The Monsoon and Its Variability

Prof. Sulochana Gadgil
Centre for Atmospheric & Oceanic Sciences
Indian Institute of Science - Bangalore

Lecture - 10
Evolution of The Ideas About the Basic System Responsible for The Indian Monsoon - Part 2

We have been talking about the evolution of the ideas of the basic system responsible for the Indian monsoon.

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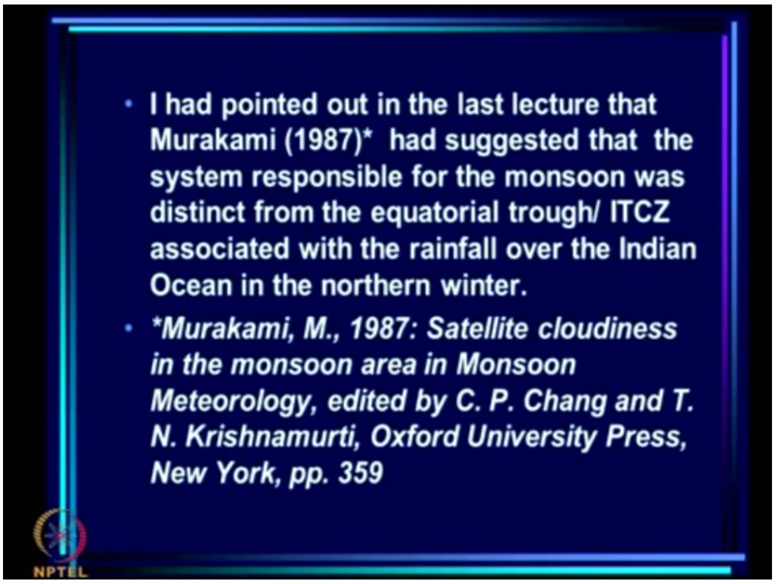

And at the end of the last lecture, we saw that in fact, there was a suggestion that the basic system may be the equatorial trough or ITCZ, but there were serious objections to that view and I mention the objection of Murakami who said that if you look at the low OLR region, then the system responsible for the monsoon has to be considered distinct from the equatorial trough or ITCZ associated with the rainfall over the Indian Ocean in the northern winter.

This is what he said in the other major book on monsoon which came out also in 1987 by Chang and Krishnamurti.

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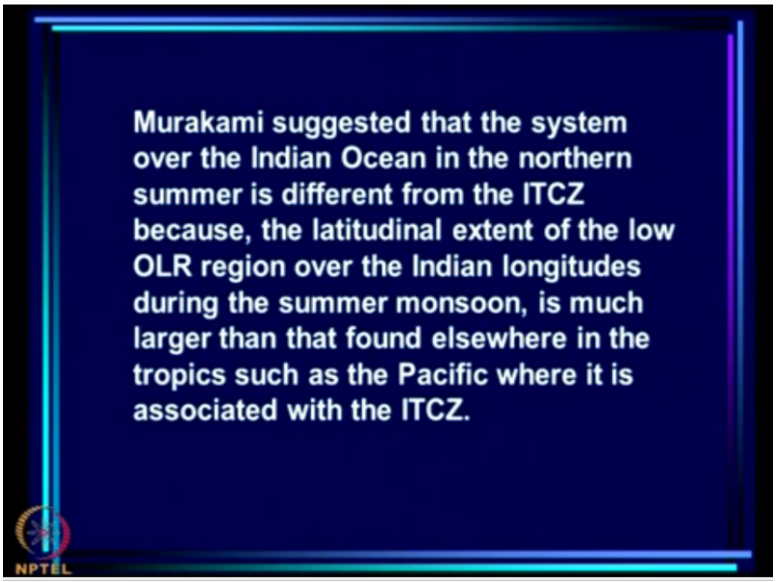

Now Murakami suggested that the system over the Indian Ocean in the northern summer is different from the ITCZ because the latitudinal extent of the low OLR region, which is the region of convection or rain over the Indian longitudes during the summer monsoon is much larger than that found elsewhere in the tropics such as the Pacific where it is associated with the ITCZ.

So that whereas the extent is about 10 degrees or so in the Pacific or Atlantic. It is much more like 30 or 40 degrees over the Indian longitudes in the summer.

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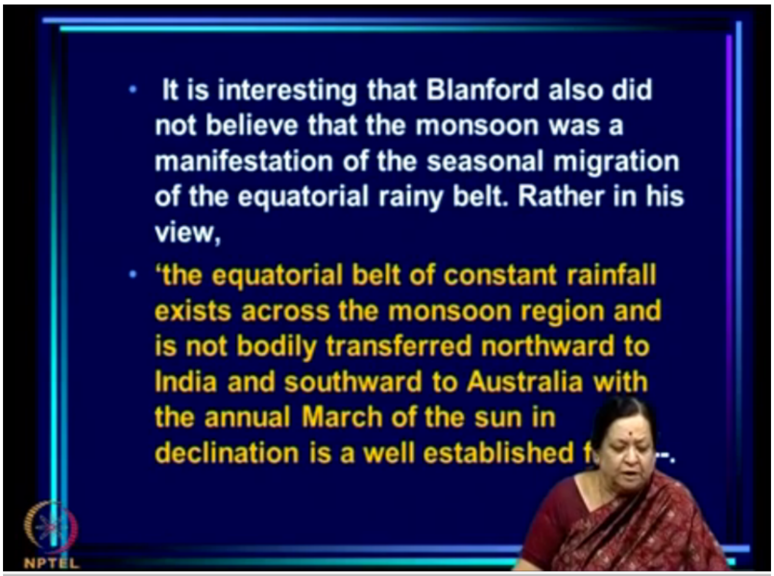

Now it is interesting that Blanford also did not believe that the monsoon was a manifestation of the seasonal migration of the equatorial rainy belt. He felt the monsoon was definitely associated with the equatorial rainy belt, but he did not believe it was a migration, in fact the way he expressed it as follows.

The equatorial belt of constant rainfall exists across the monsoon region and is not bodily transferred northward to India and southward to Australia with the annual March of the sun in declination is a well-established fact is the way he puts it.

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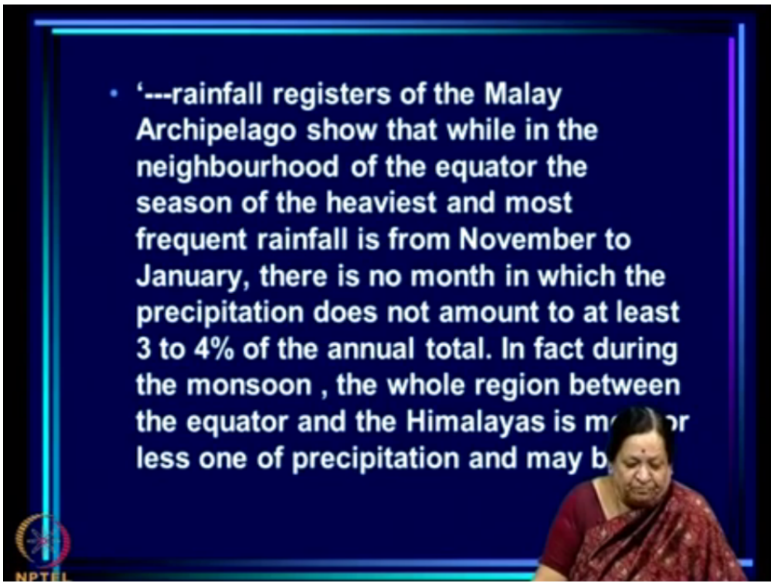

He says rainfall registers of the Malay Archipelago remember his talking in 1886 show that while in the neighborhood of the equator, the season of the heaviest and the most frequent rainfall is from November to January. There is no month in which the precipitation does not amount to at least 3 to 4% of the annual total. In fact, during the monsoon, the whole region between the equator and the Himalayas is more or less one of precipitation.

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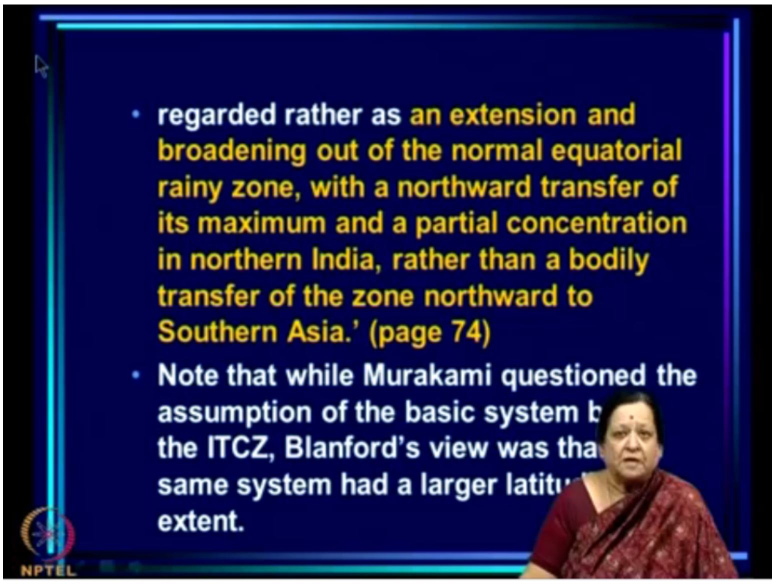

And may be regarded rather as an extension in broadening out of the normal equatorial rainy zone with a northward transfer of its maximum and a partial concentration in north India rather than a bodily transfer of the zone northward to Southern Asia. Now this it turns out to be a very, very perceptive remark and we will see that in many ways this is borne out by the later studies.

So there is a difference now between Murakami's approach and what Blanford said while Murakami questioned the assumption that the basic system is the ITCZ. Blanford's view was that the same system meaning the basic system for the monsoon was the equatorial trough for the ITCZ, but it had a larger latitudinal extent. He says the system is kind of spread from equator to north India.

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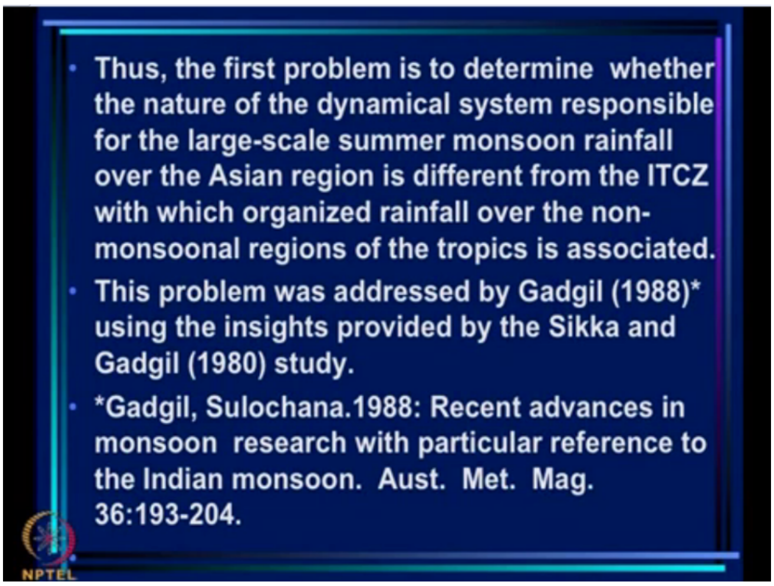

Thus the problem is to determine first whether the nature of the dynamical system responsible for the large-scale summer monsoon and rainfall over the Asian region is different from the ITCZ with which organized rainfall over the non-monsoonal regions of the tropics. This problem was addressed by Gadgil in 1988 using insights provided by Sikka and Gadgil 1980 study, which I have mentioned before.

Now it is worthwhile I think to look into the details of the results of the Sikka Gadgil study because it is very pertinent to the question at hand.

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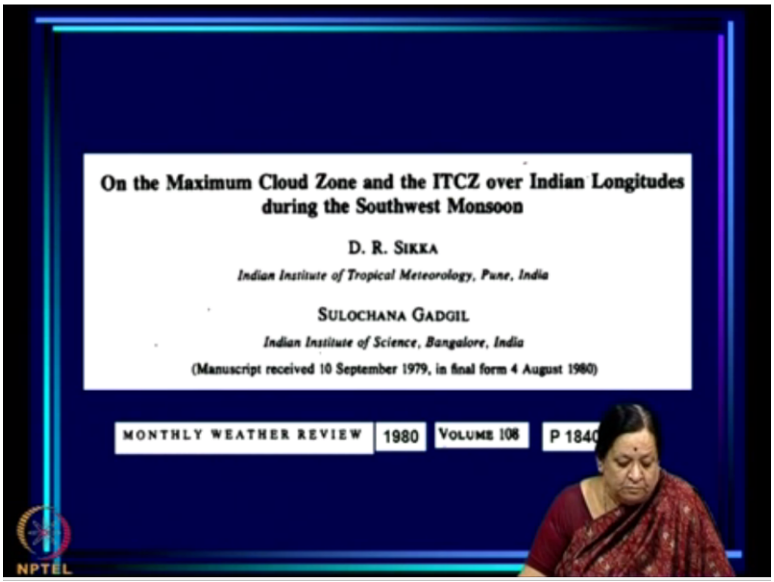

This was the paper published in 1980 called On the Maximum Cloud Zone and the ITCZ over Indian Longitude during the Southwest Monsoon.

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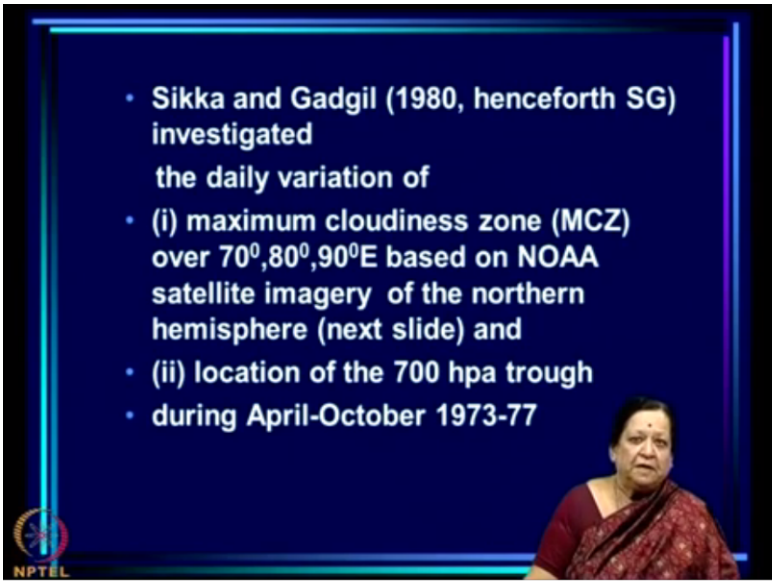

And it was the first systematic study of satellite imagery what Sikka and Gadgil I will refer to them as SG from now on investigated was the daily variation of what they call the maximum cloudiness zone and I will define how they defined it over 70, 80 and 90 degrees east based on NOAA satellite imagery of the northern hemisphere and also the location of the 700 millibar equatorial trough.

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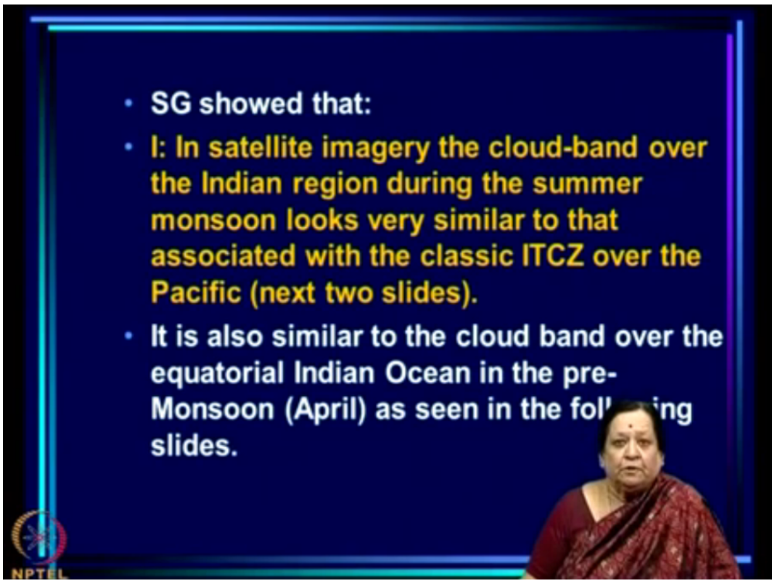

Now SG showed that in satellite imagery, the cloud-band over the Indian region during the summer monsoon looks very similar to that associated with the classic ITCZ over the Pacific okay and it is also similar to the cloud-band over the equatorial Indian Ocean in the pre-monsoon that is April.

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And we will see that in the slide. So this is the kind of imagery that they looked at satellite imagery from NOAA, this is the kind that used to be available in those days. This is for 8th July, 1973.

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And you see the band is somewhat very similar in terms of appearance at least to the 1 in the Pacific and this is the classical ITCZ over the Pacific with the tropical cyclone or the typhoon taking off from it.

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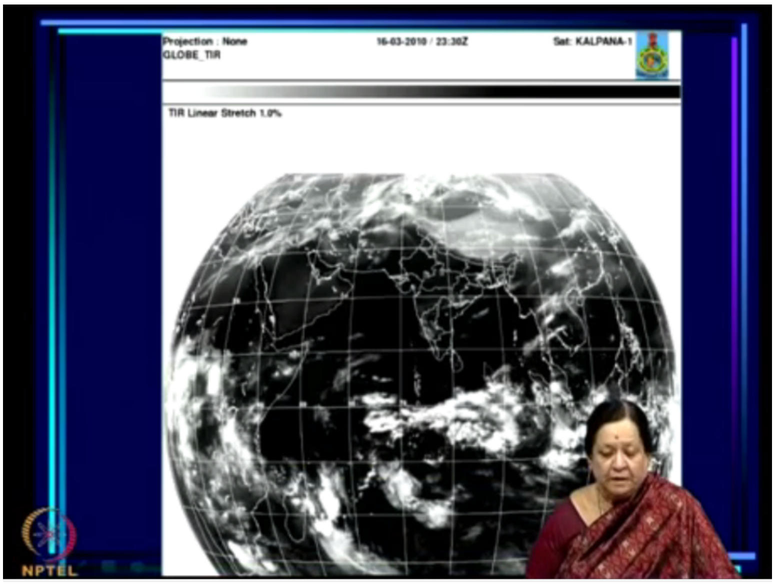

It is also similar in looks to this equatorial band here, which you see this is in March. This is in equatorial band. So as far as appearance goes the band that we see over India looks rather similar to these bands. This is the 1 in spring, again you see the ITCZ stretched across the equatorial region here.

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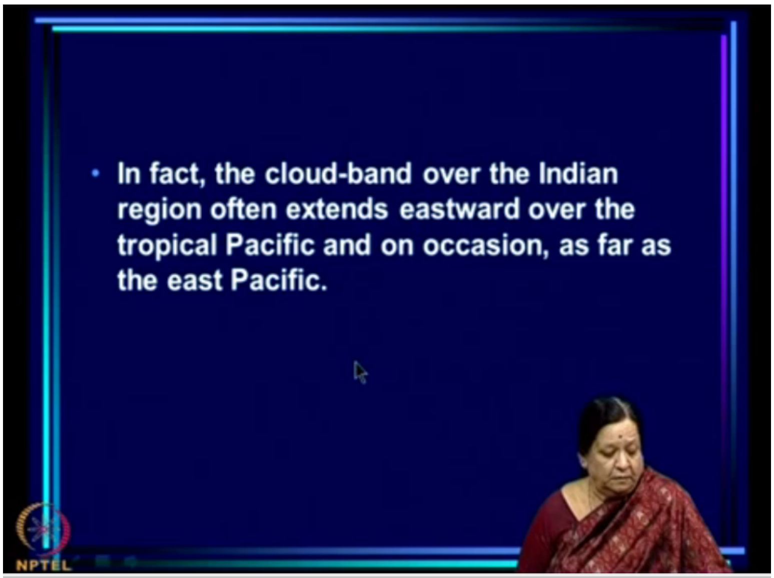

So in fact what they found was the cloud-band over the Indian region often extends eastward over the tropical Pacific and on occasion as far as east Pacific.

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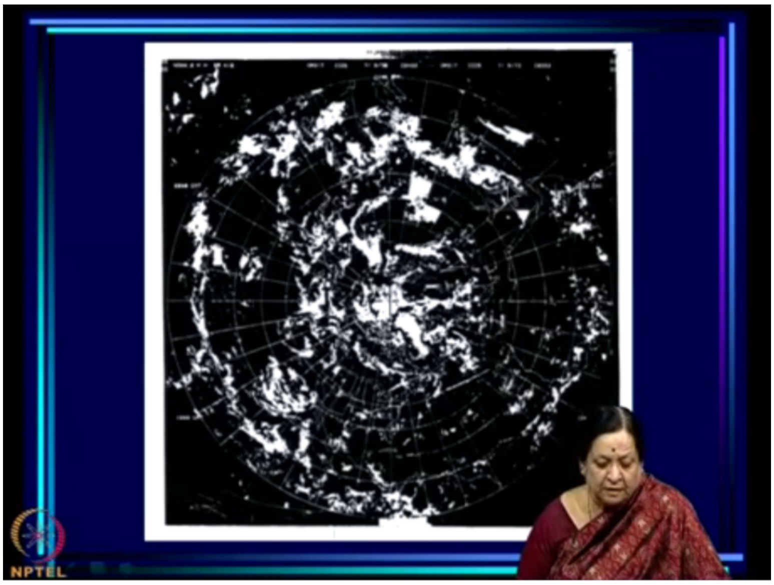

So it descent as if it is an isolated cloud-band rather the same band is seen as being part of a band, which is almost girdling more than half the earth. So this is the band that you saw earlier. India is here, Ceylon is here, Sri Lanka is there. So this is the band you saw earlier. This is going towards the west. This is west Pacific now. Now it is going slightly equator ward here in this imagery.

This is still a hemispheric imagery, this is over the Pacific and you see it as a continuation almost up to about half the hemisphere as you can see. So this is sort of giving even more support to the idea that it is the same beast that we see here we see a part of the same creature here and that is what is giving us monsoon rainfall.

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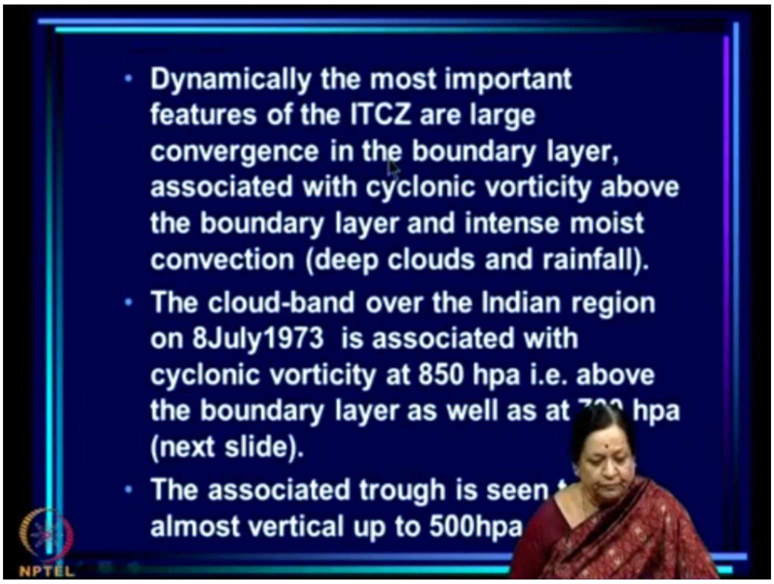

This is only of course imagery can only suggest. Now question is we have to also see if dynamically you know the rain system over the monsoon region has the characteristics of an ITCZ. So what are the important characteristics of an ITCZ? See dynamically the most important features of the ITCZ are large convergence in the boundary layer, which as you know in rotating systems is associated with high cyclonic vorticity above the boundary layer.

So in turn cyclonic vorticity above the boundary layer, large convergence in the boundary layer and deep clouds and rainfall, which means intense moist convection. So these are the characteristics of the ITCZ. Now the cloud-band over the Indian region on 8th of July is associated with cyclonic vorticity.

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Fig 6. Satellite imagery of an active monso... day (8th july 1973).

Now let us go back and see that is the cloud-band we are looking at, this is the cloud-band for 8th of July, 1973 and let us see what is the circulation associated with this cloud-band on 8th of July that is shown here.

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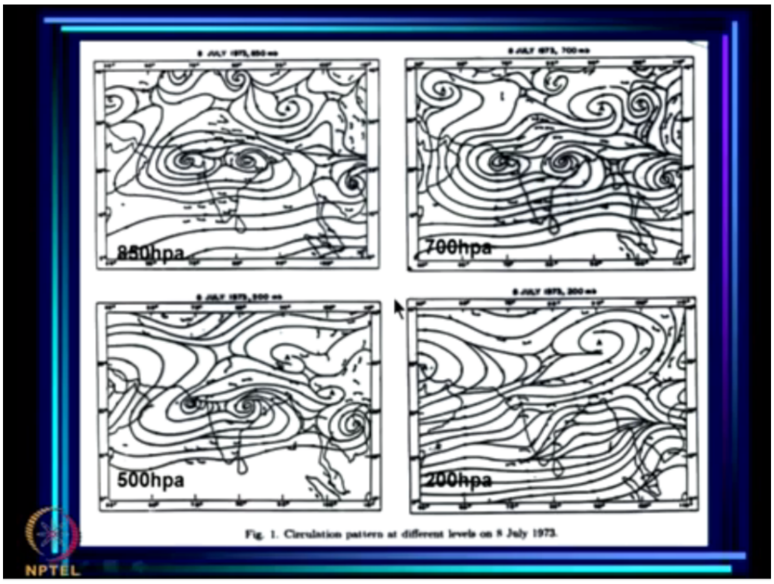

Fig. 1. Circulation pattern at different levels on 8 July 1973.

This is from Sikka's paper in 1977. Now what you see here is the story at 850 hpa. This is just above the boundary layer. This is about 1.5 kilometers above the surface of the earth. So what you see here is cyclonic vorticity. See in fact the winds are westerlies here and easterlies to the north. So these are vortices, which are anti-clockwise or cyclonic. They are going like this and so you see a region of high cyclonic vorticity just where the cloud-band was.

This is at 850. Now see what is happening at 700 and you will come to realize the importance of this level 700 as we proceed in the lectures, but the important point is that when you have intense moist convection you also see high cyclonic vorticity at 700 hpa and the trough, which would be here is in fact just above the trough at 850 here and same thing at 500, 500 also you have the trough more or less at the same location.

So the system is essentially vertical okay with intense cyclonic vorticity and convergence up to a level beyond 700 hpa even higher than 700 hpa up to 500 and beyond. This is 200 hpa.

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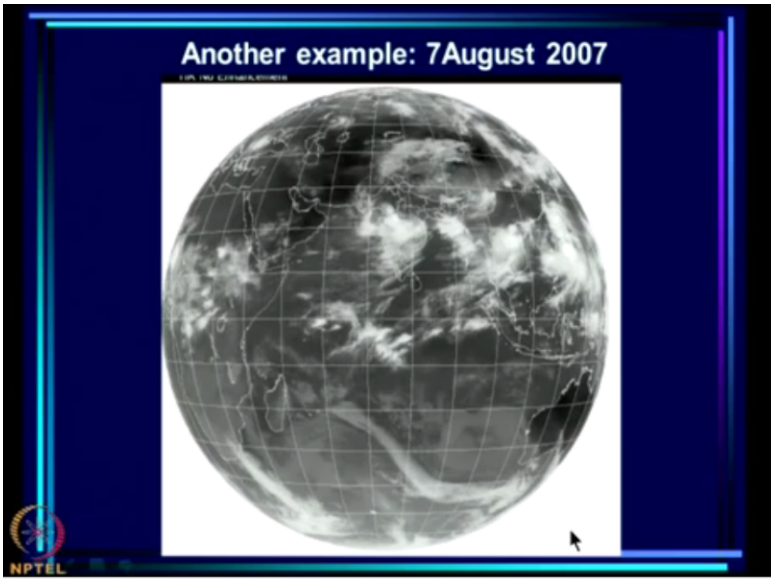

Now this is another example that 1 was from the Sikka Gadgil paper that example of the cloud-band and as I said the cyclonic vorticity pictures and so on were from Sikka's paper in 77. Now this is another example, you see the ITCZ very good band, coherent band here and let us see what is the vorticity of this thing?

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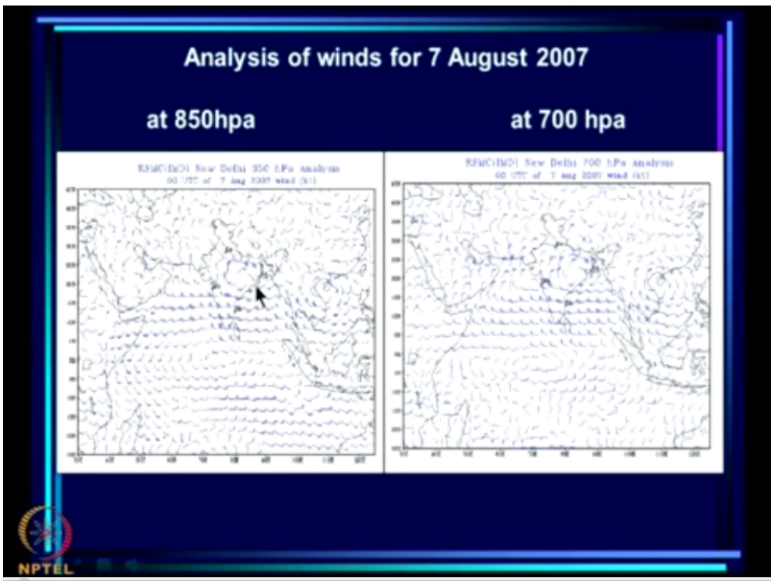

So this is from the IMD charts now, this is at 850 hpa and you see a cyclonic vorticity where the cloud blob was and you see that it is also occurring at 700 hpa. So the 700 hpa trough would also be over this region and 850 hpa trough would also be over this region.

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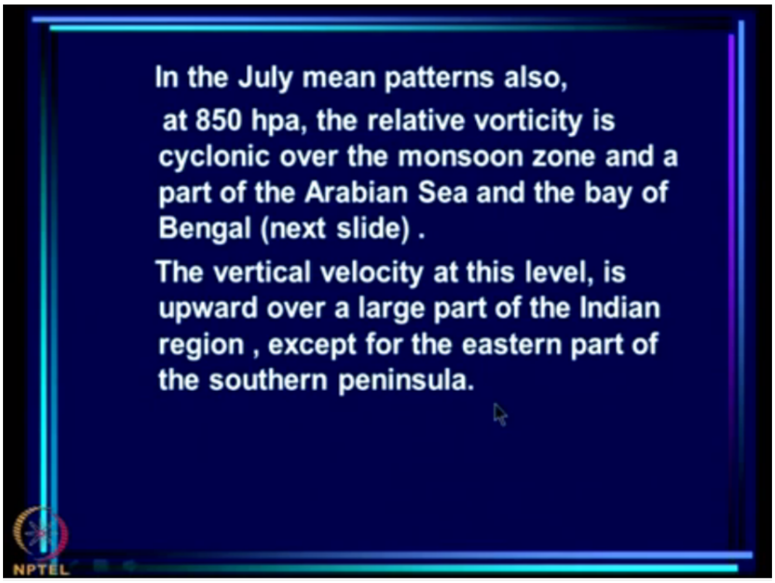

So we have seen that under daily scale if we look at the picture of an intense cloud-band associated with the rainfall over the monsoon then it is also associated with the high cyclonic vorticity above the boundary layer and we see that the trough is almost vertical up to 500 hpa and it is associated of course with moist convection and heavy precipitation as is evident from the nature of the clouds.

It is a maximum cloudiness zone okay. Now that was the daily scale let us see what happens in the July mean patterns also.

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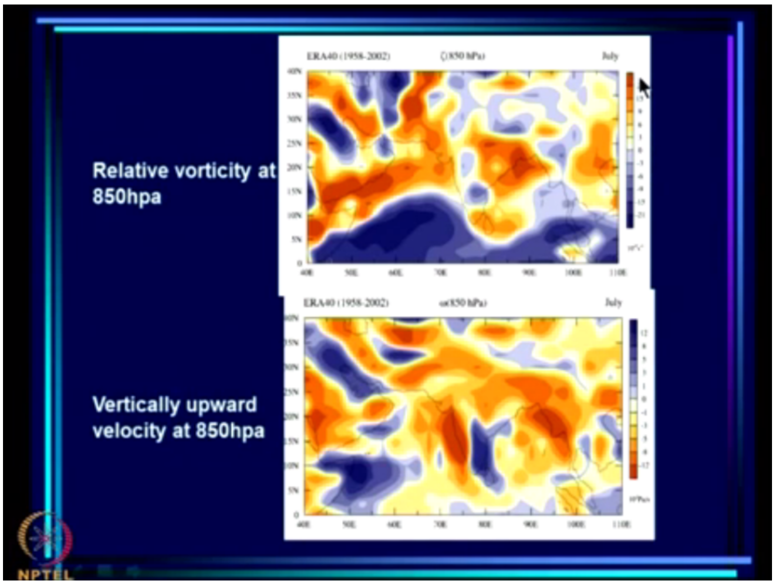

Now let us look at here we see relative vorticity at 850 hpa, this is above the boundary layer at 1.5 kilometers. All the blues are negative okay so this means anti-cyclonic vorticity. These yellows and oranges rather are all positive relative vorticity and you see that as far as the 850 millibar vorticity is concerned over the entire monsoon zone, the relative vorticity is positive okay.

And this is omega or the vertical velocity again what we have done is shown that the vertically upward velocity is the same colors, this is orange and yellow and you see that at 850 hpa, it is actually upward everywhere. Notice one more thing you know; we had said when we looked at boundary layers in rotating system that if the vorticity is cyclonic above the boundary layer then you have upward velocity at the upper edge of the boundary layer.

If it is anti-cyclonic it is downward. Now notice that there is a blue blob here and here a very strong blue blob here. This is over southeast coast of the peninsula around Chennai and so on. During July mean you see a blob here and this means there is negative vorticity here or anti-cyclonic vorticity and correspondingly you have descending air here into the boundary layer. So in a way this confirms what our Ekman boundary layer theory had shown.

That if you have cyclonic vorticity only then you will get ascent of air. If yo have anti-cyclonic vorticity, the air will descent so this is the July picture now.

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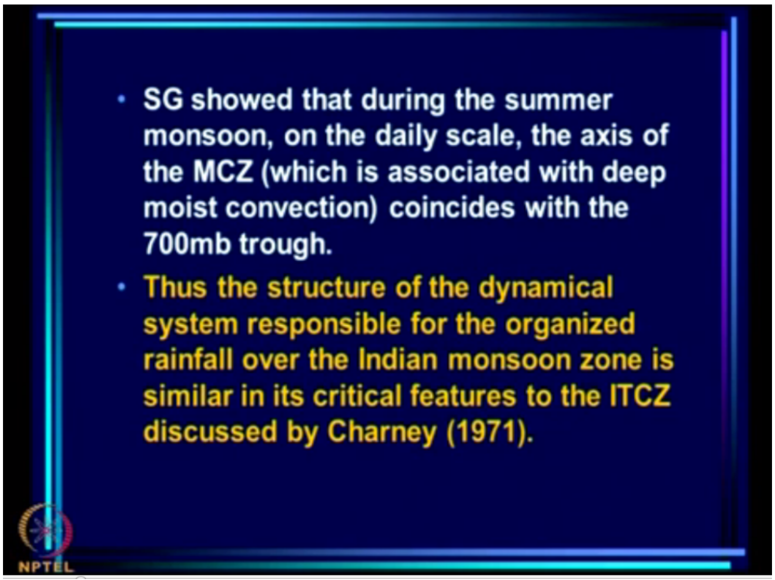

So now we look at what happens on a daily scale. There is the axis of the MCZ situated and they showed in fact that the access of the MCZ, which is associated with deep moist convection in fact coincides with the 700 millibar trough. So this means not only is it do we have cyclonic vorticity above the boundary layer, furthermore at 700 millibar trough, which in fact delineates the axis of heavy rainfall region actually coincides with the axis of MCZ okay.

So the structure of the dynamical system responsible for the organized rainfall over the Indian monsoon is similar in its critical features to the ITCZ discussed by Charney. This is the conclusion we have come to.

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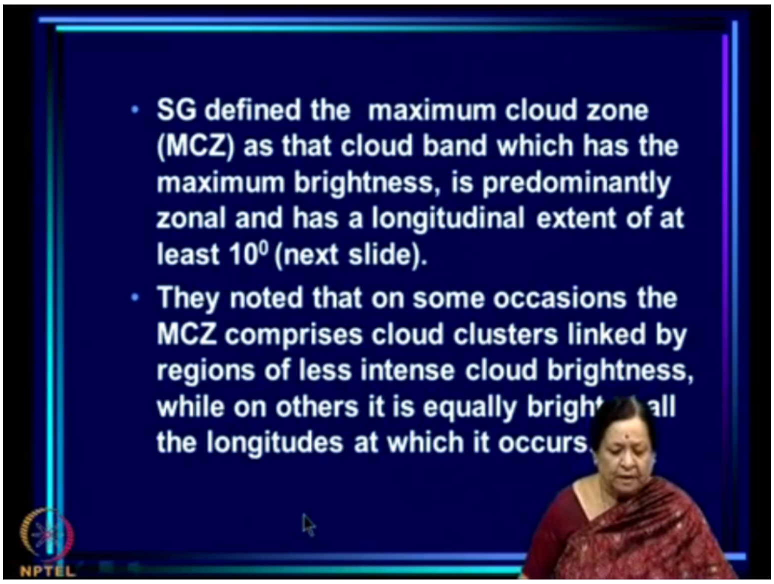

Now how do we define the maximum cloud zone? They define maximum cloud zone as that cloud-band, which has the maximum brightness is predominantly zonal, zonal meaning in east west direction and has a longitudinal extent of at least 10 degrees.

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So this is their classic picture of course. This is the band and you can say by enlarge it is in the east west direction, it is zonal and it is coherent all the way from this is about 60 degrees east to beyond 100 degrees east. So it is coherent over more than 40 degrees of longitude. So it satisfies the condition they had that it has a longitudinal extent of at least 10 degrees.

Now they noted that on some occasions, the MCZ compresses cloud clusters linked by regions of less intense cloud brightness while on others it is equally bright at all longitudes at which it occurs. So it is not necessary that the band is equally intense everywhere. In fact, this is the case where you have clusters of intense clouds joined by relatively less clouding in between, but it is very clearly a coherent cloud-band okay.

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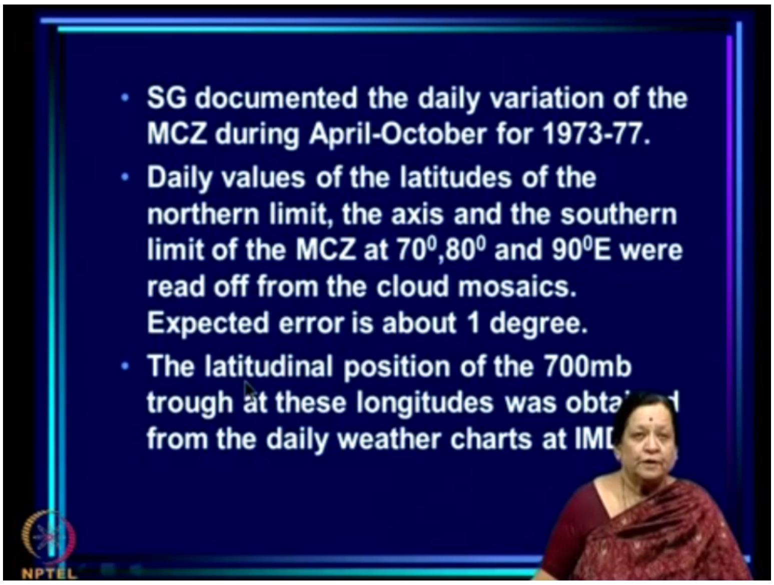

So then they documented the daily variation of the MCZ during April and October and what they did was they took daily values of the latitudes of the northern limit, the axis and the southern limit of the MCZ at 70, 80 and 90.

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So here we are in the same picture. Now this is 70 degrees east here. This is the longitude of 70 degrees. I do hope you can see India quite clearly and you can see Sri Lanka there. So that will be a good way to see where India is and 80 degrees is sort of consider the central longitude of India, this is 80 degrees and this is 90 degrees the 1 that passes through head Bay okay.

So at these 3 longitudes, 70 degrees, 80 degrees and 90 degrees what did they read? From imagery like this they would read what is for example this is the southern limit of the MCZ.

This is the northern limit of the MCZ and there would be an axis in between. So these 3 things were read off at 70, 80 and 90 from imagery of everyday okay.

So daily values of the latitude of the northern limit, the axis and the southern limit of the MCZ at 70, 80 and 90 were read off from the cloud mosaics. They estimated that the expected error in the reading would be about 1 degree because this was the fairly large pictures, good satellite imagery okay. The latitudinal position of 700 millibar trough at these longitudes, they got from the daily weather charts at IMD.

So this is the basic data source then. First of all, the satellite imagery, which gives the maximum cloudiness zone and then daily weather charts from which 700 millibar trough position was read off.

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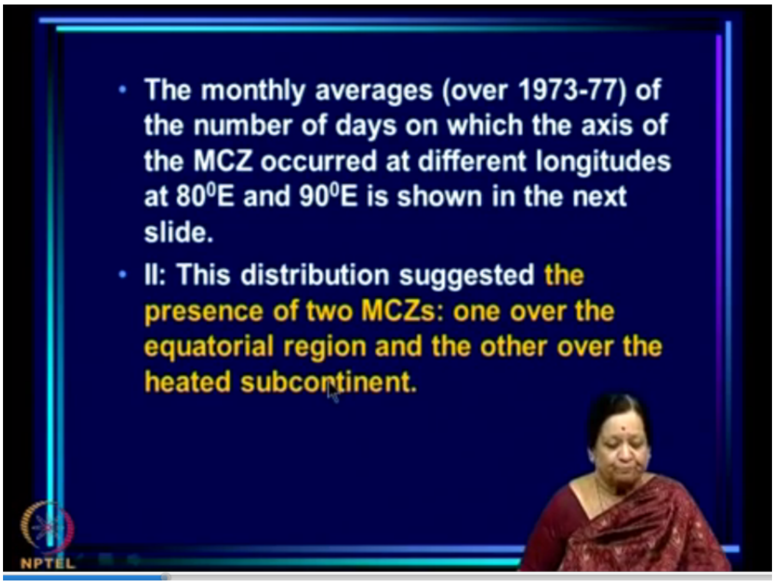

Now the first thing we want to do is how frequently does the MCZ occur at different latitudes okay? So the monthly averages we take over 73 to 77 of the number of days on which the axis of the MCZ occurred at different longitudes at 80 and 90. So that is what we want to see here.

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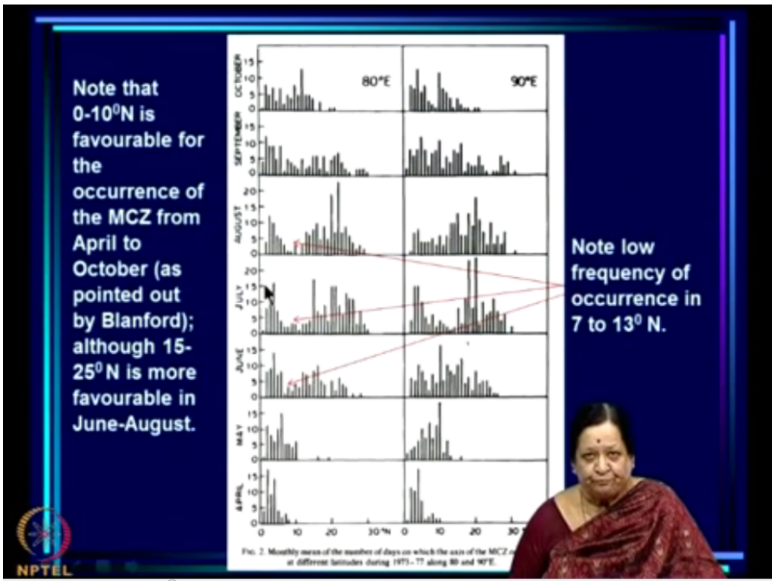

And this is the picture now. This is going all the way from April here May, June, July, August, September, October. This is 80 degrees here and this is 90 degrees on the right okay. Now what we have plotted is number of days on which the access occurred within a certain latitude. Now this latitude is here. It goes only from 0 to about 30 north or so okay, 0, 10, 20 and 30 north.

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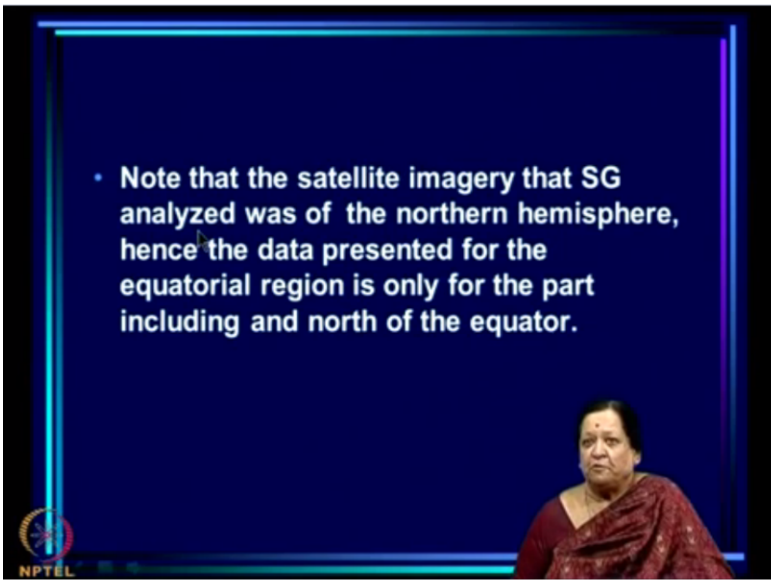

Now why does it start only from 0? In fact, the imagery that Sikka Gadgil had was that of the northern hemisphere only. So the data began from 0 and went northward. So data presented for the equatorial region is only for the part including a north of the equator. This is why we see from here; the latitude begins with 0 here. Later on, when we look at what happens with digital OLR data, which became available much later.

Then we will see that actually this equatorial band extends also to southern hemispheric equatorial region 0 to 10 south or so, but that we will see later. So what they have done is plotted here and what you see okay.

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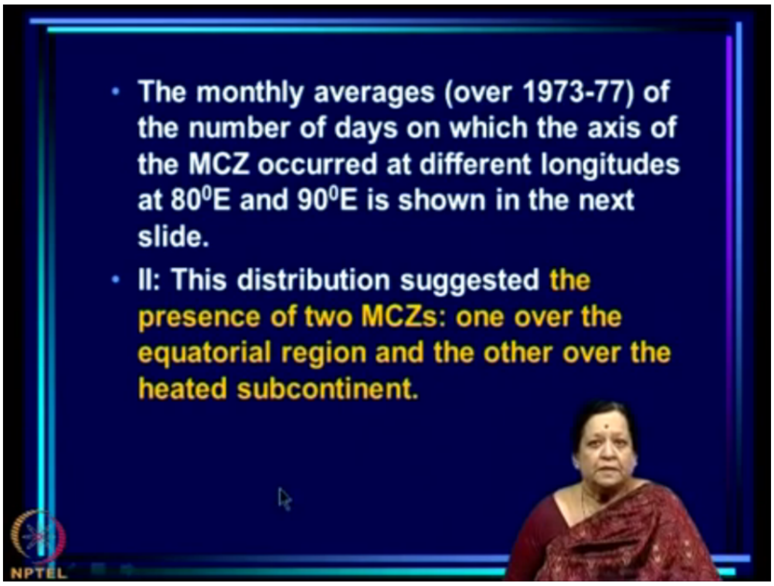

This distribution suggests that the presence of 2 MCZs, 1 over the equatorial region and the other over the heated subcontinent.

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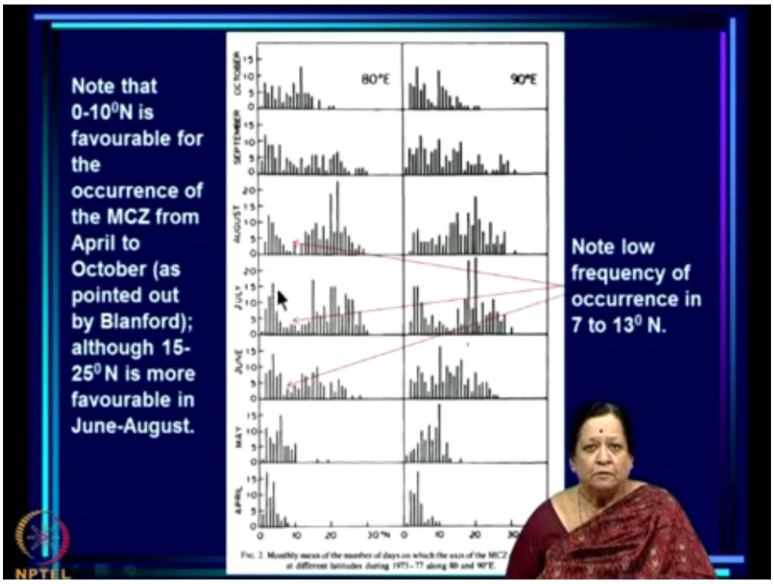

Let us see if that is suggested to you. You see the distribution first of July and August here okay. Now you see very clearly that there are 2 modes, 1 is over the equatorial region and the other peak is here over land from 15 degrees and it is a fairly spread out mode here, but there is a region here between 7 and 13 or so where the chance of occurrence is very, very low. So you have 2 modes here.

This is over the equatorial Indian Ocean and this is over the heated subcontinent in the north and you see a similar thing in August also. In September also you see it, but here at 80 degrees this looks more like a secondary and this looks more like a primary mode and that is also to here but July, August the bimodal nature comes out very, very clearly that you have 1 mode over the equator and another mode over the northern part here.

Now how has this come about? In April actually most of the clouding is between 0 and 10 okay. Most of the time MCZ is over the equatorial region and this is more or less a unimodal distribution okay with the maximum somewhere in between. Now this pattern will not be exactly same when we include data from southern hemisphere, but it will be very similar, May also it is unimodal.

You have a lot of high number of cloudy days here and then it decreases as you were northward and in May already at 90 degrees you notice that the mode has shifted a bit from the equator region, but interestingly it is still unimodal, but you see it has begun to be bimodal here in June and that bimodality persist here.

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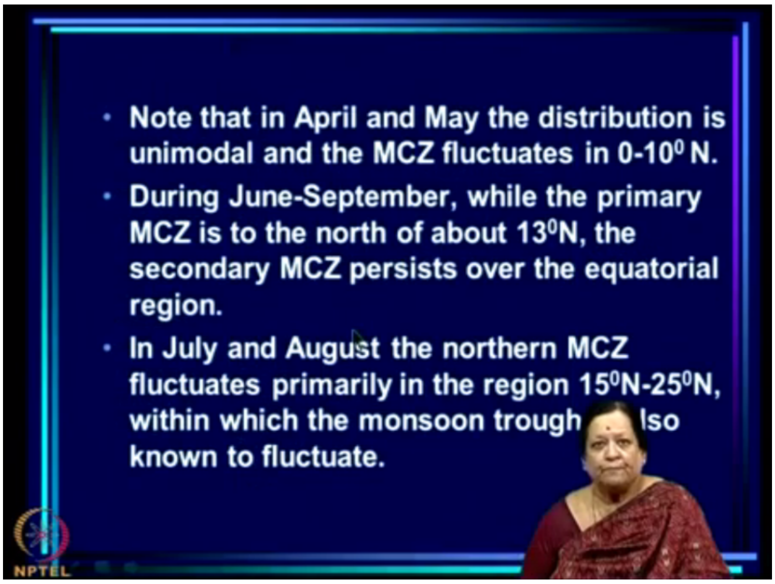

So what is interesting is that it is a bimodal distribution and as I mentioned here in April and May, the distribution is unimodal and the MCZ fluctuates between 0 and 10 north. During June to September while the primary MCZ is to the north of about 13, the secondary MCZ persist over the equatorial region. In July and August, the northern MCZ fluctuates primarily in the region 15 to 25 north within which the monsoon trough is known to fluctuate now.

Monsoon trough fluctuations have been documented for a very long time so it is well known that it fluctuates between 15 and 25 and you can see that this is about 15 here and this is 25 and that is where most of the fluctuations are occurring in July and August. So in July and August the northern MCZ fluctuates primarily where the monsoon trough is also known to fluctuate.

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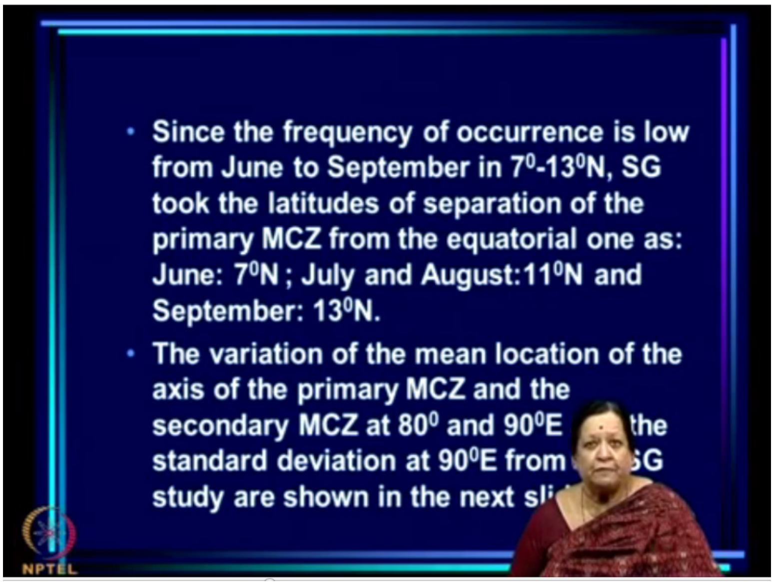

Now since the frequency of occurrence is low, from June to September in 7 to 13 degrees and we have seen this before here see it is very low here and low here, but SG did was to look at where the frequency of occurrence is minimum and took that as the latitude of separation between what is considered a primary MCZ and a secondary MCZ. The primary 1 being the one which has a very high frequency of number of cloudy days whereas the secondary one has relatively lower, but there are clearly 2 distinct modes.

So this is how they took the boundary of the 2 primary and secondary MCZ were determined by taking where it was the lowest probability of having. So since the frequency of occurrence is low from June to September in 7 to 13, SG took the latitudes of separation of the primary MCZ from the equatorial one has 7 degrees in June, 11 degrees in July and August and 13 degrees in September.

This was done simply by looking at the distribution okay. So what did we learn then? That in fact the distribution is bimodal, there is a primary MCZ, which occurs north of about 15 or so and secondary MCZ which is the equatorial MCZ. Now since we have separated the thing into 2 bands, the primary and the secondary we can look at the variation of mean monthly location of each of those and that is what we see in the next slide.

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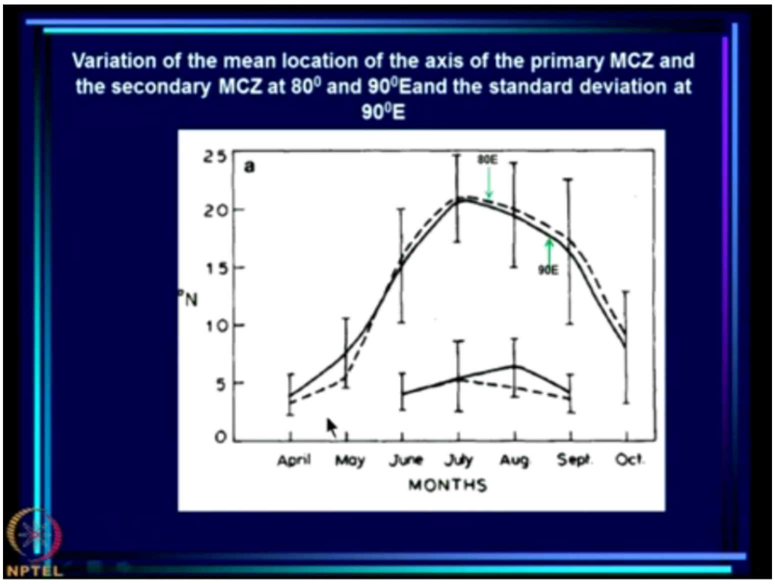

See this is the variation of the primary MCZ that we looked at and this is the variation of the secondary MCZ. You have to remember in April and May, there is only 1 MCZ. So this itself is the equatorial MCZ, which if you like continues as the equatorial MCZ here in some sense, but what you can see very clearly is that this in fact we notice that in May itself at 90 degrees, the MCZ had begun to move northward.

So you see it in May and that continues. So what you see here is if you focus on the primary band primary MCZ then it moves northward up to July is more or less in the same location till August and after August, it starts retreating southward. So this if you like is the onset phase of the monsoon where it is going northward up to July and September onwards is the retreat phase of the monsoon.

So what you see here is the very clear seasonal migration of the band. Now what Sikka and Gadgil did was they showed both the things 1 was at 90, which is the solid line and the dash line is 80 and you can see that the movements are very, very similar except as I mentioned that in May the 1 over Bay of Bengal seems to move northward before the 1 over the Indian region.

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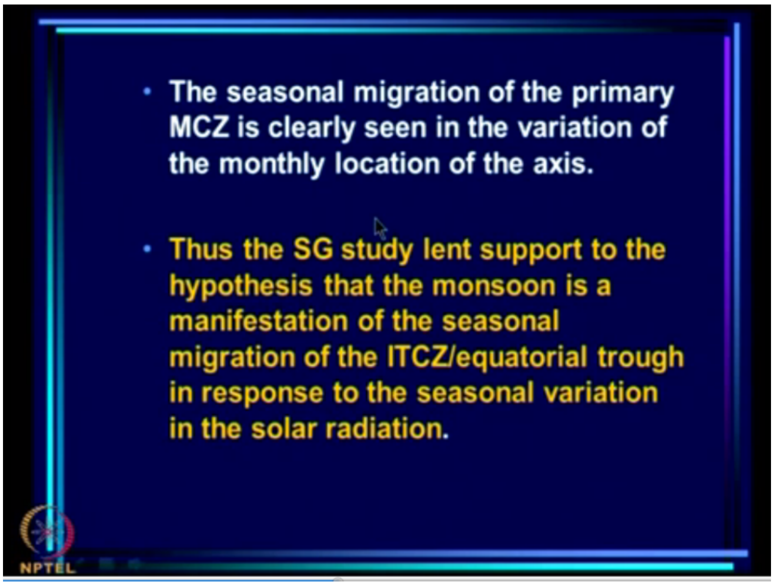

So this is the seasonal migration that we have seen. So seasonal migration of the primary MCZ is clearly seen in the variation of the monthly location of the axis. This means that Sikka Gadgil study has lent support to the hypothesis that the monsoon is the manifestation of the seasonal migration of the ITCZ or equatorial trough in response to the seasonal variation in the solar radiation.

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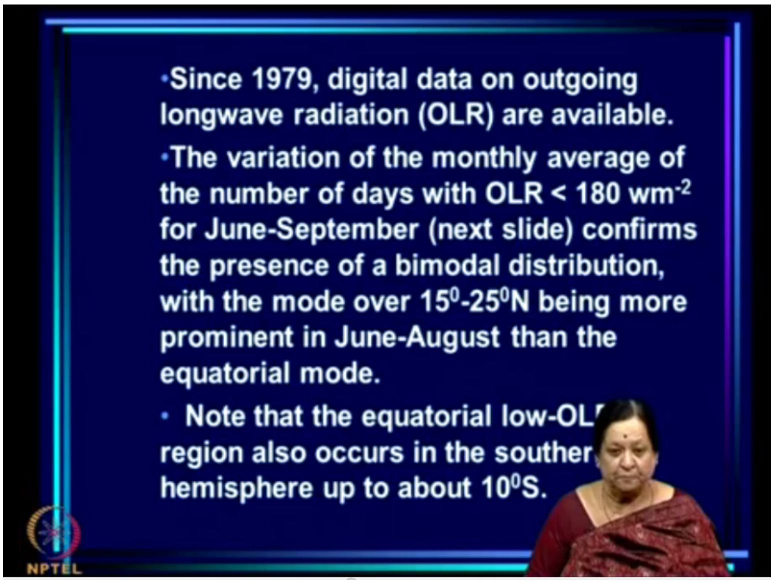

So this is what they have shown. Now all this was done with analysis of satellite imagery seen where the band is by eye, noting down where it is and doing the analysis. Now since 79 at that time, we did not have disposal any digital data. From 79 now, digital data on ongoing longwave radiation have become available and as you know low outgoing longwave radiation is a way to trace where the brightest clouds were in the visible imagery that we looked at where the deepest convection is occurring.

So just like we ask the question where does the MCZ occur we can ask the question the number of days with OLR at particular latitude. How many are they? So we take a fairly stringent criteria OLR less than 180 watts per meter square for June to September.

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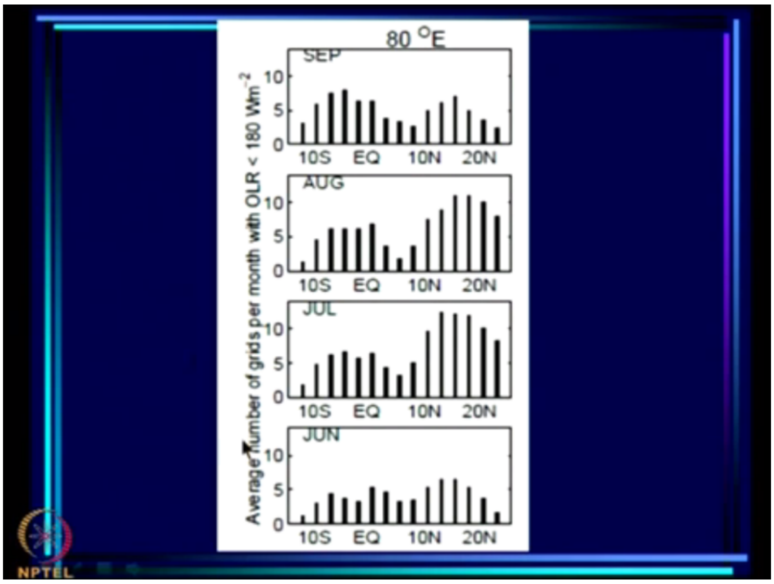

And what we see is here. Now this is June and this is again you can see here this is latitude and this is average number of days. You see the bimodality spectacular, actually the bimodality is very good in July, August and September as you see, but in July and August the primary mode is definitely over the heated subcontinent. This is at 80 degrees and that is why it is more so.

By September, they became more or less even (()) (26:48) like they were in June, but July, August the primary mode definitely dominates so the basic result that Sikka Gadgil obtained by looking at satellite imagery and plotting the frequency distribution of the occurrence of MCZ at different latitudes is very similar to the result.

We now get with modern data with OLR < 180 watts per meter square when we ask what is the number of days at this latitude such a band occurs with OLR < 180 watts per meter square.

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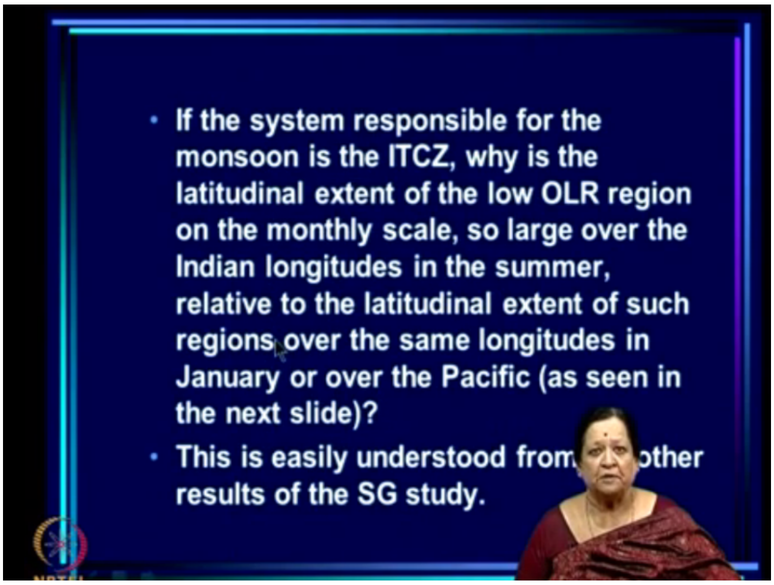

So this means that although the Sikka Gadgil result was with images of clouds rather than digitized low OLR data, it has been proved to be valid even when we looked at digital data as far as the bimodal distribution is concerned as far as the primary and the secondary MCZs that they found were concerned okay. So what we have done so far is the following. We have asked the question what are the important dynamical characteristics of the ITCZ?

Listed them and shown that in fact the maximum cloudiness zone that we see by satellites, which looks very much like an ITCZ actually satisfies also the dynamical constraints, dynamical characteristics associated with the ITCZ. So we saw that on the daily scale at least, the ITCZ does resemble the dynamical characteristics of the MCZ are the same as those of the ITCZ and so we can attribute monsoon rainfall to an ITCZ type of dynamical system.

This we have seen. Now this is all okay, but then what happens to Murakami's objection? That you know the low OLR region is so broad. Why does that occur when we look at the monthly scale? So relative to the same you know low OLR regions over same longitudes over January or over Pacific and so on this is the one.

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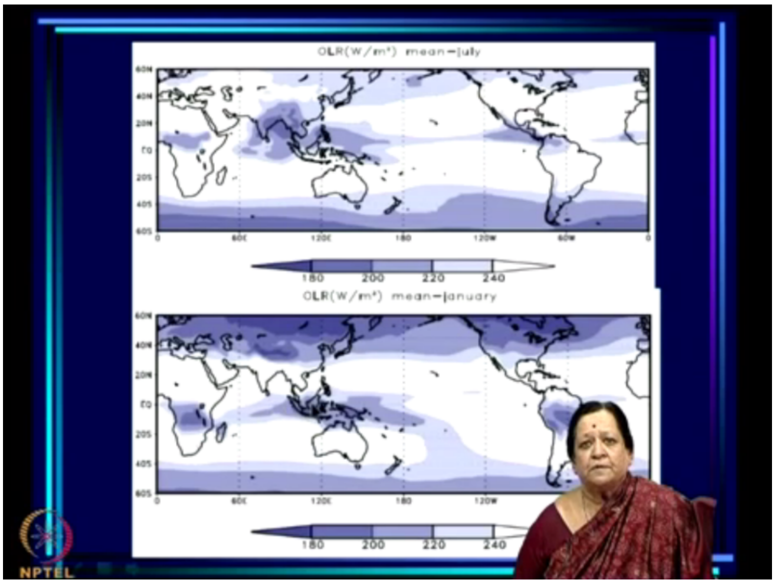

See just to remind you, this is the low OLR now from more modern data than Murakami's and this is the winter situation. You can see that over the Indian longitudes, it is a very narrow region. It is about 10 degrees in latitude, but when it comes to the monsoon it becomes so spread out here, huge as compared to say the Pacific one or the Atlantic one. So this is what Murakami's objection was.

And question is if it is the ITCZ why does it look so different when we look at monthly scales? Now to understand this we have to look at few more results of the Sikka Gadgil study.

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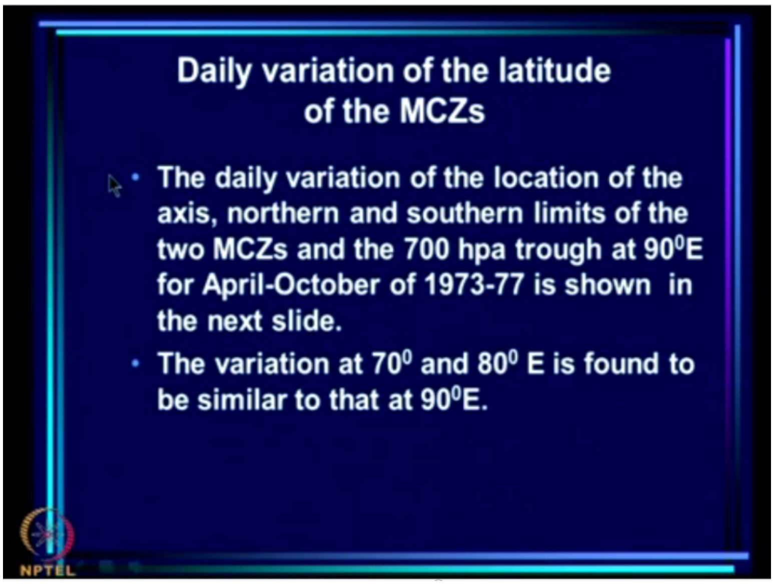

And that is their detailed analysis of the daily variation of the location of these 3 parameters, remember axis the northern limit and southern limit of the 2 MCZs and the 700 hpa trough at 90 degrees, which you will see here.

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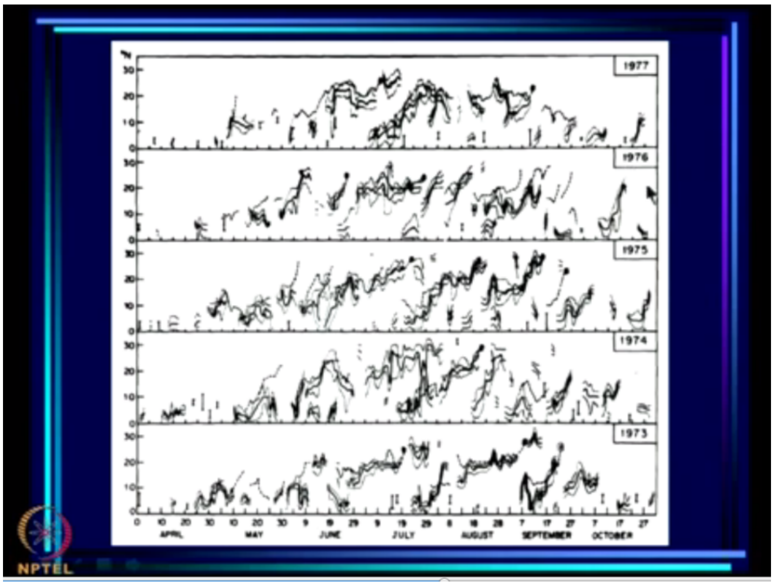

This is from their paper. This is 1977, 1976, 75, 74 and 73, so 5 years are involved. It is all at 90 degrees east. This is the latitude going north for each of the years and these are the days April, May, June, July up to October okay and what you see here is actually those 3 things and I will show simpler pictures of the same phenomena later, but it is always good to see first you know what the real picture is like.

And this one here is the 700 millibar trough and these are the 2 limits of the MCZ okay. So what is the most prominent feature? The most prominent feature of this is these northward propagations. Northward movements of the band, you can see them here for example this is in May and part of June you see. This is the beginning of June and this is when the MCZ has got established over the monsoon zone.

So this is the northward progression in the onset phase, but in addition to that you will also see other northward progression. This is always typically occurring towards the last week of July and you see that also year after year. So there are a large number of northward progressions. The first can occur even before the onset, see here you can have a phase here in May for example before the onset phase of the monsoon.

So there is a series of northward progression. The time scale between these 2 varies from anywhere between 2 weeks to 4 weeks or 6 weeks, but the common element of this very complicated behavior is that bands tend to form in the equatorial region and move northward up to the monsoon zone and then hang around there. This is the common feature.

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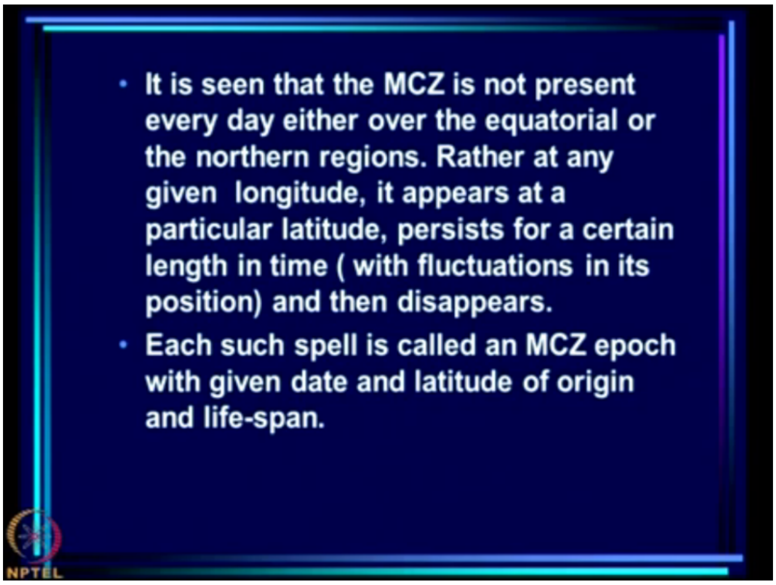

So MCZ is not present everyday either over the equatorial or the northern region rather at any given longitude it appears at a particular latitude persists for a certain length of time with fluctuations in its position and then disappears. Each such spell is called an MCZ epoch with given data and latitude of origin.

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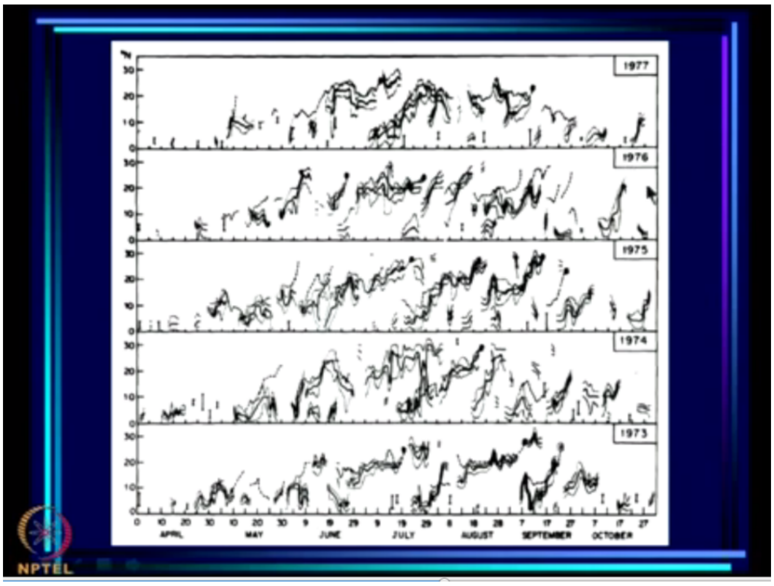

So let us go back to this. What we are saying is if you look at any latitude or time, you do not see suppose you look at this latitude here 15 degrees or whatever, then you do not see MCZ there present everyday even near the monsoon zone around 20 north, you will see MCZ present on quite a few days, but not every day by any means. So it appears and disappears that is the nature of the beast okay.

These cloud-bands appear and disappear. They appear at some latitude, then they occur for a certain length of time and they may not move northward like in this case, it appeared at this latitude and then died after 3 days. Here it appeared and died and then it appeared here and moved north. So this is considered MCZ epoch with a latitude of origin given here, time of origin is the date here.

And in this case we would say latitude of origin is that wherever it was and time of origin we note and this is the case in which it moved northward. You see that so this is the northward moving epoch and then its life-span is actually just the time between its demise and birth. So you can see that the best way to represent variation of this kind is by saying that at every longitude like 90 degrees east, there are a series of MCZ epochs okay, which are born at a certain latitude on a certain day, which die at a certain latitude on a certain day.

So that determines both the birth latitude as well as the lifespan and within their life-span they may also move northward like here, very big northward movement here. So you can think of the variation as comprising several MCZ epochs, which are characterized by latitude of birth, date of birth, date of demise and also whether they moved northward or not.

So because it is not something that is present day after day, we should represent it in this way and each such spell we call an MCZ epoch with the given date and latitude of origin and life-span.

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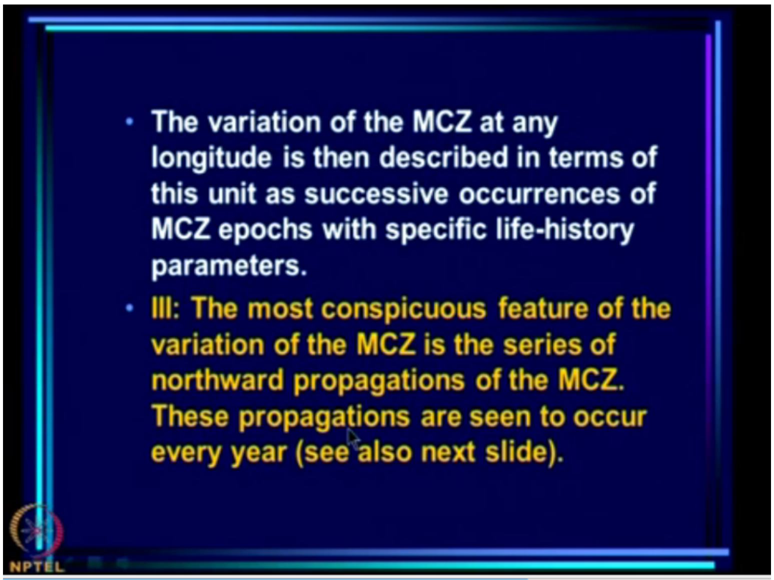

Now the variation of the MCZ at any longitude is then described in terms of this unit as successive occurrences of MCZ epochs, which specific life-history parameters okay. So the most conspicuous feature of the variation as I pointed out is the series of northward propagations of the MCZ.

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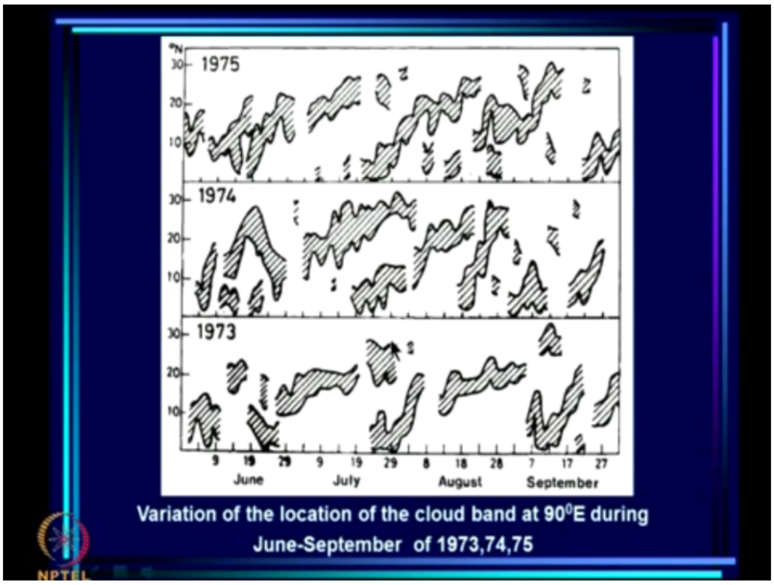

And these are seen to occur every year. Now this is a simpler picture of the MCZ than the original Sikka Gadgil picture, what I have shown here is merely the northern limit and the southern limit of the MCZ and between a hatch region showing where the cloudy zone is. Now this is somewhat easier to look at and what you see here is again very nice northward propagations.

Here 1, here 1, and yet another 1 here okay and note this is again at 90 degrees. Note that they occur year after year 75, 74, 73. So it is a basic feature of the variation of the MCZ over the Indian longitudes that these propagations occur year after year, it is a basic feature of the variation and furthermore they occur irrespective of whether it is a draught or a good monsoon season.

74 was a severe draught, 75 was a very good monsoon season even then in that good monsoon season it descent as if MCZ hung around over the monsoon zone every day, no in fact it disappeared in between, you see it disappeared here and it appeared again, it disappeared here and then came on northward movement. So even in good monsoon years, you do have disappearance as of the MCZ again revival.

And you can actually see and I will preempt what will come in later lectures that the revival can occur either by generation within the same latitudinal band as here or by northward movement of the oceanic band as here. So you see those 2 here, here also you can see. This is the revival by what we call in situ generation and this is the revival by northward propagation.

But the important thing to see is that these northward propagations are basic to the variation.

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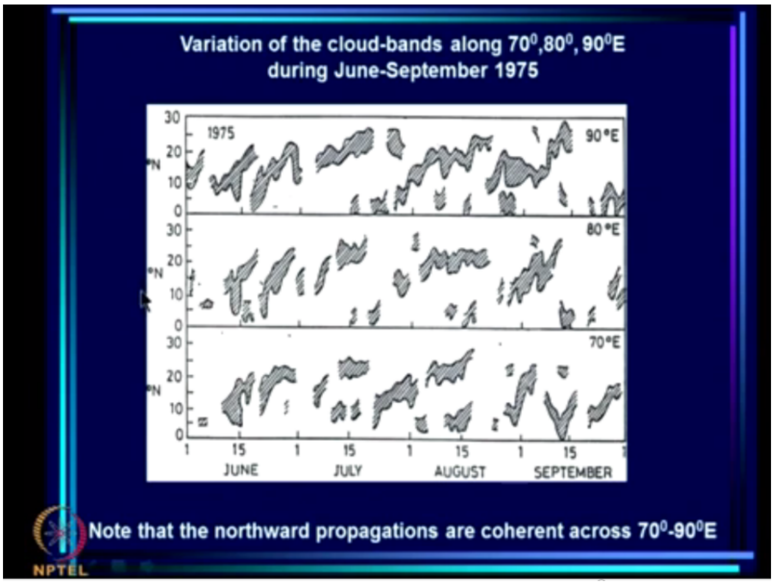

And now here you see 75, but at 3 longitudes 90, 80 and 70, which we call the Indian longitude and what you see is that these propagations that we saw are rather coherent across the longitudes. See here this is the propagation here and this is the same propagation here. So the propagations tend to be rather coherent. What does that mean?

That means that the entire band is extending from 70 to 90, is moving northward all the way from the equatorial region to north of 20 north or so okay.

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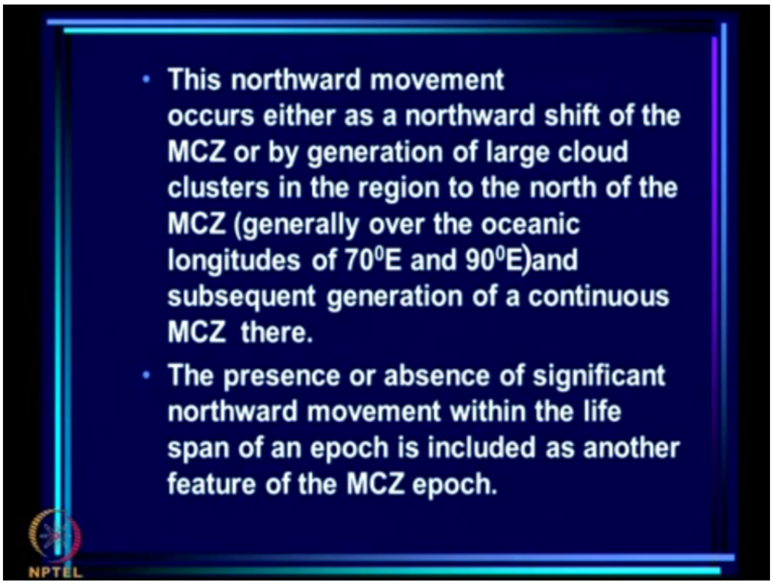

So this northward movement occurs either as a northward shift of the MCZ or by generation of large cloud clusters in the region to the north of the MCZ. So what happens is either it moves as a band, but more often than north. In fact, what happens is to the north of the MCZ some cloud clusters get generated 1 over the Arabian Sea, 1 over the Bay of Bengal and then it forms a continuous band there.

And the older MCZ dies that is how it moves northward. The presence or absence of significant northward movement within the lifespan of an epoch is included as another feature of the MCZ epoch. So in addition to latitude of origin and lies a latitude of birth and lifespan, we have 1 more feature, which we have used in the analysis.

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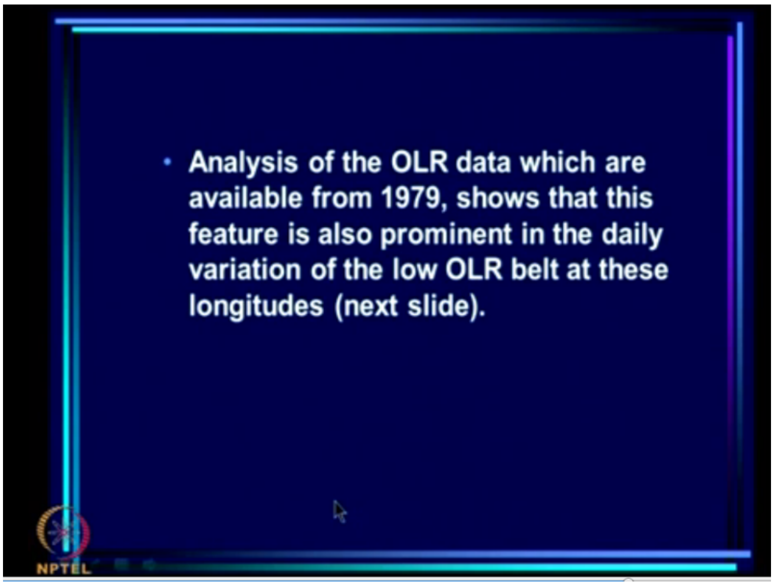

Now again we have to see all this analysis was done by looking at the MCZ from satellite imagery. We have to see if it is what we get from digital data, which are available from 79 show this important feature discovered in the study namely northward propagation.

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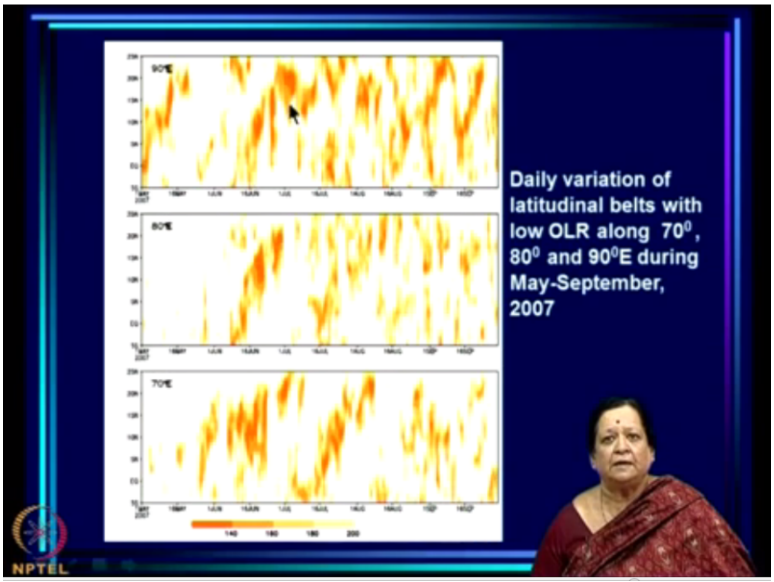

So what we will see is again now we plot instead of the maximum cloudiness zone it is the low OLR belt okay. It is the belt with OLR less than 180 and what you see this is again 70, 80 and 90 and this is from May to September 2007 and what you see here is again rather coherent northward propagations occurring across the region 70, 80 and 90.

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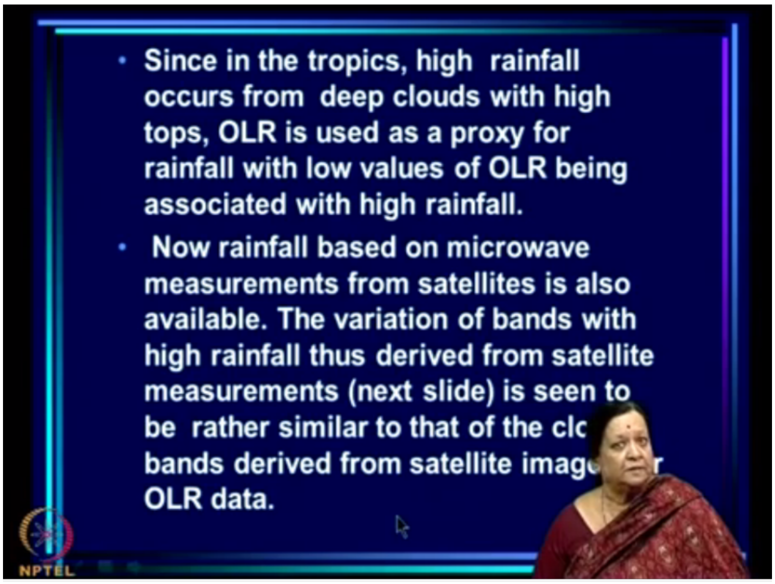

So what we saw with satellite imagery analysis of the satellite imagery we have also seen with the digitized OLR data. Now since in the tropics high rainfall occurs from deep clouds with high tops. OLR is used as proxy for rainfall with low values of OLR being associated with high rainfall, but now rainfall based on microwave measurements from satellite is also available.

So let us look at how the rain bands look if we use rainfall data from satellites.

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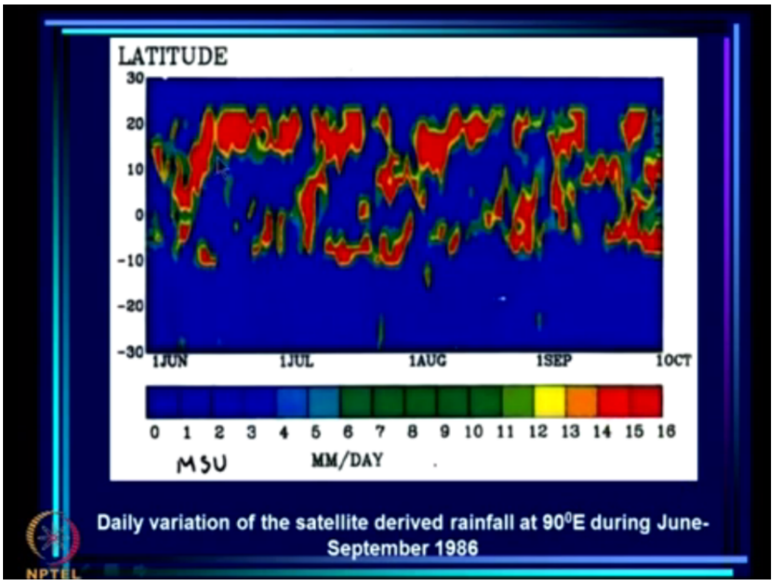

And what we see is even more beautiful picture. This is from Srinivasan's work and what you see this is at 90 degrees east and this is June to September 86 and what you see is a really spectacular northward propagation. You see this is the secondary ITCZ and again northward propagation. Notice, it is good that the Sikka Gadgil study detected the secondary ITCZ, but you can see that quite often it occurs in the southern hemispheric equatorial region rather than in the north.

But there are enough occurrences in the north so they could also see it and you see very similar phenomena to what we saw earlier northward propagation, then it hangs around here for a long time, the MCZ hangs around in the monsoon zone, disappears another northward propagation, revives, another northward propagation and so on and so forth.

So this is really the typical variation of the MCZ or the ITCZ whatever you wish to call it over the Indian region.

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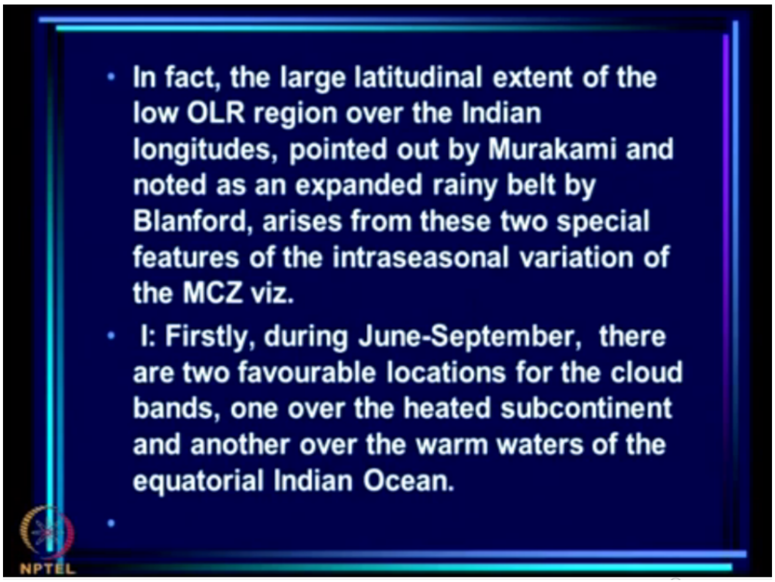

Now how does the large latitudinal extent occur? It is very easy to explain it once we see this. First of all, there are 2 locations right. There is the primary MCZ and the secondary MCZ and so the distribution will be bimodal okay, but if it was a story that the primary MCZ you know fluctuated within the monsoon zone and the equatorial MCZ fluctuated within the equatorial region you would see still 2 bands of low OLR with nothing in between.

But what you see is almost a continuous belt of low OLR, which is what Murakami is talking about. Now that occurs because it descent as if the equatorial ITCZ or the MCZ stays put in the equatorial region, no in fact very often it moves northward on to the monsoon zone. So it is the northward propagations that give rise to the occurrence of low OLR region in between the locations of the primary and the secondary zone.

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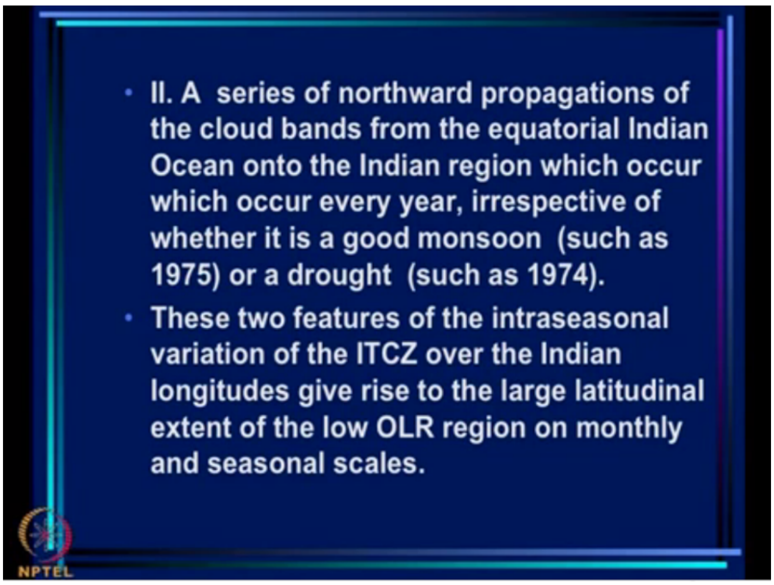

So this is how the 2 features then because it is the series of northward propagations of the cloud-bands from the equatorial ocean onto the Indian region, which occur year after year irrespective of whether it is a good monsoon or a draught. Because of these 2 features then what we will get is a large latitudinal extent of low OLR region on monthly and seasonal scales.

You very seldom see it on the daily scale though, on the daily scale either you see distinct cloud-bands 1 or 2 distinct cloud-bands or none at all, but you never see a band stretching all the way from the equatorial region to the monsoon zone. So that low OLR region that is so large in latitudinal extent arises because the band moves around so much.

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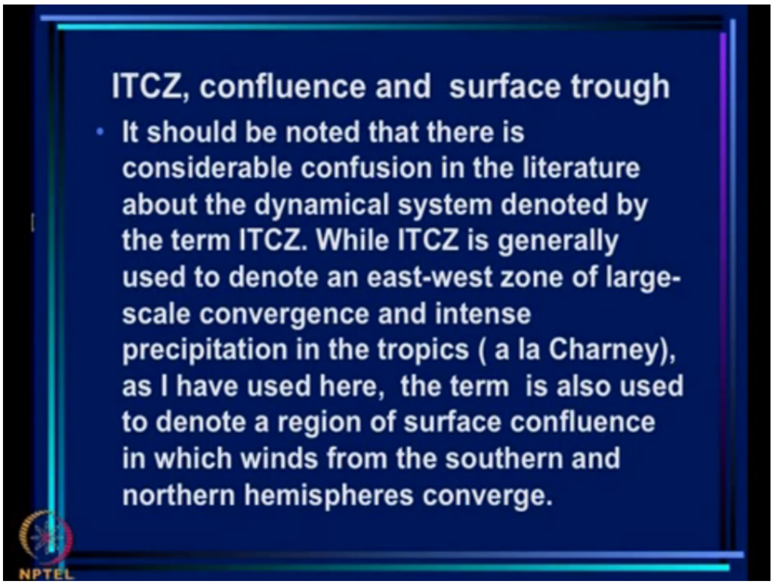

So I think with this then we have given enough evidence to show that the monsoon is a manifestation of the seasonal migration of the ITCZ onto the Indian monsoon zone in response to the seasonal variation of the incoming solar radiation. So this is now where our understanding stands. There is something to now clarify because there is some confusion in literature about the term ITCZ itself.

Remember that ITCZ stands for intertropical convergence zone okay or where there is confluence of winds from the northern hemisphere and the southern hemisphere that is where the word intertropical comes from okay. So while I have been denoting by ITCZ the dynamical system that Charney talked about or that Riehl described as equatorial trough in the sense of being a last scale convergence zone with intense precipitation.

The same term is also used to denote a region of surface confluence in which winds to hemispheres converge okay. So if winds from the northern and southern hemisphere converge onto a zone that is also referred to as ITCZ even if it is not associated with intense rainfall last scale convergence and so on at higher levels.

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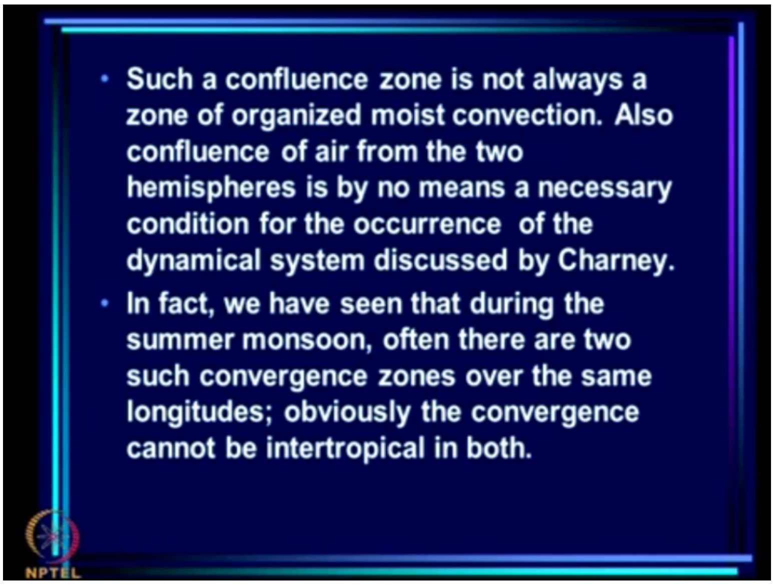

Now such a confluence zone is not always a zone of organized moist convection, also confluence of air from the 2 hemispheres is by no means a necessary condition for the occurrence of the dynamical system. It so happens that if the air happens to be from 2 hemispheres and is converging and all the other conditions are favorable you can become an ITCZ of the kind we are discussing.

But it does not have to be from 2 hemispheres if you have large-scale convergence generated by cyclonic vorticity above the boundary layer even in the northern hemisphere, northern hemispheric air itself converging can lead to a tropical convergent zone. So in fact it is very clear that the convergence in that kind of a dynamical system does not have to be intertropical and also we have to note that we have seen that over the Indian longitudes in the summer there are 2 such convergence zones over the same longitudes.

So if there are 2 convergence zone over the same longitudes obviously the convergence in both of them cannot be intertropical.

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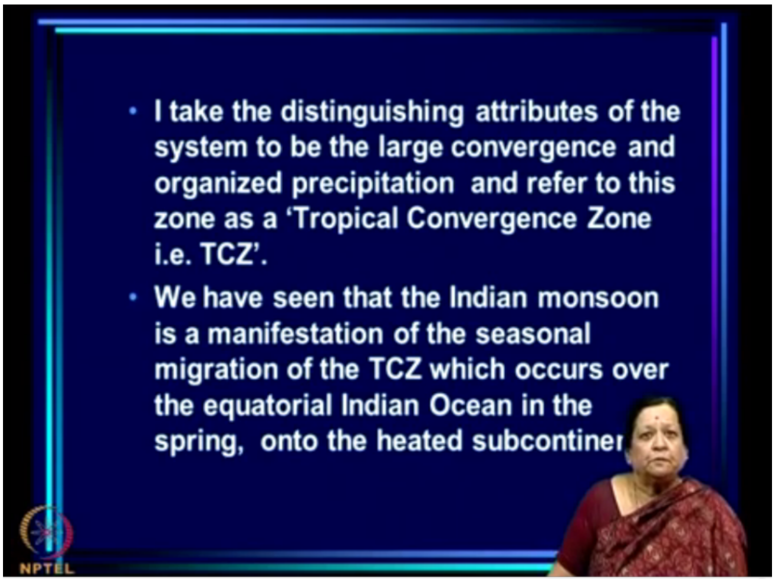

So it is a good idea not to harp too much on the intertropical instead of that I take the distinguishing attributes of the system to be the large convergence and organized precipitation and referred to this zone as a tropical convergence zone that is TCZ. Now we have seen that in the Indian monsoon is a manifestation of the seasonal migration of the TCZ, which occurs over the equatorial Indian Ocean in the spring on to the heated subcontinent.

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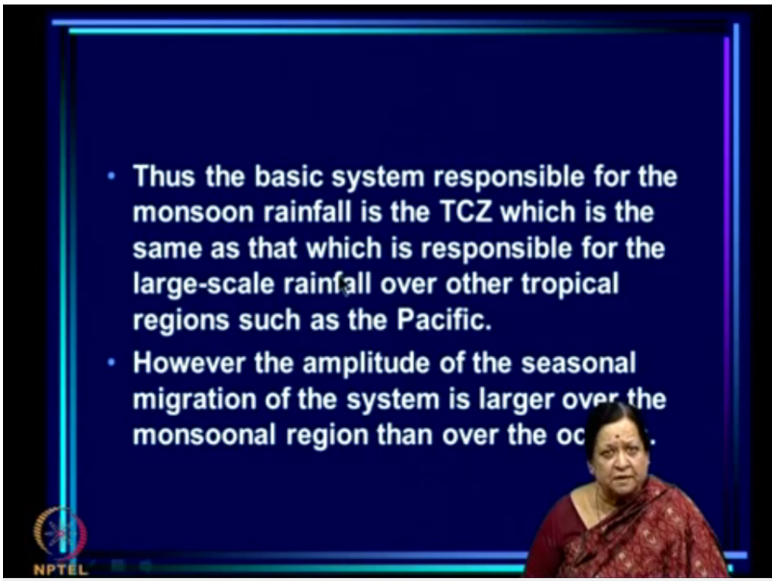

So I will refer to this as TCZ and thus a basic system responsible for the monsoon rainfall is the TCZ, which is the same as that which is responsible for the large-scale rainfall over other tropical regions such as the Pacific. However, the amplitude of the seasonal migration of the system is larger over the monsoonal region than over the oceanic region.

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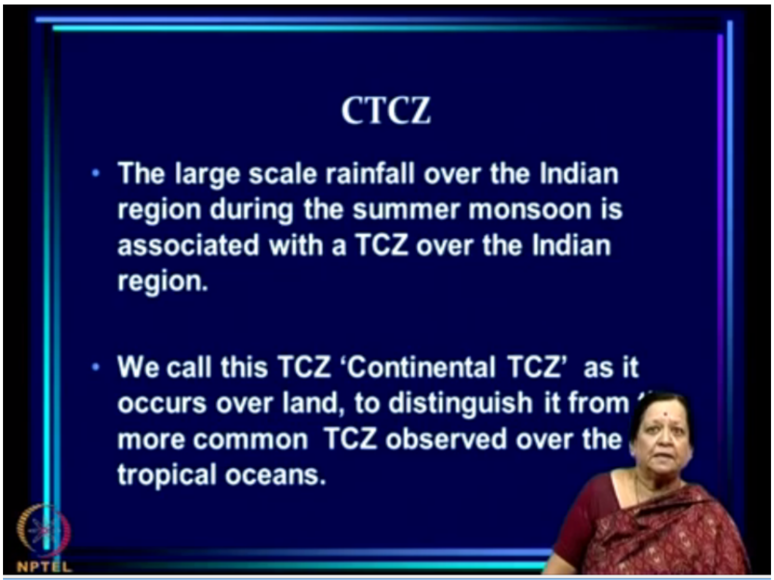

So we call this the large-scale rainfall associated with the Indian monsoon, which is Indian summer monsoon is associated with the TCZ over the Indian region. This TCZ remember occurs on the Indian subcontinent. So we call this TCZ a continental TCZ as it occurs over land to distinguish it from the more common TCZ observed over the Atlantic and Pacific Oceans as you have seen.

So this is what we call continental tropical convergence zone or CTCZ.

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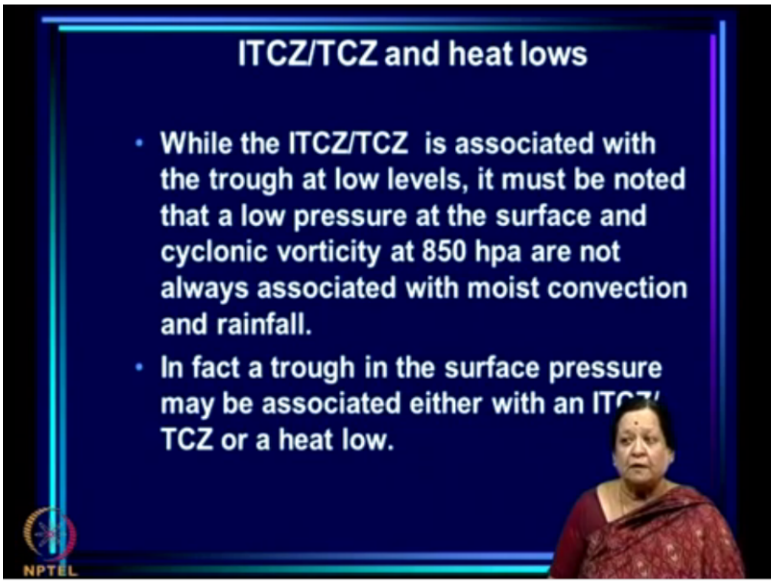

And in fact there is a major program of the Indian climate research program, which is focusing on understanding the processes that lead to the variability of CTCZ and hence the variability of monsoon rainfall. So CTCZ creature is the beast that is of greatest interest to us if we are interested in large-scale monsoon rainfall. It is a system with the dynamical characteristics of an ITCZ.

But which lies on land and that is what we will have to look at. Now I just want to end with showing one more confusion in terminology, which we should avoid that while the ITCZ or TCZ is associated with the trough at low levels it must be noted that a trough or a low pressure at the surface and cyclonic vorticity at 850 hpa are not always associated with moist convection and rainfall.

In fact, in a trough in the surface pressure could be associated either with an ITCZ or TCZ or a heat low and what is the difference between a heat low in tropical convergence zone?

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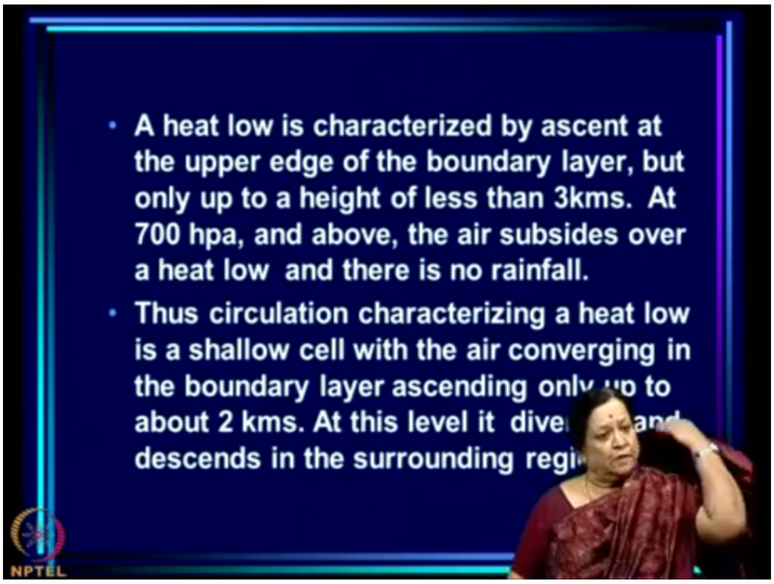

There is also convergence in the heat low near the surface and this convergence persist till the boundary layer till about 2 kilometers or so from the surface, but above that there is no convergence in fact it reaches about 2 kilometers or so and then the air diverges and sinks. So it is a very shallow cell with convergence restricted to about 2 kilometers, divergence about this level and subsidence throughout the lower 2 kilometers away from this loop.

So this is a shallow vertical cell. On the other hand, so this is what I have emphasized here that a heat low is characterized by ascent at the upper edge of the boundary layer and of course 850 millibar vorticity being cyclonic. So it is consistent to have ascent at the upper edge, but only up to a height about < 3 kilometer. Therefore, at 700 hpa and above air is subsiding over a heat low and that is why there is no trough.

There is no low at 700 hpa above the heat low. This is why the 700 was a very critical level to look at the trough for the MCZ study of Sikka and Gadgil. So above 700 hpa, the air is subsiding at 700 hpa as well above a heat low and there is no rainfall. So the circulation characterizing a heat low is a shallow cell with the air converging in the boundary layer ascending only up to 2 kilometers.

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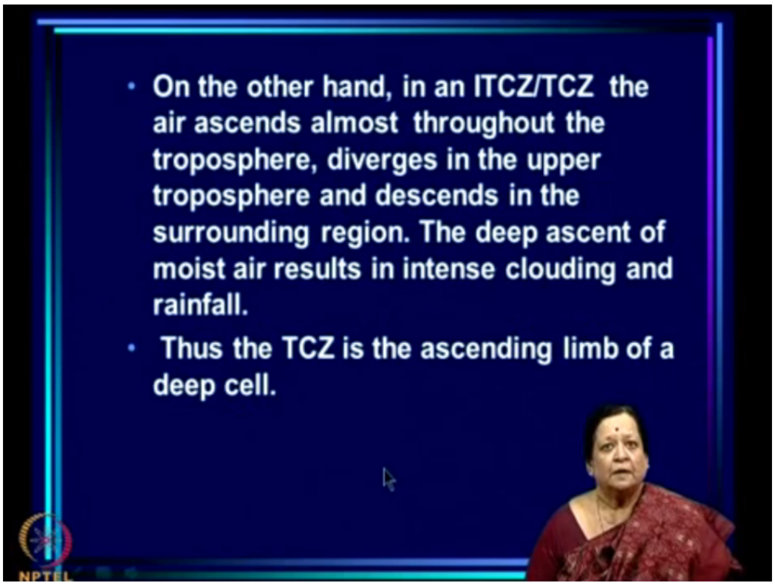

Now on the other hand, the TCZ is a very deep cell. You have seen TCZ or ITCZ the ascending limb of the (()) (49:33) cell and that is the very deep cell in which low level convergence leads to ascend almost throughout the entire troposphere and only at the upper tropospheric levels, the air diverges and then sinks in the region around. So there is very deep ascent of moist air and that results in intense clouding and rainfall.

So the TCZ is the ascending limb of the deep cell, but what occurs over a heat low is a very shallow cell, these are the differences.

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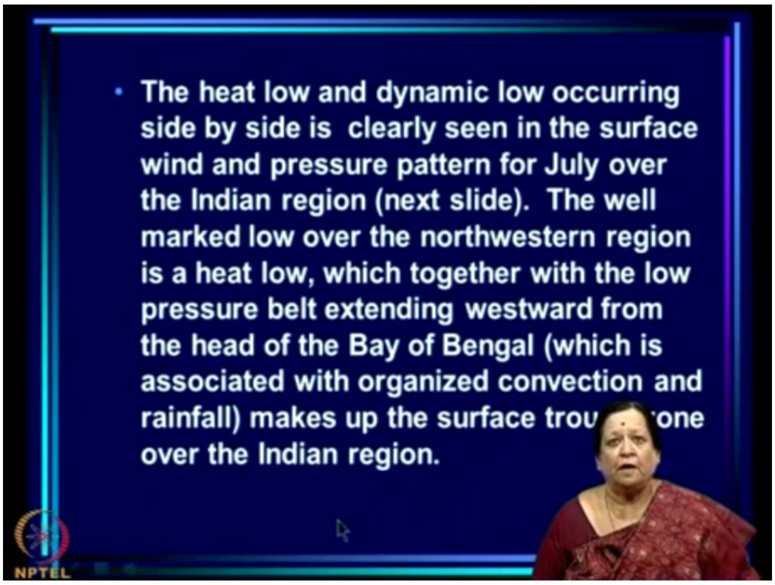

Now heat low and dynamical low occurring side by side actually happens quite often.

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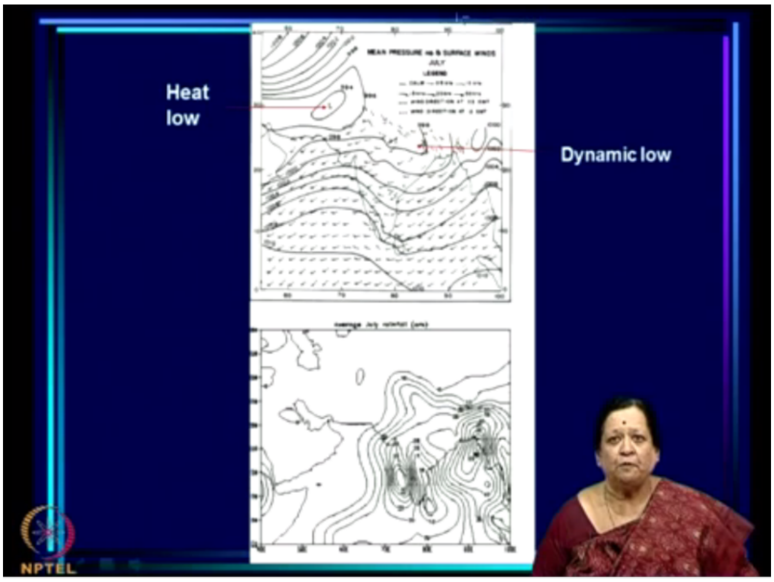

You look at our July picture. This is the mean pressure pattern for July and this is the low pressure region the trough of which the lowest is here, this is the low that you see here. Now in fact, this is the heat low and this is what we call a dynamic low in contradistinction to a heat low so over this region you have only a shallow cell okay. This is the heat low with the shallow cell.

And this is the one that has the characteristic of a TCZ and you see this is the rainfall and you can see that over the region of the heat low, which is here there is no rain at all okay and the rain occurs over this region primarily, which is the trough here okay.

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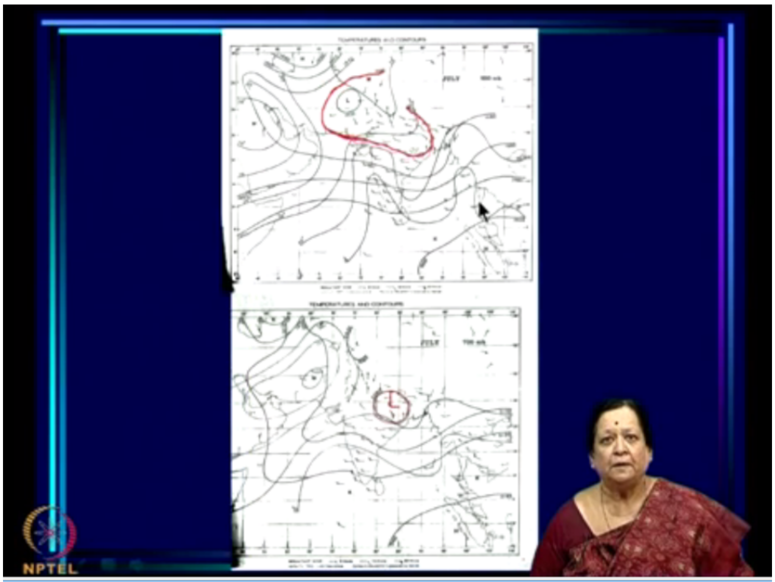

But now you can see the same thing here, this is the July 850 mb, this is from the IMD atlas and this is the entire low pressure region here and the lowest of that pressure is the heat low here, but if you go to 700 millibar, which is 3 kilometers then the only low you see is over the dynamic low. The heat low does not appear at 700 at all, descent is taking place here over the heat low.

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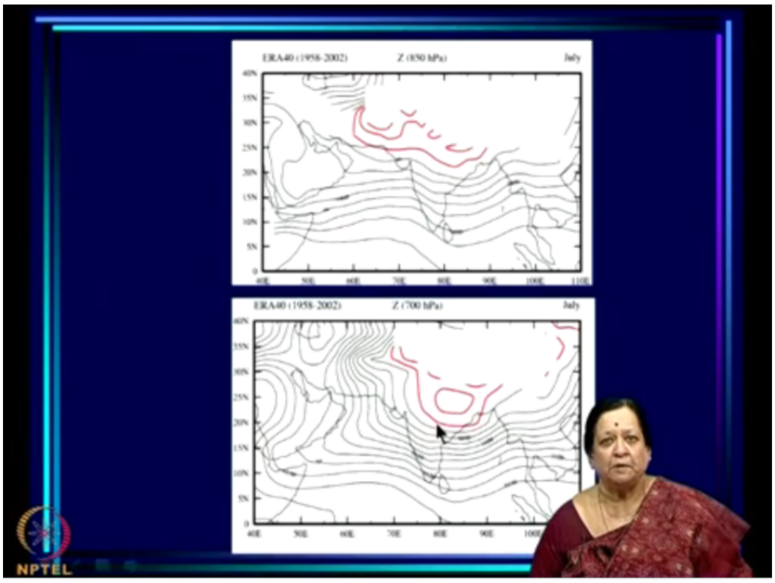

And the low is only the dynamic low and this is again from the reanalysis. This is the 850 where you see a clear low here and at 700 the low is entirely over where it rains.

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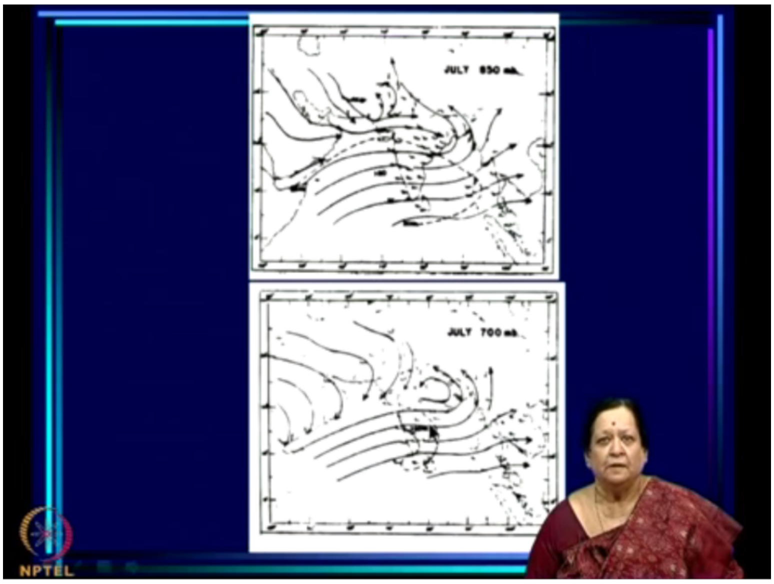

And these are streamlines. This is July at 850 and you can see that at 850 you have a very clear cyclonic vorticity of the westerlies here and the easterlies to the north, but at 700 you see the circulation is entirely different and there is no cyclonic vorticity above the heat low.

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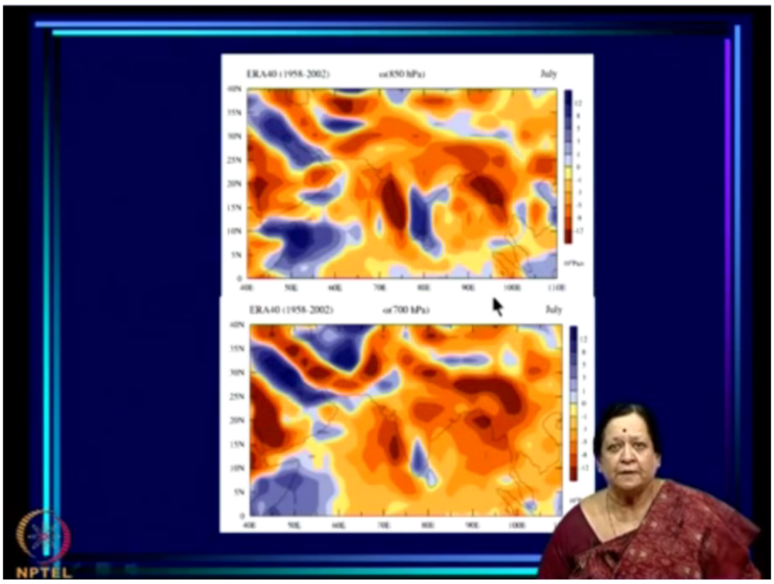

So this is the difference and now what you can see here is from reanalysis. This is showing vertical velocity again upward is oranges and so on and this is the vertical velocity at 850. So this is just at the upper edge of the boundary layer and you find over almost the entire region the velocity is upward, this is because almost the entire region the vorticity is cyclonic, but you see here this was that hole that southeast peninsula hole in which it is sinking.

Because there is negative vorticity, but if you go to 700 millibar then you see that over the heat low, there is descent and rest of the region there is ascent. So this is the dynamic low and this is the heat low corresponding to the Rajasthan desert.

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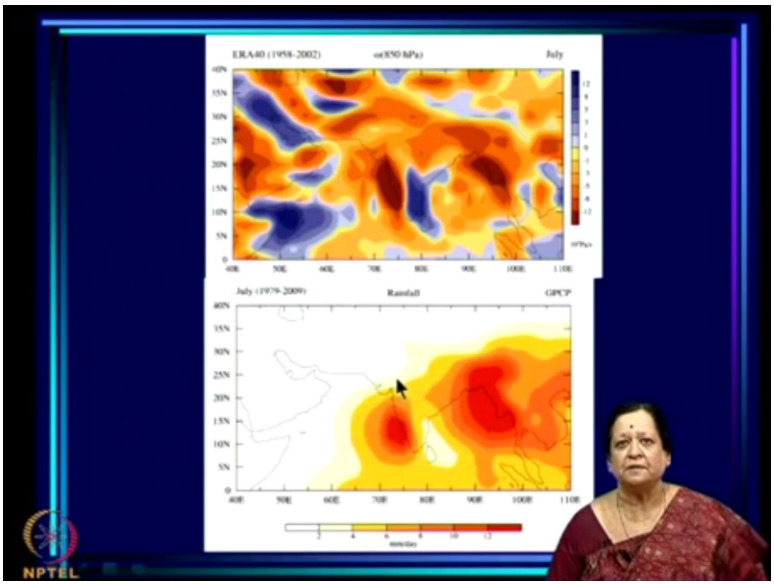

And that is very clearly seen here, this is vertical velocity at 850 millibar, which is upward everywhere, but you see the rainfall, there is no rainfall over heat low even though the vertical velocity is upward at the edge of the boundary layer okay.

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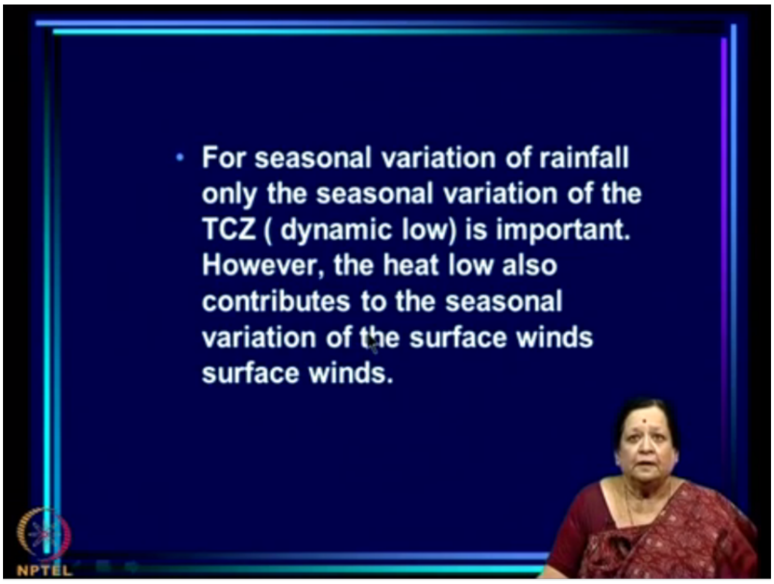

So I am going to stop here except to say that for seasonal variation of rainfall only the seasonal variation of the dynamic low a TCZ is important; however, the heat low also contributes to the seasonal variation of the surface winds okay.

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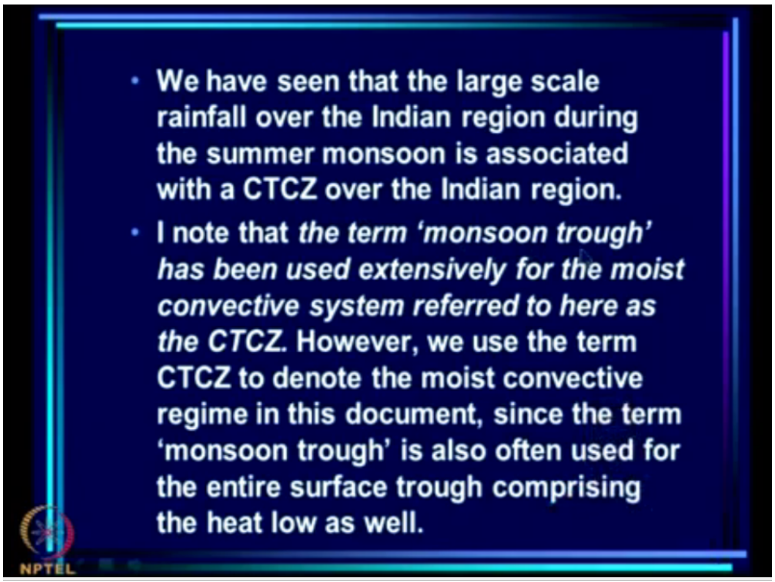

And now just another thing that we have seen that the last scale rainfall over the Indian region during the summer monsoon is associated with the CTCZ over the region, but somehow the term monsoon trough has been extensively used for the moist convective system referred to here as CTCZ; however, while we use the term CTCZ to denote moist convective regime since the term monsoon trough is also often used for the entire surface trough comprising the heat low as well.

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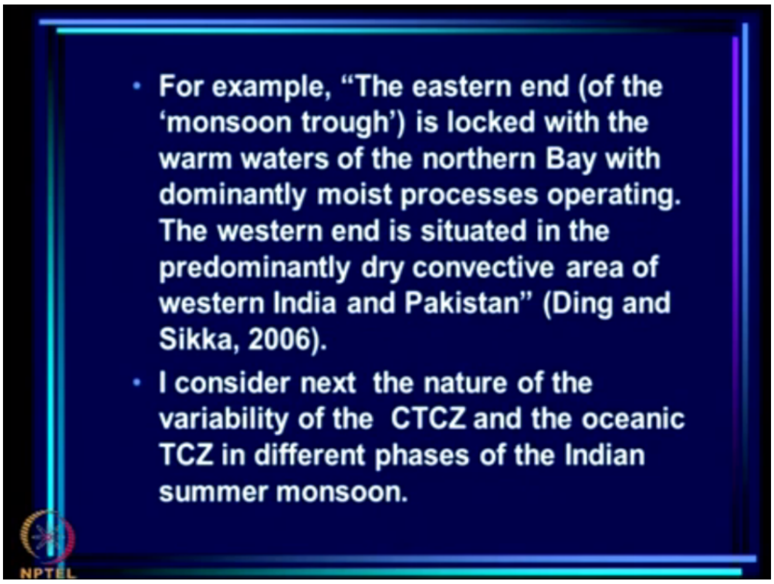

So there is a big confusion because monsoon trough very often this is from a very big review by Ding and Sikka and they said the eastern end of the monsoon trough is locked with the warm waters of the northern bay with dominantly moist processes operating, the western end is situated in the predominantly dry convective area of the western India and Pakistan. So this is the point.

The western end of the monsoon trough is the heat low, so calling the same system as monsoon trough does create a lot of problems. Now I am going to stop here and next we will consider the nature of variation of the CTCZ. Thank you.