, and planetary scale which is 1000s of kilometers.

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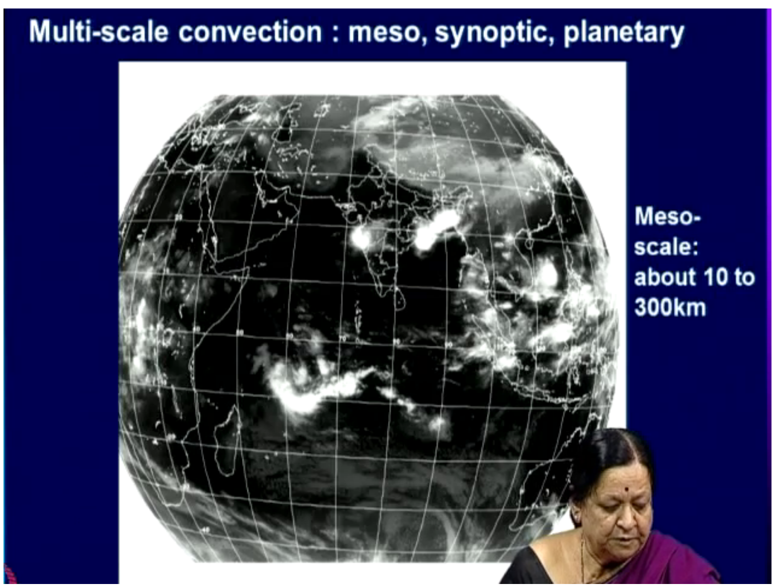

Let us see example of this, now thanks to satellites, we see examples of this very readily. This is the picture which shows nicely the meso-scale convection that you see here on the west coast of India here a nice small blob, but notice see this is about 1000 kilometer, so this is only about few 100 kilometer maybe 200 kilometers or so in extent, and it is isolated all around it is clear sky, so this is a meso-scale convection you see here which is a scale of about 10 to 300 kilometers.

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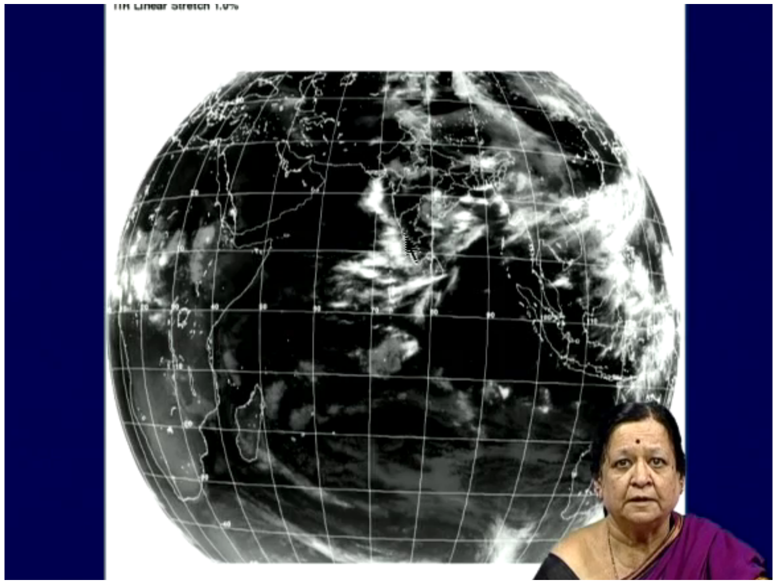

This is another example of meso-scale convection, you see cloud-band stretching all along the west coast here, so this is another example of meso-scale convection.

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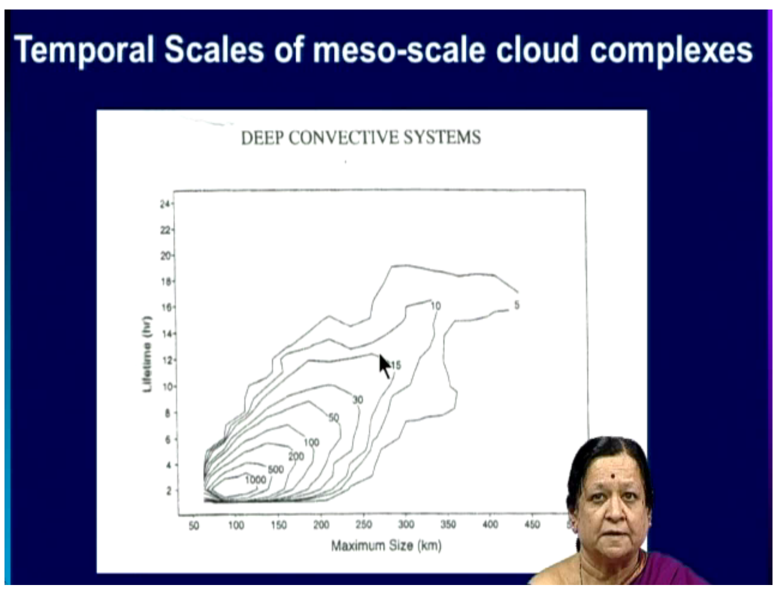

Now meso-scale convective cloud complexes could be studied only with the advent of satellites, but over the last decade or so there has been intensive study of the system, and in all systems of every sale that spatial and temporal scales are intimately related. So now if you look at meso-scale cloud complexes here is the size in kilometers, and this is from the study done over the Pacific, and this is the life time in hours.

So what you find is that the smaller clouds stay around only for a couple of hours or so, as the cloud complexes become larger and larger then they stay almost to 18 hours or so, these are the big clouds and this is the frequency distribution. This is saying that the small clouds are much more frequent and larger cloud complexes are less frequent but once they occur they last much longer.

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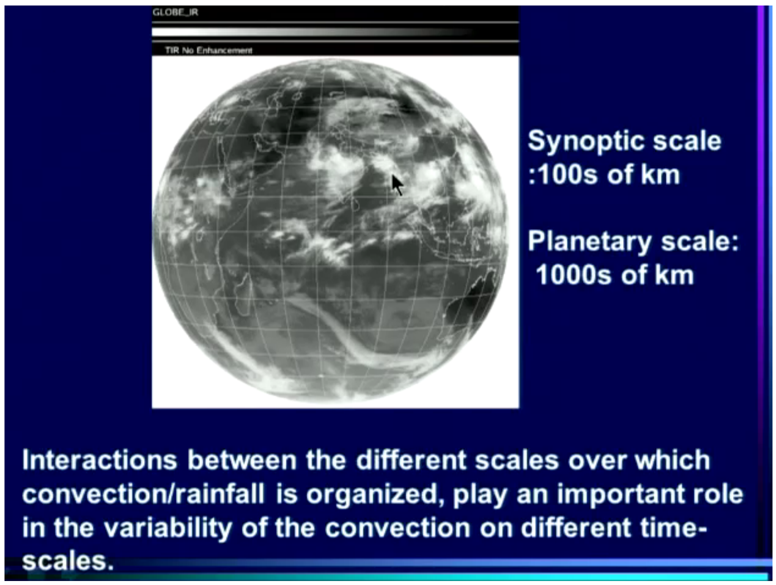

Now next we see this is the meso-scale. Next, we see the synoptic scale, now synoptic scale disturbances we have already come across before, these are like the monsoon disturbance that we talked about last time, the synoptic scale disturbances are of the order of 100s of kilometers, and you see here this is one synoptic scale disturbances, this is another and there is another over west Pacific here okay.

Now in addition to that there is planetary scale disturbances as well, and you can see that the synoptic scale disturbances or synoptic scale systems are organized over a much larger scale of 1000s of kilometer, this is the planetary scale which is 1000s of kilometers. Now if so happens the interactions between the different scales over which convection or rainfall is organized play a very important role in the variability of the convection on different time-scales.

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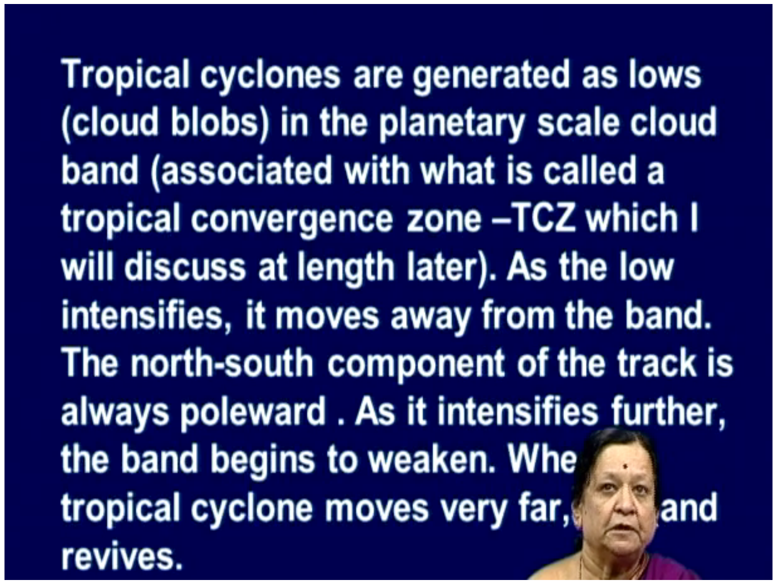

Now an interesting example of this interaction is what we will talk of now, tropical cyclones are generated as lows or cloud blobs in the planetary scale cloud-band associated with what is called a tropical convergence zone, now I will explain in detail in the next set of lectures, what tropical convergence zone is what are the dynamical characteristics and so on, but we have looked at already looked at the cloud-band which is associated with a topical convergence zone this is an east west cloud-band which occurs on the tropics.

So tropical cyclones are generated as cloud blobs in this cloud-band as this low intensifies it move away from the band, and north-south component of this track is always poleward. In other words, in the northern hemisphere it will move to the north in the southern hemisphere it would move to the south, and as it intensifies further the band begins to weaken okay the parents that give birth to these cyclones begins to weaken.

And when the cyclone move away very far only then the band revives okay.

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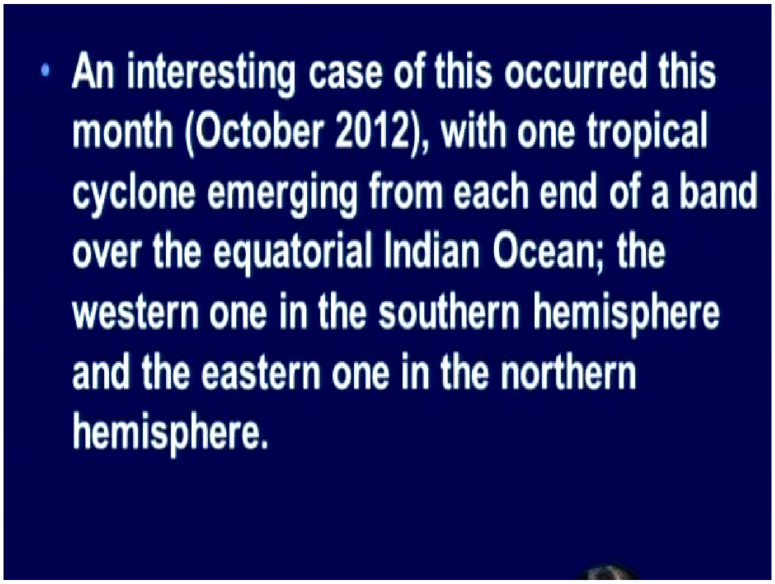

A have very interesting case of this occurred this month in October 2012 with one tropical cyclone emerging from each end of a band over the equatorial Indian Ocean.

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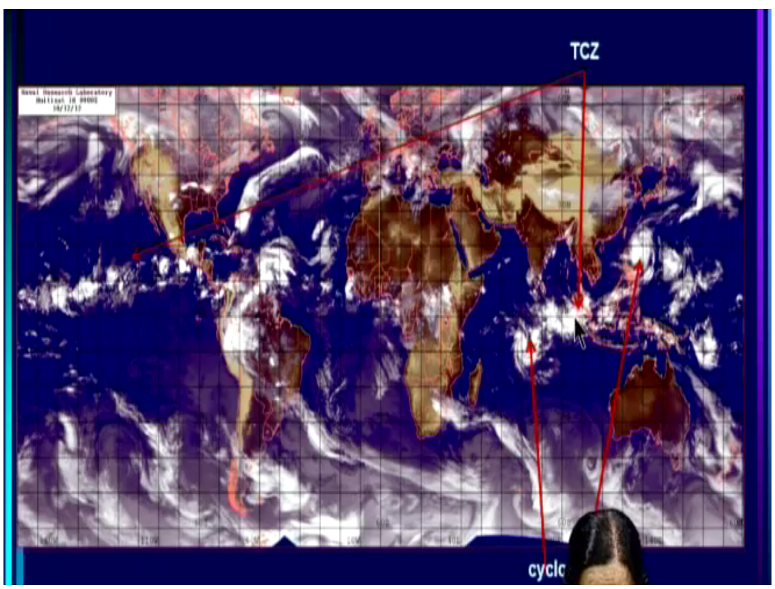

Now this is the picture where the equatorial Indian Ocean on a date in October and it is 17th of October and what you see here is the cloud-band okay, this is the TCZ, at either end of the cloud-band are lows okay high clouding or intense clouding in blobs this designates the lows of the thing and there are either end of this band. Now let us see what happens?

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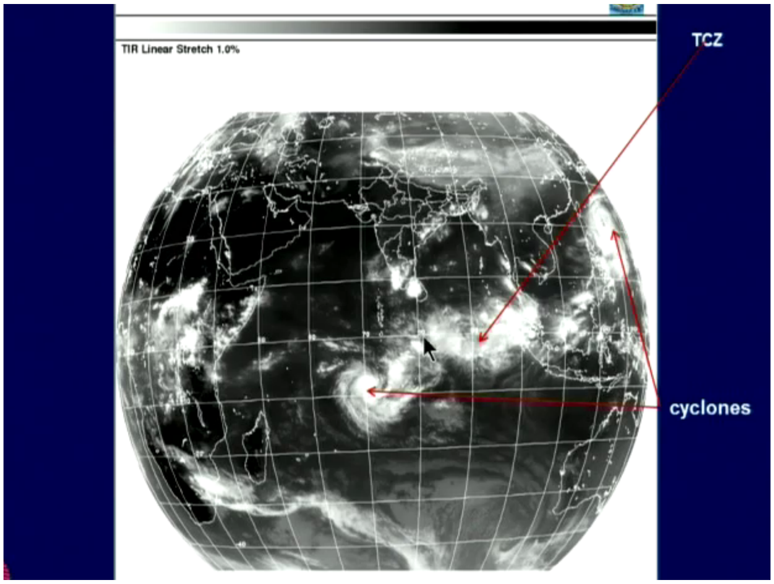

Now this is the same band seen through an INSAT satellite and you see again see this cyclone here, cyclone here and this is the tropical convergence zone this is the band, at either end of the band there are cyclones that you see here, now let us see what happens to them.

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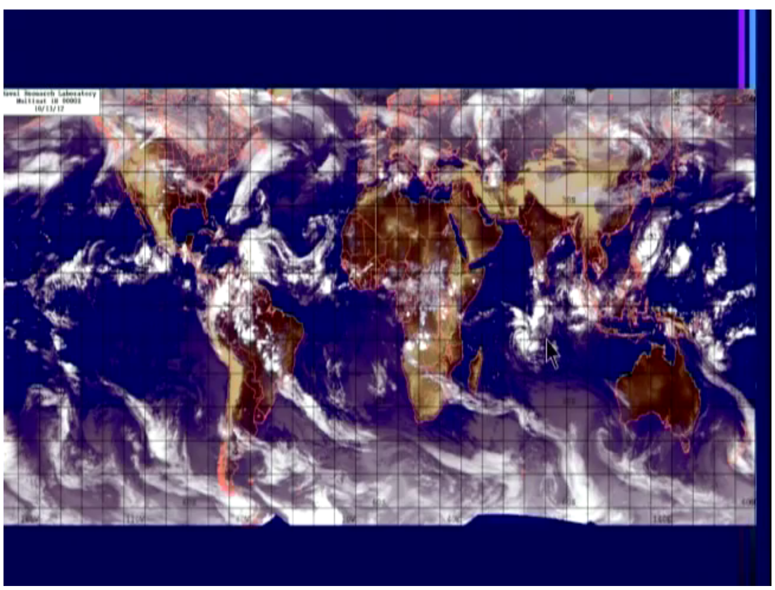

Now what happens is this cyclones intensifying okay, you see this one is intensified, this one is also intensified and the band in between has weaken on the next day.

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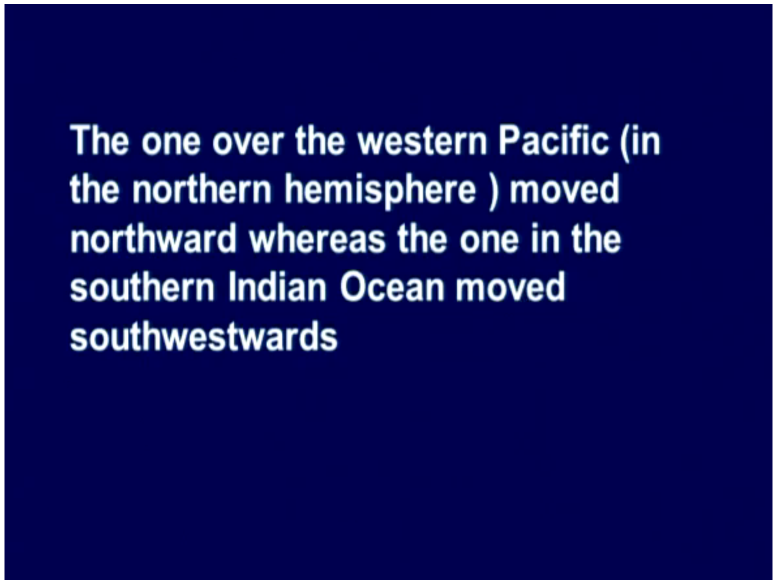

So the one over the western Pacific moved in fact. See there were 2 cyclones that you saw this is the cyclone over the western Pacific, this is the cyclone over south Indian Ocean okay. And if we go back okay these were the 2 cyclones that you had, and now you see this band has become weaker as the one over the west Pacific has moved northward, the one over the south Indian ocean is moving southward as I mentioned before as they always move towards the pole okay.

So the one over the western Pacific moved northward, whereas the one over the south Indian Ocean moved southward.

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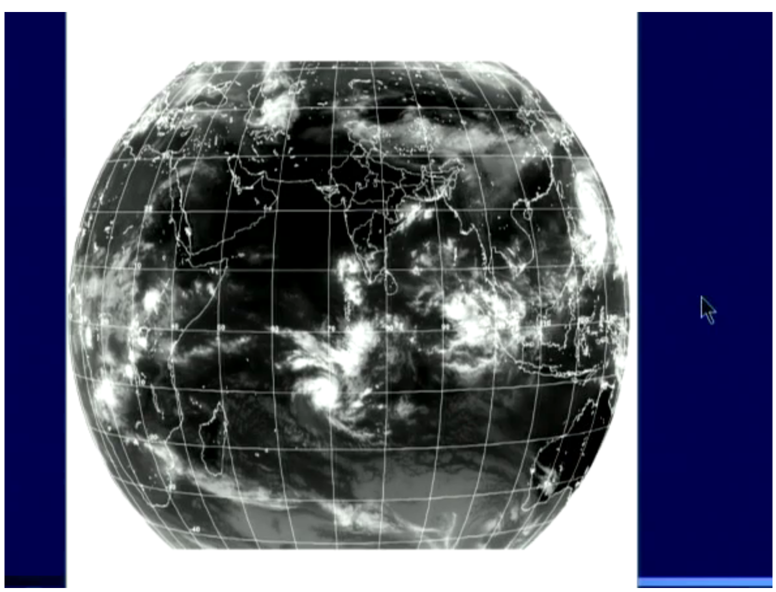

And now you see that the band has actually disappeared, there is not much of a band here only one blob remains, this is the typhoon over the west Pacific it has intensified to become a typhoon and this is the cyclone over the south Indian Ocean, and you see the band structure that you had has very much weaken.

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Now you see the band has actually disappeared the TCZ has actually disappeared and what you see here is a typhoon over west Pacific, and a tropical cyclone over south Indian Ocean you can say that they have both moved poleward. The one in the northern hemisphere has moved to north, the one in the southern hemisphere has moved to south, and this band which gave birth to both of them has actually disappeared.

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What happens the next day? Next day now these cyclones have moved further off, you can actually see the eye of the cyclone here, and this is the typhoon here of which also you can see the eye, so these are both becoming very, very intense systems, but they moved away from the original location, they moved very much northward so this is almost at 20 north this all began at the equator here, this has moved to the 20 north and this has come close to 20 south.

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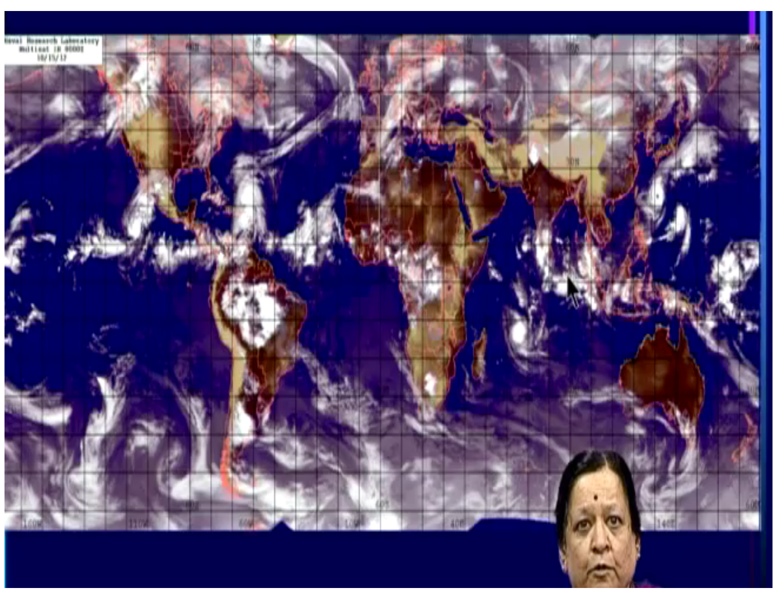

So the system has moved northward and the band has revived has appeared again. And you see that here as well in the global picture, and notice by the way that the band I am talking about the TCZ is seen all over the globe in the equatorial region, you see it here in the Pacific you see it here across the Atlantic, and here it has now weaken because of the cyclones. But what you see here are the 2 cyclones a typhoon in the west Pacific and a cyclone in the south Indian Ocean.

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And now this has very much weaken the south Indian ocean one, this one is still alive the west pacific typhoon and meanwhile this band the TCZ has flared up, because this have moved away.

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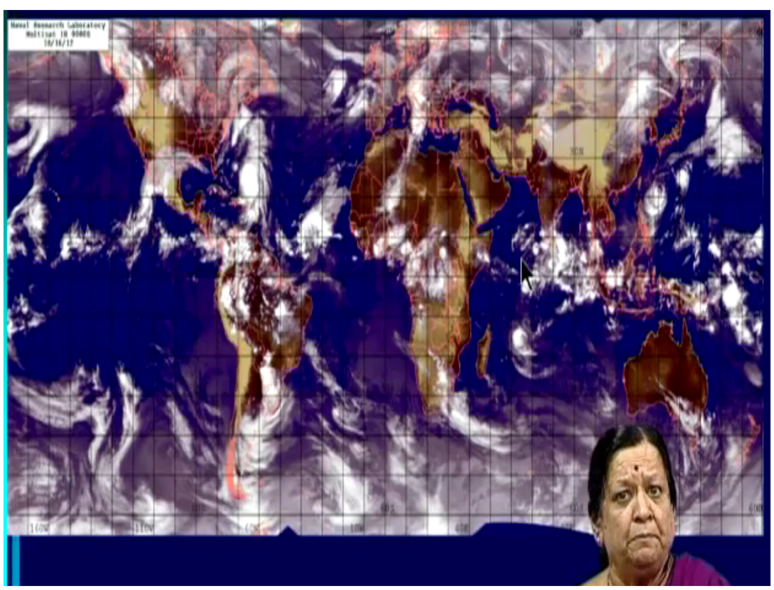

You see the same story here in the global picture and you can see how the band is stretching right across the equatorial region right across the globe, so the TCZ has revived here and the 2 systems have moved far away okay. So this is a very, very interesting case of an interaction between a planetary scale and a synoptic scale. These synoptic scale systems were born in this planetary scale TCZ.

Then they intensified moved away and went poleward which while they were close to it the band has disappeared, once they moved sufficiently far the band has appeared again.

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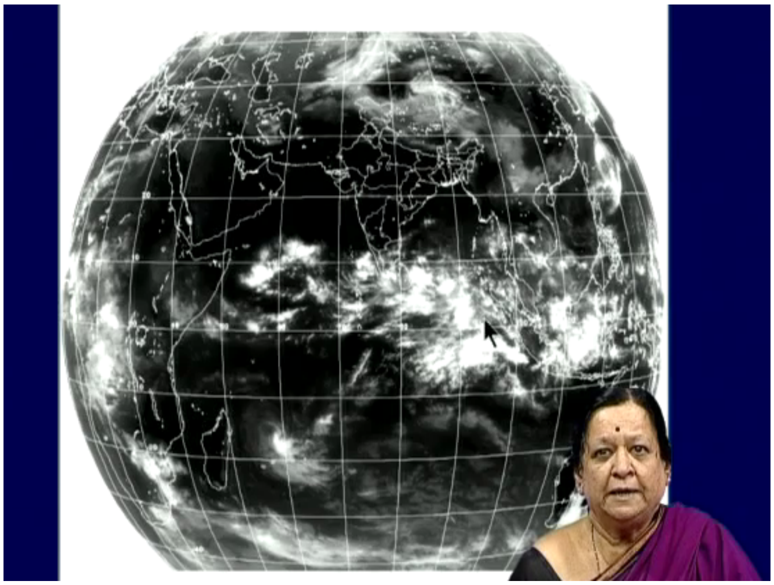

So now you see the band in all its glory very much intensified back in action, whereas this is the remnant of that cyclone that was over the south Indian Ocean, and this is the remnant of the typhoon over Pacific both of them are about to die and this band has revived again.

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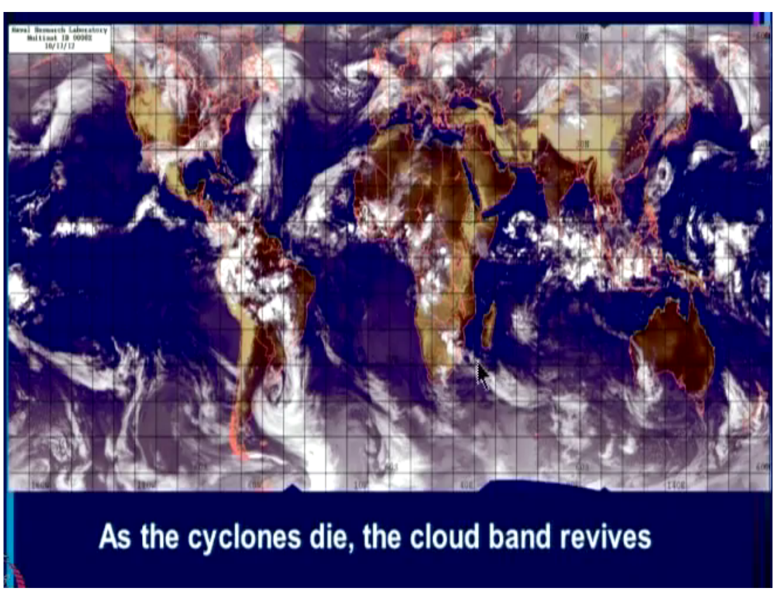

So this is the same story you see here again, this is almost reached coast of China now, this is completely died and we have revival of the planetary scale. So as the cyclones die in the cloud-band revives.

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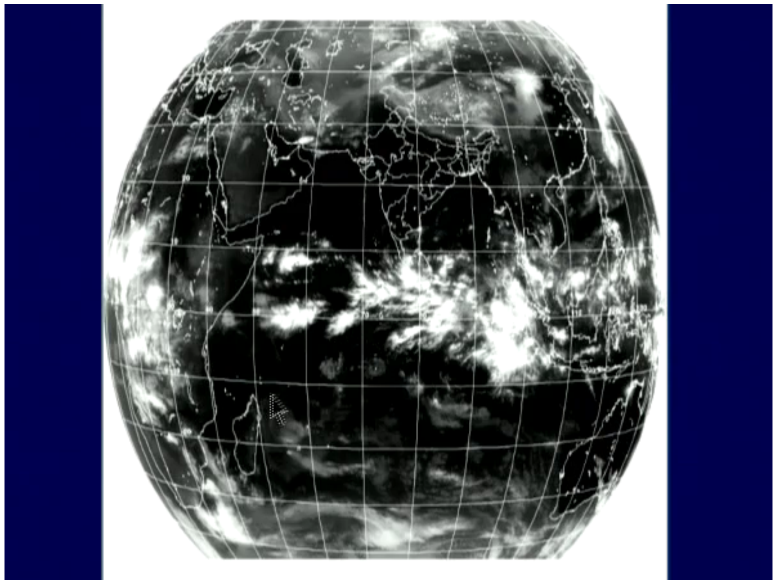

Now it is very important to understand you see now how the intense cloud-band has become nothing is left of the south Indian Ocean cyclone and this is also west Pacific typhoon is also disappeared. See these kind of interactions are very, very important to study in the tropics. And understanding these will have a major contribution to our understanding the variability of the tropics.

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And now you see totally revived planetary scale cloud-band stretching again right across the globe okay.

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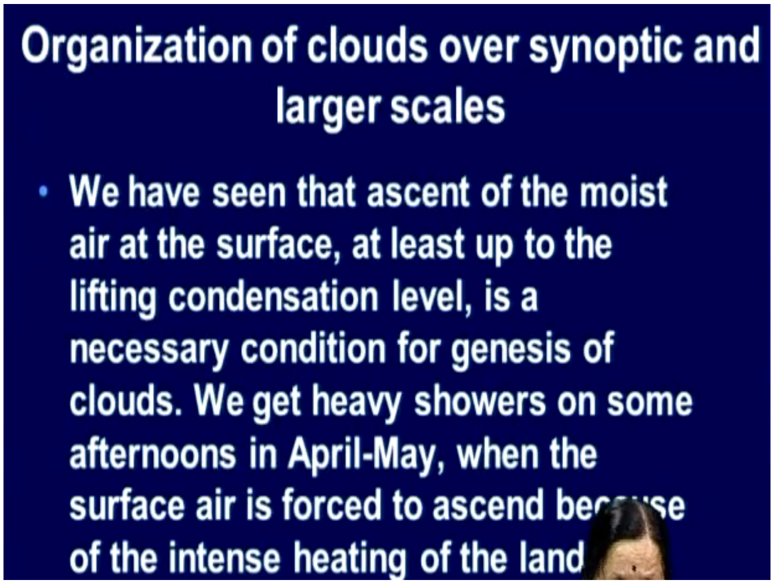

So now we have to try and understand organization of these clouds over synoptic and larger scales, you saw one nice example of organized clouds over synoptic and larger scales and the 2 systems interacting. Now how come they get organized and synoptic and larger scales was the question that was very much challenge in the mid-60s, now why is that a challenge to understand?

Because we have seen that ascent of the moist air at the surface at least up to a lifting condensation level is a necessary condition for getting clouds okay, this we have seen because without ascending to lifting condensation level water vapour cannot become water, so we cannot get cloud, so we need ascent of air to get clouds. Now we could have got an individual clouds and in fact rarely, but we do experiencing them in the pre-monsoon seasons of April and May.

You know we get very heavy showers on some afternoons in April-May, when the surface air is forced to ascent because of the intense heating of the land, you know in the summer the land gets very hot and this causes a low pressure and ascent and this leads to formation of clouds.

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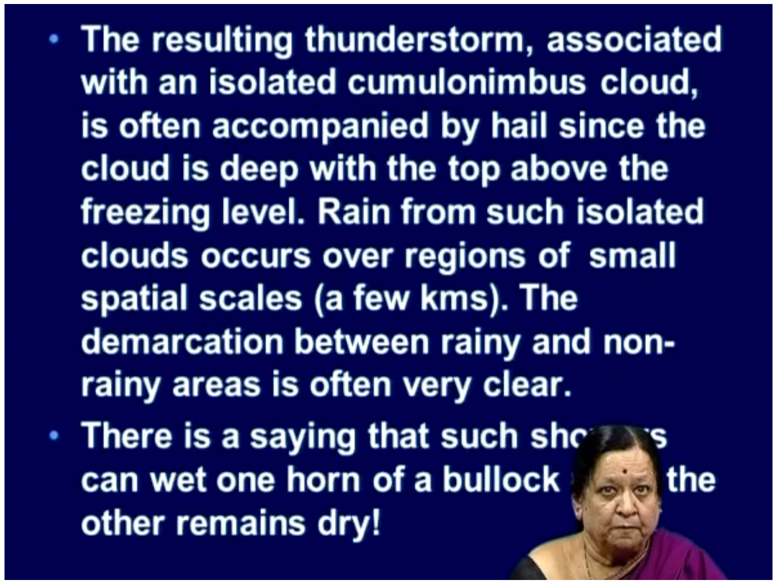

And thunderstorms are a very familiar occurrence in April and May, the resulting thunderstorms associated with an isolated cumulonimbus or isolated clouds is often accompanied by hail why? Because the clouds are very, very tall they go way above the freezing level, so not only do you have liquid water in them but you have ice as well. So these thunderstorms are often accompanied by hail, since the cloud is deep within the top above the freezing level.

Now rain from such isolated clouds occurs over regions of very small scales, because we have seen that the clouds have horizontal extent only of few kilometers, so the rain from such clouds will also have typical scales of few kilometers, and the demarcation between rainy and non-rainy areas is often very clear. In Maharashtra they saying goes that such thunderclouds give rain which can get one horn of a bullock leaving the other horn dry.

Now this is this something we experienced all the time part of the road is wet, the other part is not wet and so on, and this is because the clouds that gives us the rain has relatively small spatial extent okay.

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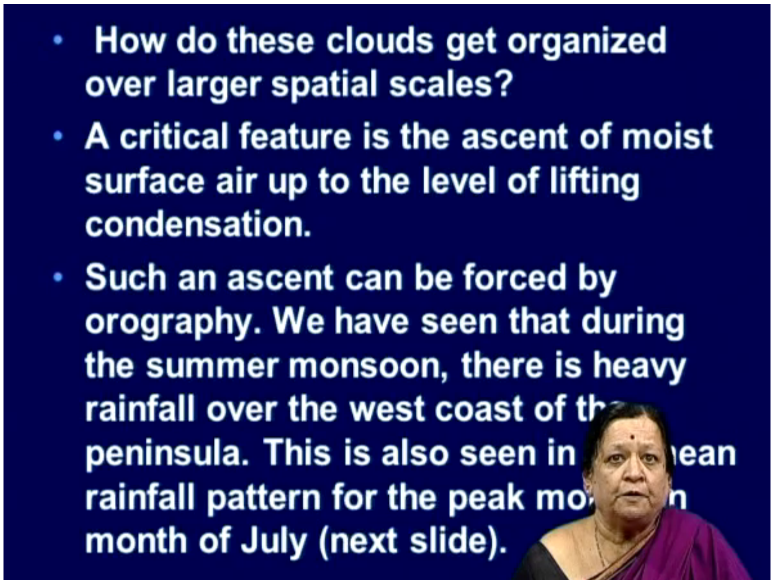

Now the major question as I mentioned earlier is how do these cloud get organized over larger spatial scales? Okay we have seen from satellite pictures that the clouds are very seldom individual clouds in fact one we see them in the satellite picture at all, if there were only few kilometers, but rather a very often we see these clouds are organized over 100s of kilometers and 1000s of kilometers.

Now how does this occur? Of course a critical feature is the ascent of moist surface air up to the level of lifting condensation without which you cannot get clouds at all, now such and ascent can be forced by orography, by orography one means topography mountains as we have seen earlier, now we have seen that during the summer monsoon there is heavy rainfall over the west coast of the Peninsula okay.

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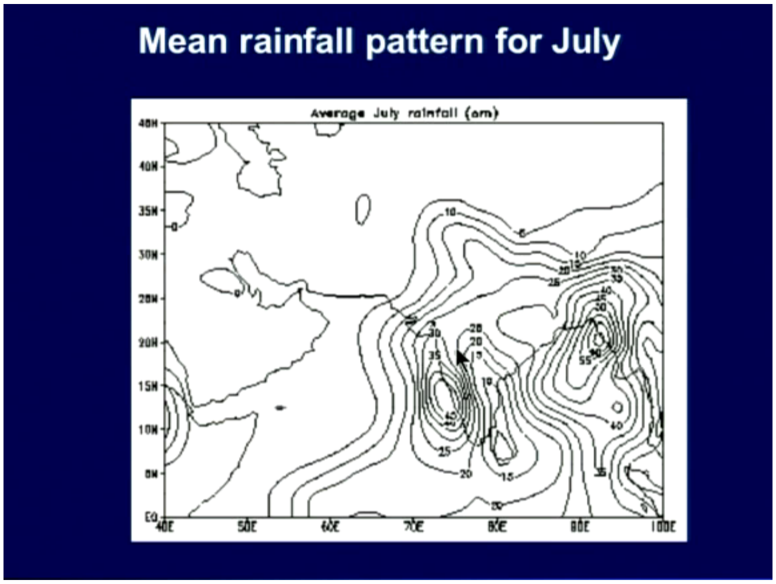

This is the mean rainfall pattern for July, and what you see here is that the rainfall is very heavy here over the west coast and Western Ghats as well. So the rainfall is very heavy here in July.

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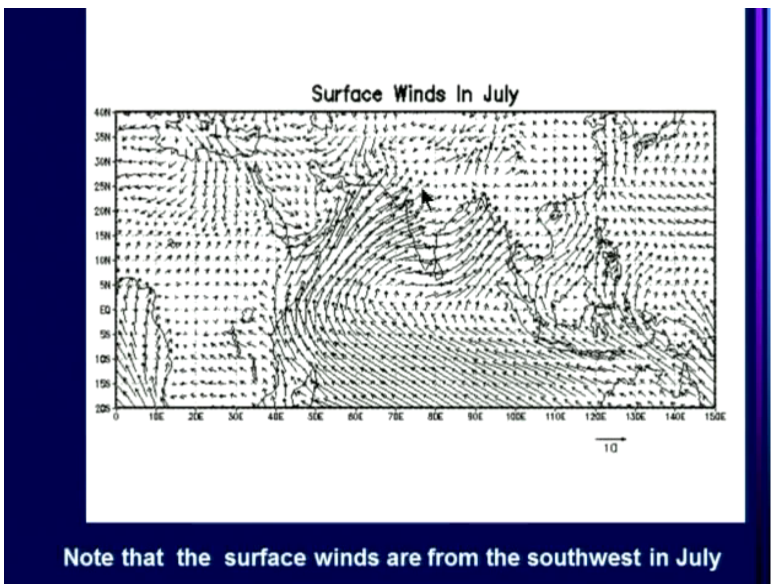

And this lies a part of this comes because of the Western Ghats, which lie all along here, you see the winds surface winds in July want to go across here but what do they meet?

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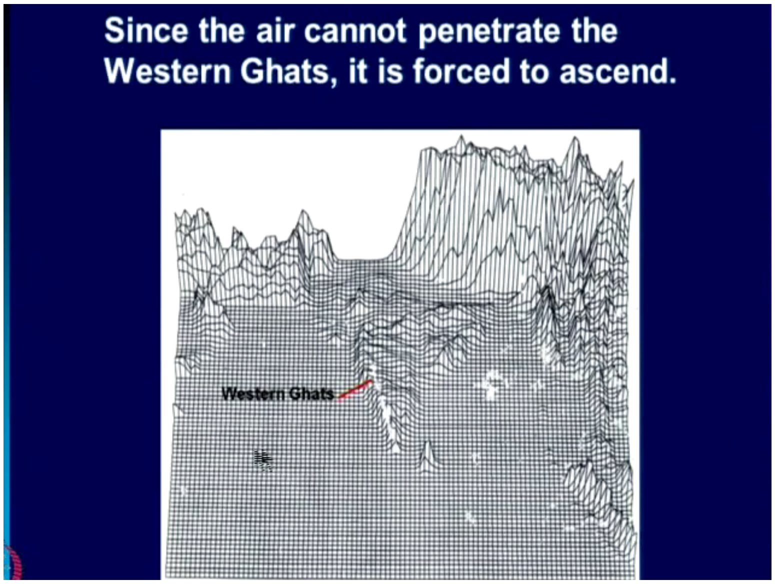

They meet the Western Ghats here and obviously the winds cannot penetrate the Ghats, so here upstream of the Ghats they have to ascent, and this ascent leads to clouding because the air is very moist.

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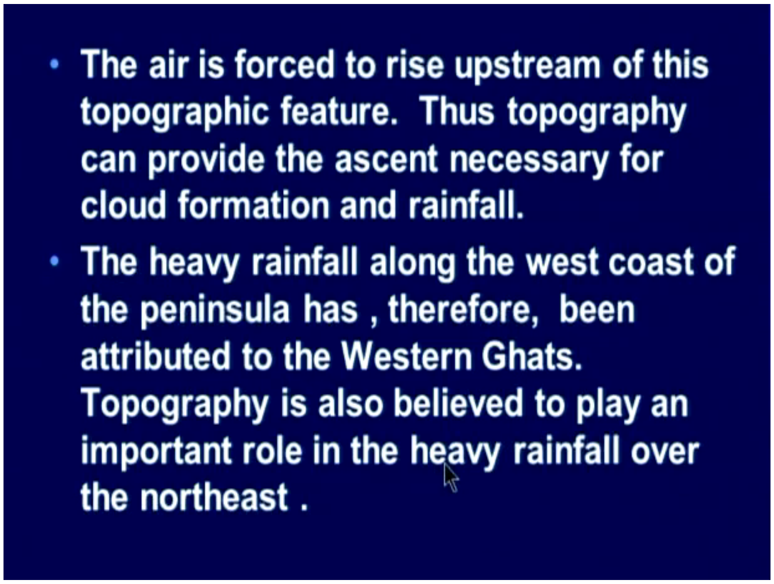

So the air is forced to rise upstream of this topographic feature, thus topography can provide the ascent necessary for cloud formation and rainfall, now the heavy rainfall along the west coast of the Peninsula has, therefore never been attributed to the Western Ghats. Topography is also believed to play an important role in the heavy rainfall over the north east.

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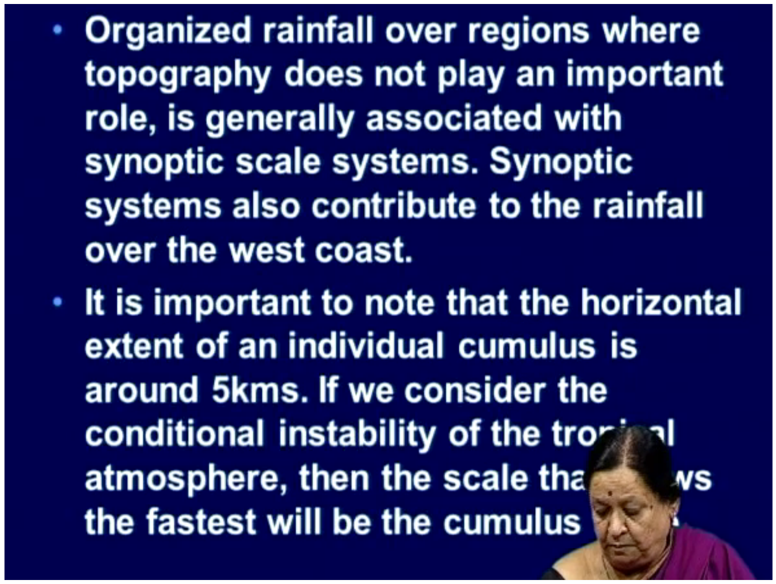

However, we do get a lot of organized rainfall over regions where topography is not important. So organized rainfall over regions where topography does not play an important role is generally associated with synoptic scale system. Synoptic systems also contribute to the rainfall over the west coast, so it is not as if the rainfall over the west coast is entirely due to orography very often the most intense rainfall over the west coast occurs in association with synoptic scale systems over the Arabian Sea.

Now it is important to note that the horizontal extent of the individual cloud is only around 5 kilometers okay, now if we consider the conditional instability of the tropical atmosphere, then the scale that grows the fastest will be the cumulus scale of 5 kilometers.

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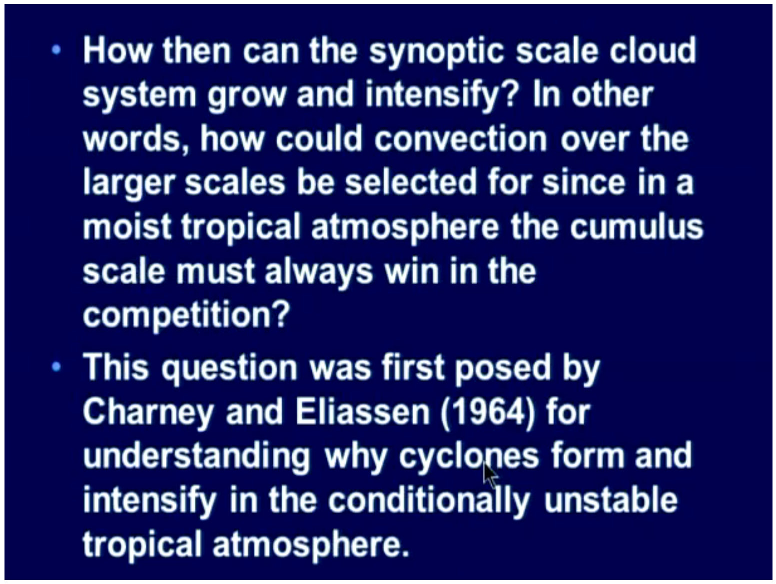

This we have seen in the last lecture that is to say if we had a disturbed atmosphere, if the perturbation had energy in all scales what will happen with it is conditional instability? Is that the smallest scale the scale of about few kilometers will grow the fastest, so eventually the perturbation will be dominated as the perturbation grows it will be dominated by that scale which grows the fastest in the instability which is actually the clouds scale.

So how can then the synoptic scale cloud system get selected for, in a conditionally unstable atmosphere can we conceive of a way by which of course clouds have to form because that is the scale which is most promoted by conditional instability the clouds scale. But how do we get scales of the higher like synoptic scales and planetary scales and so on. So could convection over larger sales be selected for?

Since, in a moist tropical atmosphere the cumulus scale must always win in the competition as I have said earlier. Now this is the question that was posed by Charney and Eliassen for understanding why cyclones formed and intensified in the conditionally unstable atmosphere. So note they are asking the question that how come in a conditionally unstable atmosphere systems of scales of 100s of kilometers can get generated can form and intensified.

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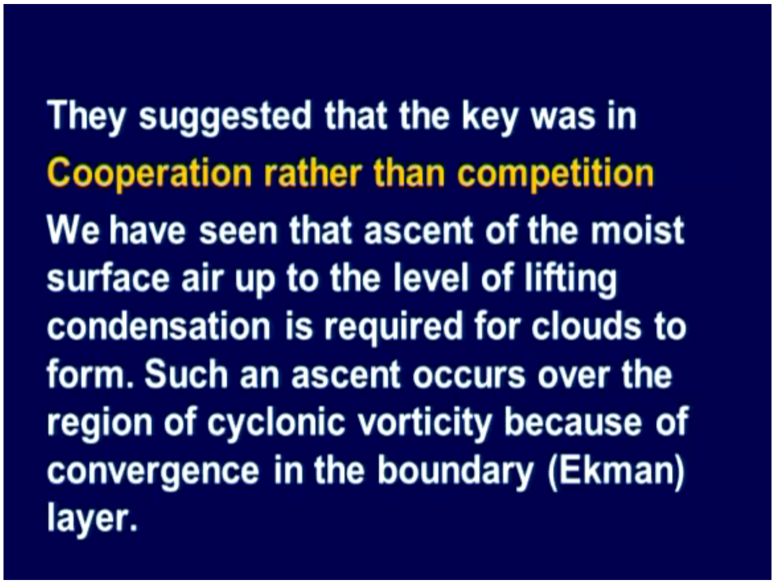

So this is this question posed by Charney and Eliassen, and they suggested that the key to our understanding this was that the 2 scales, the synoptic scale and the cumulus scale actually do not compete but co-operate with one another. Now this was the entirely original suggestion that they come up with that the interaction between the cumulus scale and the synoptic scale involves co-operation rather than competition. How do they corporate?

Now we have seen that ascent of the moist air surface air up to the level of lifting condensation is essential for clouds to form right, now such an ascent occurs over the region of cyclonic vorticity because of the convergence in the boundary layer.

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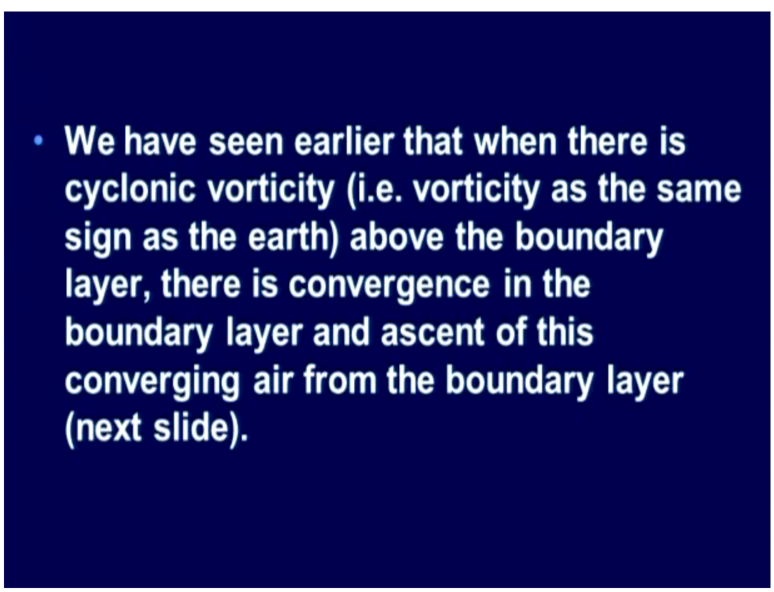

See this is again something we have seen in the earlier lectures that when there is cyclonic vorticity. What do we mean by cyclonic? By cyclonic we mean vorticity which is the same sign as the rotation of the earth okay.

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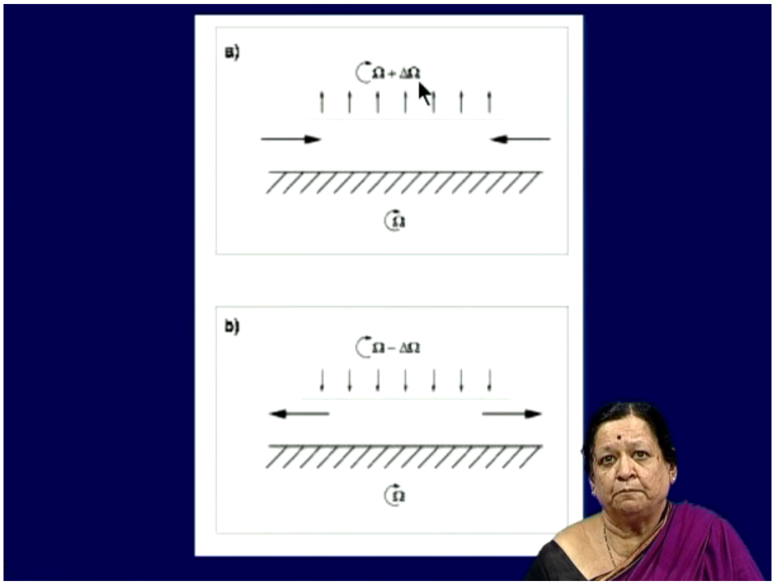

So when there is a cyclonic vorticity above the boundary layer there is convergence in the boundary layer you may remember this picture we have seen earlier. When there is cyclonic vorticity above the boundary layer it is like the fluid is rotating faster and the earth itself is rotating with this velocity omega, so the air above the boundary layer is rotating with omega + delta omega.

In this situation what you get is convergence in the boundary layer and ascent of air from the boundary layer, this is the special property of the Ekman layer or the boundary layer in a rotating fluid that we had seen earlier, and this becomes very, very critical in understanding this cooperation interaction.

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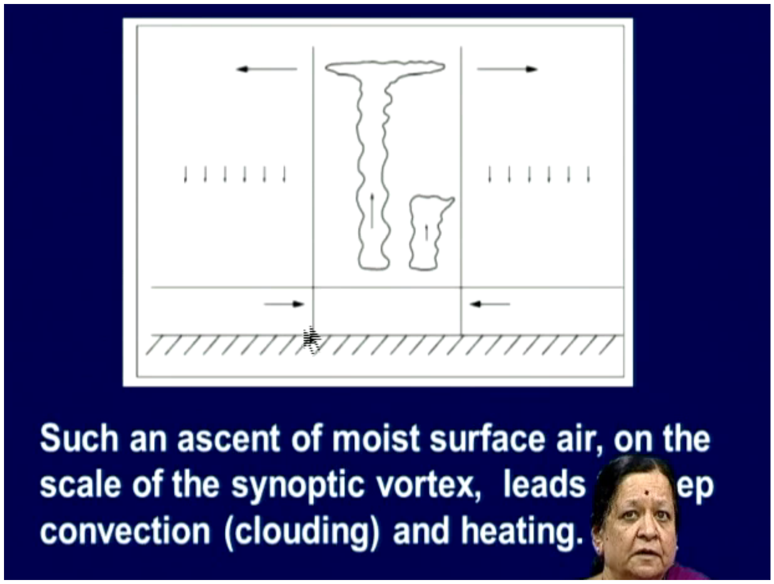

So how does the cooperative interaction occur? We have a cyclonic vorticity over this region this is the vortex cyclonic vortex that you call a low or whatever, low or depression whatever it is. But Charney is thinking of in fact genesis of the low, so suppose you have cyclonic vorticity here it leads to convergence in the boundary layer and ascent of air in the region of cyclonic vorticity. Now since the air is moist this kind of strong ascent of air will lead to clouds and deep convection of this kind.

Now this is what leads to organization of individual clouds on the scale of the vortex itself which is on the scale of the synoptic system. Now what is the cooperation involved? The cooperation is the following, see initially for clouds to form you need ascent of air and this assent of air is provided by the vortex by the cyclonic vorticity associated with the synoptic scale system. So the synoptic scale system by having the cyclonic vorticity triggers ascent and therefore, clouds.

Now what happens when we have clouds? When we have clouds we get heating in there, why is there heating? Because latent heat of condensation is released when water vapour gets converted into water droplets in clouds. So we have heating within the clouds, now what will happen with this heating? When you have heating in this region the pressure will become lower in this region which would mean that the convergence will intensified which means that ascent will intensified which means you will get more clouds.

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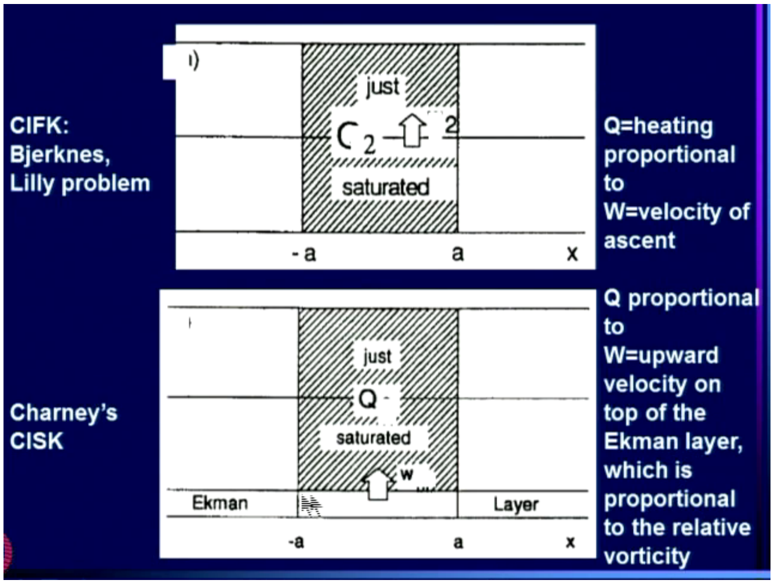

So this is what we see here this is the second situation here that we have an Ekman layer or a boundary layer here, this is the vertical velocity upward because there is a cyclonic vorticity and this releases a lot of heat and how much heat is released is actually proportional to this upward velocity. Now let me distinguish this from the earlier problem which was the Bjerknes or what we called the Lilly problem as well, in which case the heating was proportional to the velocity of ascent and this is how clouds is got selected.

Now when we have synoptic scale then Ekman layer becomes very, very important in creating the convergence which is required for the ascent and development of clouds within the synoptic scale okay.

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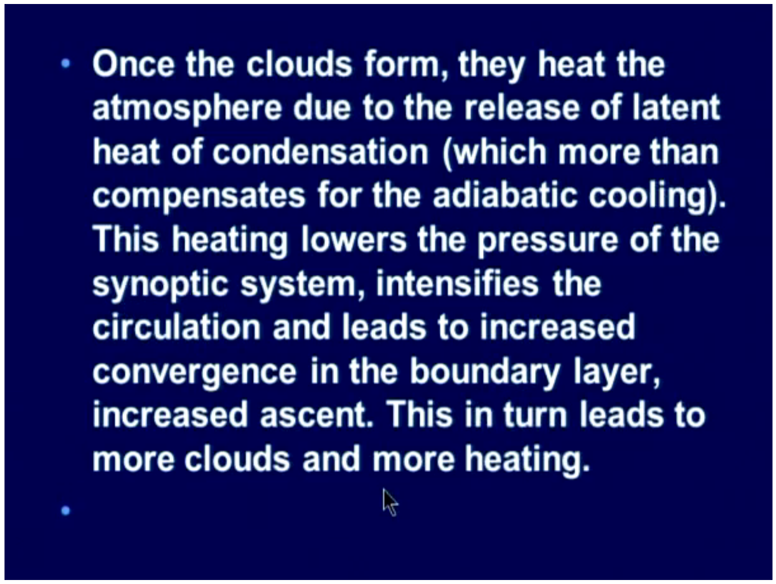

So now once the clouds formed they heat the atmosphere due to the release of latent heat of condensation which more than compensates for the adiabatic cooling, because you know as air parcels are rise up to higher and higher levels you know that they cool because of adiabatic processes. But latent heat release more than compensate for the adiabatic cooling, so we have overall heating with in the clouds.

This heating lowers the pressure of the synoptic system intensifies the convergence and leads to an increased convergence in the boundary layer increased ascent, this in turn leads to more clouds and more heating. So we have this kind of interaction in which for clouds the ascent required up to lifting condensation level is provided by the synoptic scale system, and clouds intern by heating all over the ascending region of the synoptic scale system intensifying the synoptic scale system.

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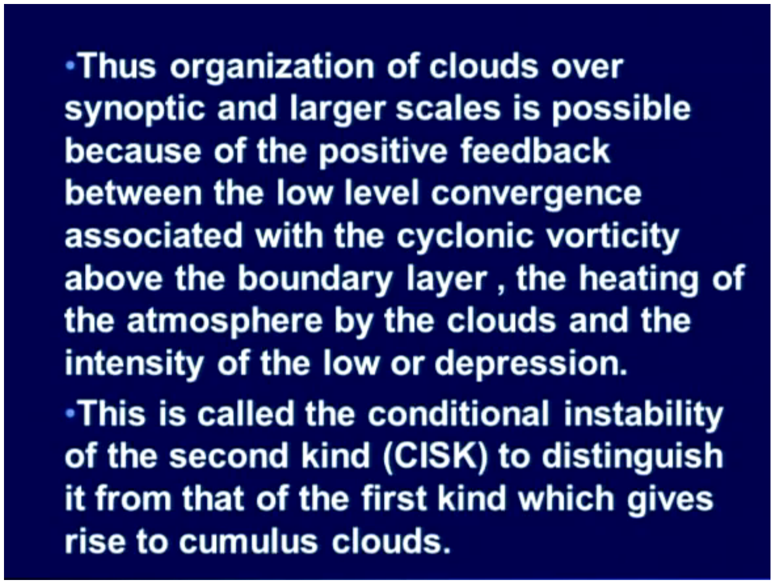

So organization of clouds over synoptic and larger scales is possible because of the positive feedback between the low level convergence associated with the cyclonic vorticity above the boundary layer, the heating of the atmosphere by the clouds and the intensity of the low or depression okay. So there is a positive feedback between the cloud scale and the synoptic scale because of the relationship of the convergence to the clouds.

Now this is called the conditional instability of the second kind to distinguish it from the first kind which gives cumulus clouds, so this was the major contribution of Charney and Eliassen.

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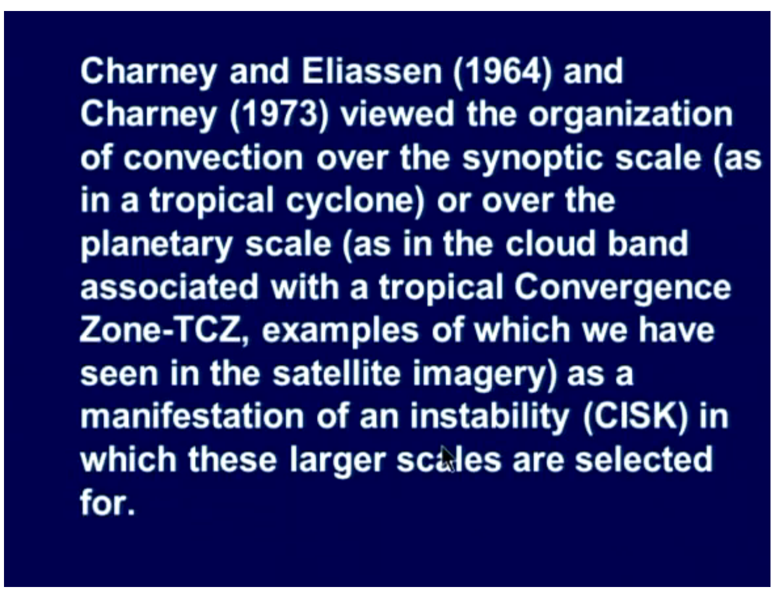

And what they said was that the organization of convection over synoptic scale as in a tropical cyclone or over the planetary scale as we have seen in the cloud-band associated with the tropical convergence zone which is TCZ, which we have seen examples of earlier in this lecture. So it is a manifestation this organization over the larger scales is a manifestation of an instability conditional instability of the second kind or CISK in which these larger scales are selected for, this is what Charney and Eliassen said in 1964.

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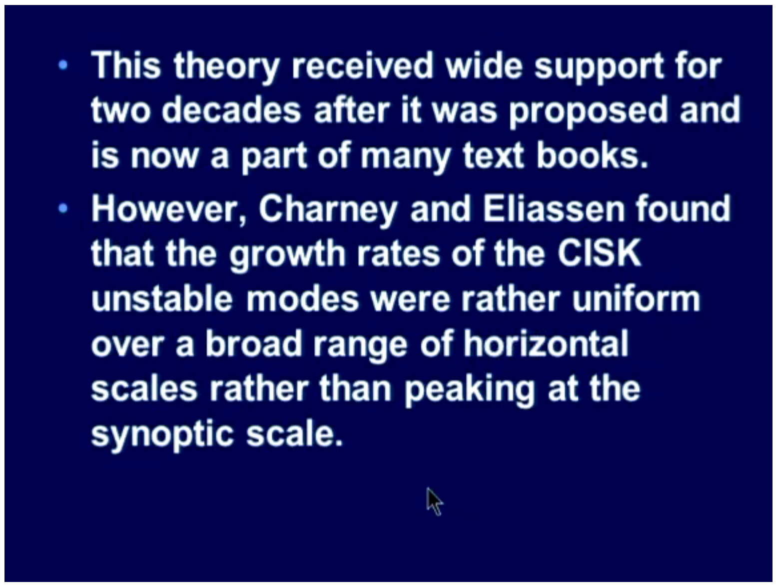

Now this theory was extremely an appealing and received very wide support for 2 decades after it was proposed, and it is actually here now a part of many text books on tropical systems and tropical dynamics. However, even in the Charney and Eliassen paper we find that the growth rates of CISK unstable modes were rather uniform over a broad range of horizontal scales rather than peaking at the synoptic scale.

So that is to say when we first considered conditional instability of the first kind, what we find that growth rate peaks at the clouds scale okay, and so we expect clouds to be promoted by conditional instability of the first kind. However, there is no such peaking at the synoptic scale when you do the mathematics of conditional instability of the second kind.

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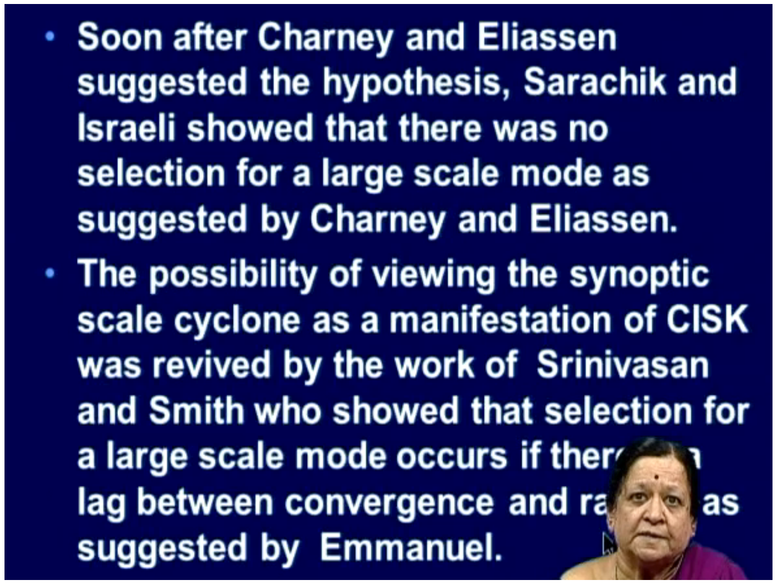

So this created a problem because soon after Charney and Eliassen suggested the hypothesis, Sarachik and Israeli showed that there was no selection for a large-scale mode as suggested by Charney and Eliassen. So although it sounded very good this kind of co-operation rather than competition and the first positive feedback between the scales and so on. Actually when the mathematics was done.

They found that there was no selection for synoptic or larger scale still it is only the cumulus scale which would get selected for. If we looked at tropical cyclones as being generated in a conditionally unstable atmosphere, so what they are saying is that you will not get systems or vortices of scale of that we see synoptic scale generated in the conditionally unstable atmosphere by this instability okay.

However, soon after this the possibility of viewing synoptic scale cyclones as a manifestation of this instability was revived by the work of Srinivasan and Smith who showed that selection for a large-scale mode occurs, if there is a lag between convergence and rainfall as suggested by Emmanuel. So it is possible under certain circumstances to actually get selection for a larger scale.

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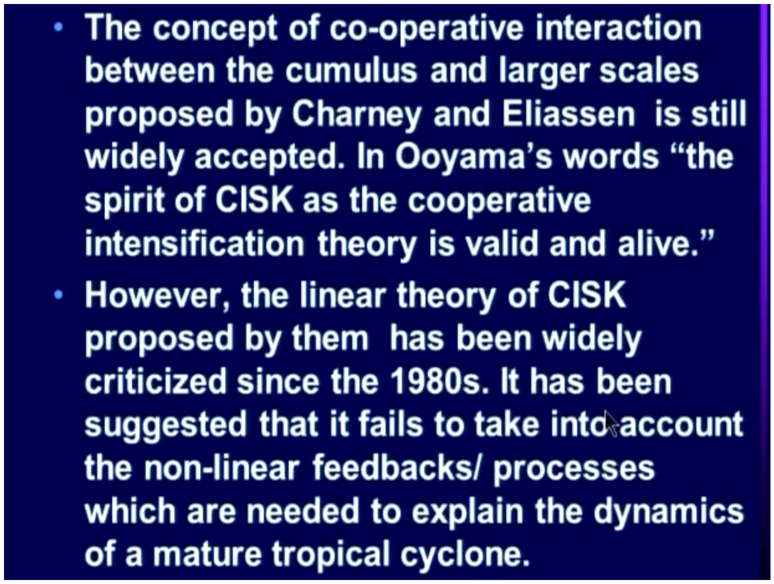

But you know there has been a lot of controversies about this concept of CISK. However, the concept of cooperative interaction between the cumulus and larger scale which was proposed by the Charney and Eliassen is still very widely accepted, so it was an idea that has found favor throughout the 4 or 5 decades after Charney and Eliassen paper. In fact, Ooyama's has done a very critical assessment of the whole thing and he says that the spirit of CISK as the cooperative intensification theory is value and alive.

So although they have been many, many objections raised to CISK, because one does not quite see the selection for the synoptic scale that one expected synoptic or larger scale the major concept introduced by Charney and Eliassen namely the fact that these 2 scales can interact in a cooperative way is still consist is valid and alive okay. So the linear theory of CISK proposed by them has been widely criticized as I mentioned since 80s.

It is it has been suggested and this is the most important criticism of the theory that because it is a linear theory it fails to take into account the non-linear feedbacks or processes which are needed to explain the dynamics of a mature tropical cyclone.

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So this is feedbacks are inherently non-linear which a linear theory cannot really take into account. So actually a cooperative intensification theory was proposed independently by Ooyama and what he did was not considered the synoptic scale vortex has been generated from the conditional instability Charney and Eliassen has done, rather he considers what would happen to a vortex which is generated in a conditionally unstable atmosphere.

So Ooyama's formulation of a theory of cooperative interaction between cumulus clouds and an incipient vortex differs in certain respects to that of Charney and Eliassen. Ooyama considered a flow configuration with the 2 layers of air above a shallow boundary-layer of uniform thickness.

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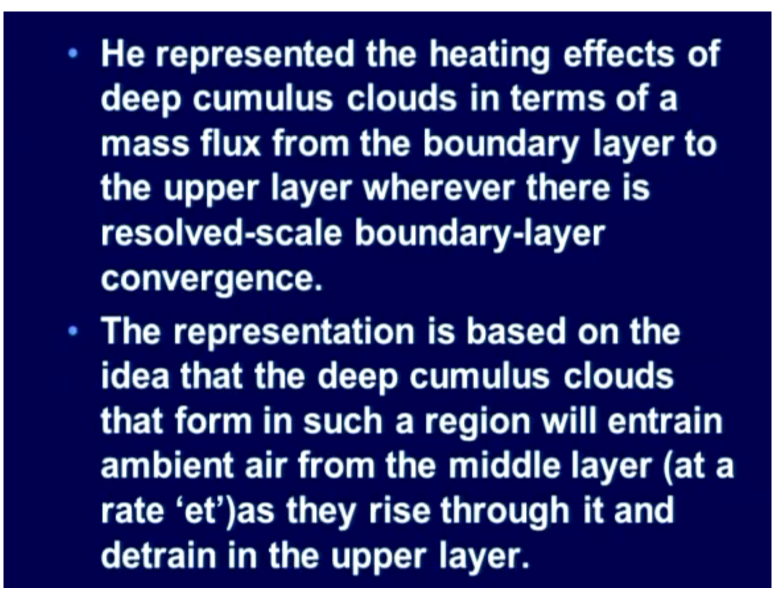

And he represented the heating effects of the deep cumulus clouds in terms of mass flux from the boundary-layer to the upper layer, so this is very similar to Charney and Eliassen right, mass flux from the boundary layer of moist air from the surface is very important. So boundary layer convergence is important in Ooyama's theory as it was in Charney and Eliassen, but the representation is based on the idea that the deep cumulus clouds that form in such a region will also entrain ambient air from the middle layers of the atmosphere.

So as the parcels of air rise from above the boundary-layer through the atmosphere, these moist parcels of air will actually entrain drier air from the surrounding region okay as they rise.

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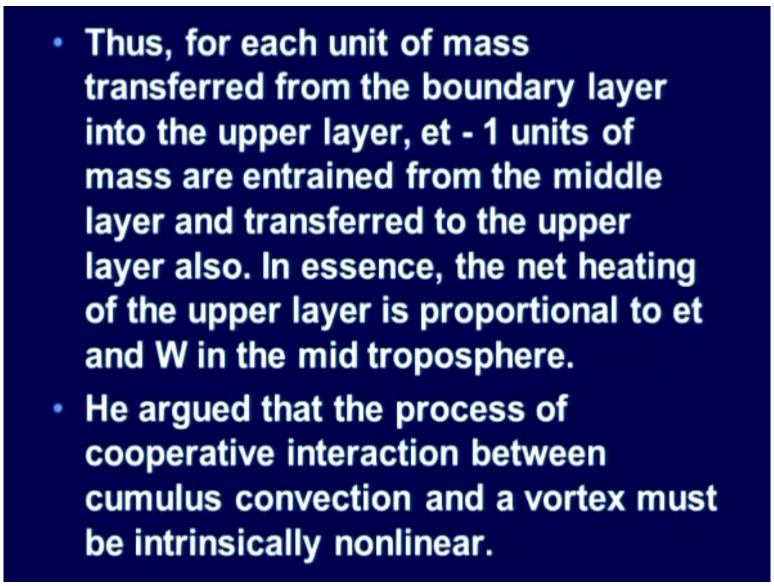

So what happens then is, thus, for each unit of mass transferred from the boundary layer into the upper layer okay, eta-1 units of mass are entrained from the middle layer okay and transferred to the upper also. So in essence the net heating of the upper layer is proportional to eta and W okay, so the dilution of eta the dilution of the air has an impact in how much heat is released the more the dilution the less heat will be released, because drier air has got mixed up okay.

So he argued that the process of cooperative interaction between cumulus convection and a vortex must be intrinsically non-linear, this was Ooyama argument.

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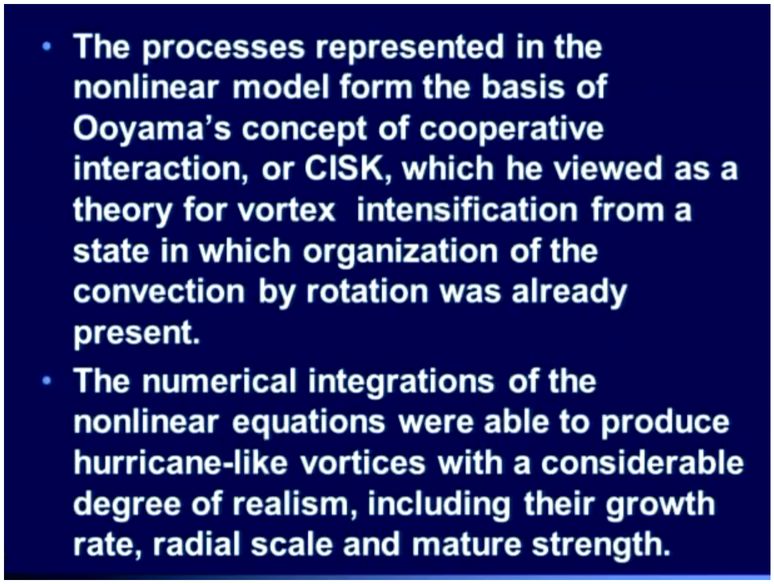

So the processes represented in the non-linear model form the basis of Ooyama's concept of cooperative interaction or CISK, which he viewed as a theory of vortex intensification from a state in which organization of the convection by rotation was already present. So he says that the vortex is already there and we talked of intensification, this is the departure from the Charney and Eliassen formulation of the theory.

Now numerical integration of the non-linear equations were able to produce hurricane-like vortices with a considerable degree of realism, including the growth rate, radial scale and mature strength. So this was the major achievement and okay.

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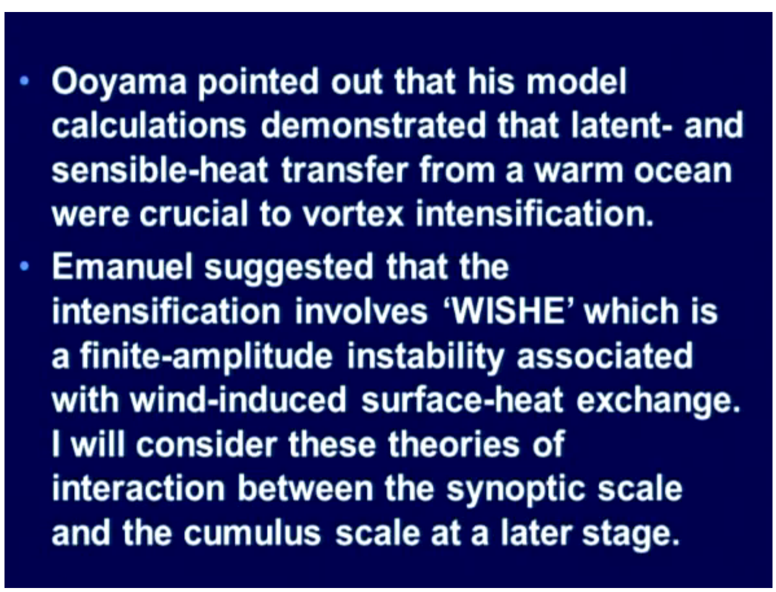

Ooyama pointed out that his model calculations demonstrated that latent and sensible heat transfer from a warm ocean were crucial to vortex intensification okay, so latent heat transfer of course Charney has talked about he said sensible heat transfer is also important, and both lead to have contributions to make to the intensification of the vortex. Now Emanuel was one of the fiercest critics of Charney and Eliassen theory.

And he said that actually intensification involves what he called WISHE, which is a finite-amplitude instability associated with wind-induced surface heat exchange, so WISHE stands for W is for wind-induced, surface is S, heat is H and exchange, so WISHE stands for wind-induced surface heat exchange. Now I will consider all these theories in detail, they cannot be considered without writing the equations and formulations and so on.

So we will postpone that to a later date and just get an idea of the kind of Physics they are suggesting okay.

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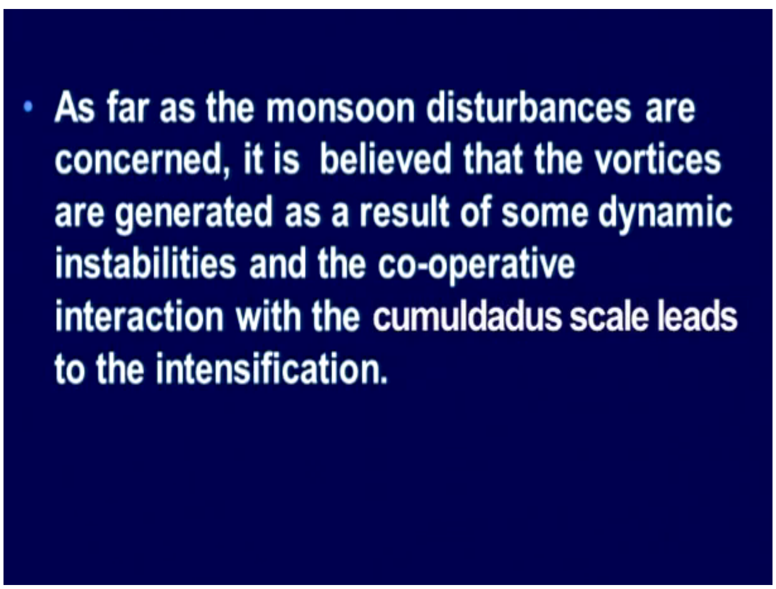

So there are these 2 streams of thought if you wish, what happens? How do we get selection for synoptic scale disturbances from the systems? And Charney and Eliassen think that in fact the conditional instability itself gives rise to synoptic scale disturbances, whereas there has been a lot of controversies of that? But Ooyama suggest that incipient vortex intensifies due to the mechanism suggested by Charney and Eliassen.

Now we have seen monsoon disturbances that occur in our systems, these are lows, depressions and so on. And we have also seen hoe over the Indian Ocean you get tropical cyclones form, now how do these systems get generated? The last word on this is yet to be said. However, what is very clear what people believe right now is that probably the vortex gets generated due to some kind of instabilities of shear flow in a rotating system horizontal shear corresponding to barotropic instability, vertical shear of wind corresponding to baroclinic instability.

And because the atmosphere is unstable to both in terms of barotropic and baroclinic instabilities, these vertices get generated. Now once they generated the kind of cooperative interaction that people talked about actually takes place, and then they intensify. So this is the present view of how the systems gets generated and so on and okay.

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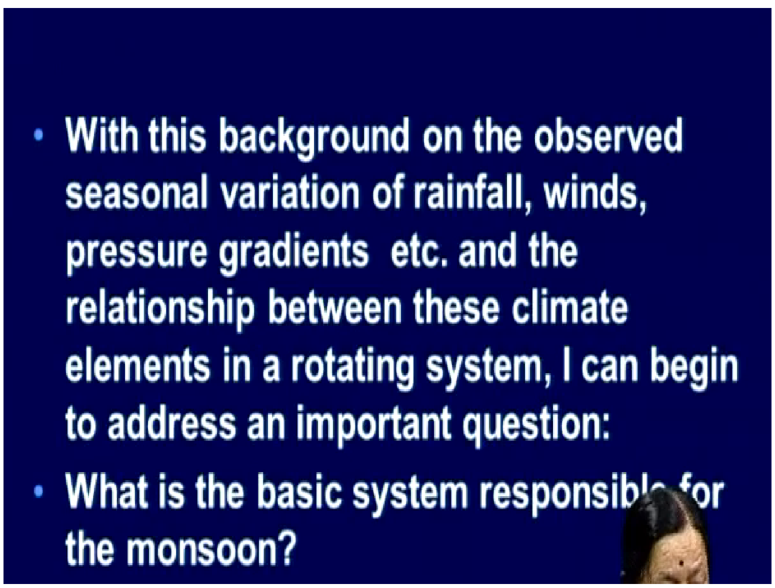

So this is the present view of how the monsoon disturbances occur and now I think we have enough of a background to ask the question, how do we get the monsoon? What is the basic system responsible for the monsoon? So again I must remind you what is the critical background that we had? We have seen that in a rotating system cyclonic vorticity leads to ascent of air, now why is the ascent of air important?

Because our atmosphere is conditionally unstable right, it is stable with respect to vertical displacement of dry air, but unstable with respect to vertical displacement of moist air parcels upward displacement of moist air parcels, the atmosphere is unstable so if you can perturb the atmosphere and make surface air which is moist rise to a certain level, then particularly when you can make it rise to a level above the lifting condensation level.

Now again to remind you what happens when we let the parcel of rise, actually if we do it adiabatically without adding any energy to the parcel, then it will expand because the pressure at the higher level is lower, and because it has to do it at its own cost it cools. so it cools and if that is all the process taking place because it cools, it finds itself denser than the surrounding and returns to the original level, this is stability of the dry parcels.

But if we can push the surface air up to a level at which condensation can begin, because as it cools the amount of water vapour it can hold decreases, so eventually as it cools it becomes saturated although it is never saturated at the surface. Now it becomes saturated at the lifting condensation level, now beyond this level then latent heat of condensation gets released.

And it so happens that the tropical atmosphere the temperature variation with height is such or the lapse rate is such that in this situation when actually water vapour condensing to liquid water, then the moist air parcel that began with the surface becomes warmer than surrounding and keeps rising, and this is the conditional instability we talked about which is in fact the critical thing required for getting clouds.

So the clouds that we see in the tropical atmosphere are as a result of the conditional instability, and this conditional instability why is it is called conditional? Because tropical atmosphere is not stable to moist parcels of air, but it is stable to dry parcels of air when lifted up. So the conditionally unstable atmosphere we showed in fact if we consider the instability problem of which scale get selected for a conditional unstable atmosphere.

Then we find that if we looked a inviscid fluid right, no viscosity at all then the thinnest cloud will get selected for that is the smallest horizontal scale get selected for, but in reality you cannot just ignore viscosity totally. So what happens is that viscosity comes into play and the thinnest clouds in fact will not be get selected for, because the thinnest clouds have much larger area related to volume.

And therefore, you know the area related to volume was like 1/radius, so the thinnest clouds have much larger area related to volume, so due to entrainment of dry air the thinnest clouds will actually not be able to grow the fastest, and in a real fluid then the cloud that will grow fastest are roughly the scale of the troposphere which is about 10 kilometer or so. So the thinnest clouds the clouds that gets selected for in a conditionally unstable atmosphere have horizontal extent of the order of 5 kilometer.

So there were 2 things then we learnt that we need ascent of surface air for clouds to form, then how do we get ascent of air over scales for which location is important, now these are the larger scales from few 100 kilometers and so on. And for this larger scales we noted that the effect of rotation of the earth becomes very important, so effect of rotation of earth is important for these scales, and so the boundary layer changes character in the rotating systems.

We have to consider the rotation of the earth, so we look at boundary layers in rotating the systems instead of non-rotating the system, now once you start looking at boundary layers in rotating the systems the major difference comes in the fact that the boundary layers are in a rotating system is highly interactive boundary layers, and when you have cyclonic vorticity above the boundary layer that is the atmosphere or ocean above the boundary layer is rotating in the way relative to the earth with the same sign as the earth rotation.

In that case we get convergence in the boundary layer and ascent of air above the boundary layer, so this mechanism is extremely important for giving ascent over spatial scales which are large enough for rotation of the earth to become important in the dynamics. So we need ascent of air up to the lifting condensation level for clouds to form ascent occurs in the rotating systems provided there is cyclonic vorticity above the boundary layer.

These were the first 2 lessons we learnt, and the third less than which is what we looked at this time was how then can in this kind of an atmosphere how do systems of a larger scale which have clouds organized over that scale in fact get selected for, what is the basis for occurrence for organization of clouds over synoptic and largest scales? And this is where an entirely new concept was introduced.

This concept that it is not that there is competition between scales, whenever we looked at the problem as an instability problem, we always consider what will happen to an unstable system when you have the perturbation which has energy in all kinds of scales. What happens is in that scenario when we have a perturbation with all kinds of scales, the scale that grows fastest which is determined by the nature of the instability itself is the one that get selected for.

So in that scenario you will get selection for that scale which is maximally efficient in tapping the instability of the system, so this is the approach we take and if we took the same approach for a conditionally unstable atmosphere then always in the competition with other scales the cumulus scale will win, because that is what the mathematics of the instability of the conditionally unstable atmosphere tell us.

So in that situation cumulus scale will always win, but if we look at systems over the tropics we have very intense systems like tropical cyclones which have scales of few 100 to 1000 kilometers. And we have day after day organized clouds over planetary scales, these are east west bands that we saw of clouds seen by satellites, which stretch over 1000s of kilometers and which are typically few 100 to 1000 kilometers in latitudinal extent as well.

So question is how then in this atmosphere we get organization of the clouds on this scales, and as I mentioned that this is the problem that was address by Charney and Eliassen, and is actually at the heart of our understanding not only the monsoon but cloud systems over the tropics of which monsoon is a specialized case.

So what we have now learned today is that early attempts to look at conditional instability of the second kind by invoking one more phenomena namely, the possibility of a cooperative interaction between the larger or the synoptic scale and the cloud scale, and doing a linear stability analysis like we do for shear flow instability or like we did for the conditionally unstable atmosphere, so if you do that kind of exercise the linear exercise.

Then what was found is that in general there is no scale selection that is to say the so-called conditional instability of the second kind will not promote the synoptic or the larger scale, there is no scale selection from the cumulus scale to the synoptic scale, so there is no reason to believe that the synoptic scale disturbances will arise as a manifestation of the conditional instability of the second kind.

Even when we take into account the new phenomenon that was proposed by Charney and Eliassen which was cooperative interaction between the cumulus scale and the synoptic scale, so even when we assume that what occurs in real life is an interaction whereby the synoptic scale system by creating convergence in the boundary layer and Ekman layer and ascent of moist air above the boundary layer can generate clouds provided the ascent is up to and beyond the lifting condensation level.

And the clouds by heating the region over which they are generated, the region of the cyclonic vortex or region over which ascent is taking place from the boundary layer by heating that they actually make the pressure of associated with vortex over intensify the convergence and therefore, intensify the ascent and clouds. So even if we take into account this kind of positive feedback between the scales which Charney and Eliassen right to do in their linear theory.

There is no selection for the synoptic scale with one exception and that as I mentioned that if one assumed that there is some time lag between the convergence and the rainfall that occurs then you can get some selection for the broader scale. But on the whole this whole concept that you can get selection with that kind of formulation was criticized heavily, then Ooyama's came up with this theory that in fact the key point of CISK and Charney work the cooperative interaction.

And it is now believed that the cooperative interaction is that a very, very important part of tropical convection over synoptic and larger scales in fact the strong link between vorticity and convection cyclonic vorticity above the boundary layer being essential for tropical convection over synoptic and larger scale which makes possible this positive feedback between the cumulus and the larger scale is an extremely important concept.

And that concept is very much still alive today, so it can help us understand how the 2 systems interact and just using the idea that this kind of cooperative interaction can play a very, very important role in intensification of the vortex. So if you start with an incipient vortex in a conditionally unstable atmosphere, this positive feedback between the 2 scales can lead to intensification of the vortex.

In fact, it was shown very nicely theoretically by Ooyama's who also pointed out that the non-linear feedback is very critical in getting a realistic intensification of the tropical cyclone. So at the end of the day then we believe that the key concept is increased by Charney and Eliassen about actually the cooperative interaction between the cumulus scale and the synoptic scale is valid is considered valid today.

But it is not theoretically possible to show that one can conceive of this synoptic scale systems has been generated from a conditional unstable atmosphere as a manifestation of the instability. I must also have mentioned that the role of sensible heat, now sensible heat is the heat transfer that occurs from a warmer surface to a colder surface, and generally you know the atmosphere is overlying an ocean which is warmer.

So sensible heat from land or ocean to the atmosphere is also supposed to play a very critical role, now this was pointed out both by the Ooyama's and Emanuel and Emanuel even coined a word special instability theory for it called the wind-induced sensible heat exchange at the ocean atmosphere interface of the tropics. So be that as it may it is very clear that fluxes of latent heat and sensible heat from the ocean are very important for tropical convection.

And this kind of nonlinear feedback between the larger scale systems and the cumulus clouds is also very critical for our understanding how tropical convection occurs on these scales. So now we have the background to actually pose the problems we started with, what is the basic systems responsible for the monsoon? What is the Physics of the monsoon? Because it is only when we identify what is the basic systems responsible for the monsoon will we be able to propose hypothesis for understanding the nature of the variability of the monsoon okay.

And only when we can test these hypotheses that are proposed for nature of variability of the monsoon with models, we will be able to incorporate the right physics in the models to make it possible to predict the variability of the monsoon. So with all these background both in rotating fluids and clouds in tropical atmosphere, we are ready to embark on the central problem of this lecture course, what is the monsoon?

What is the basic system responsible for the monsoon? And that is what we look at in the next lecture, thank you.