The Monsoon and Its Variability
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Lecture - 22
Intraseasonal Variation and Intraseasonal Oscillations

So, today I am going to discuss intraseasonal variation and intraseasonal oscillations.

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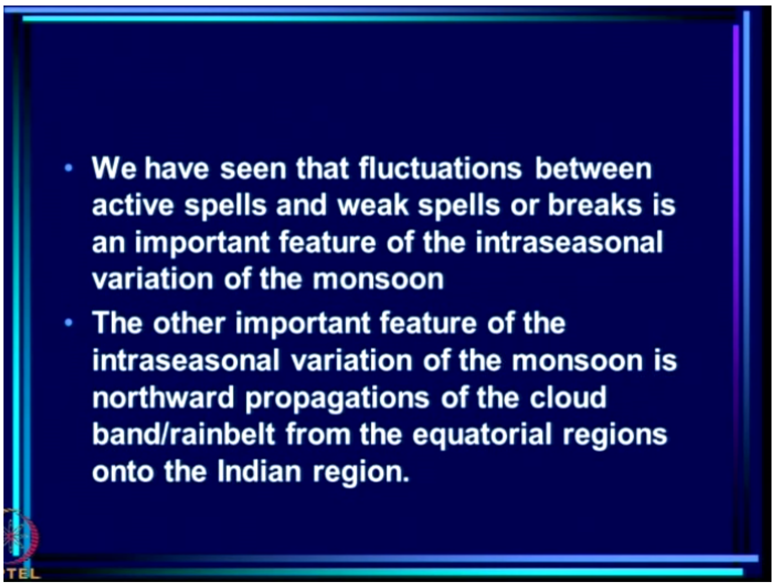

Now what is intraseasonal variation? Intraseasonal variation is variation on the super synoptic time skill. Synoptic time skills are up to 5 days or so, typical of synoptic skill systems. Intraseasonal variation involves variation over a larger scale then synoptic, but not as larger seasonal or monthly. Now we have seen that the fluctuations between the active spells and weak spells or breaks, is an important feature of the intraseasonal variation of the monsoon.

The other important feature of the intraseasonal variation of the monsoon is northward propagations of the cloud-band or rain-belt from the equatorial regions on to the Indian region.

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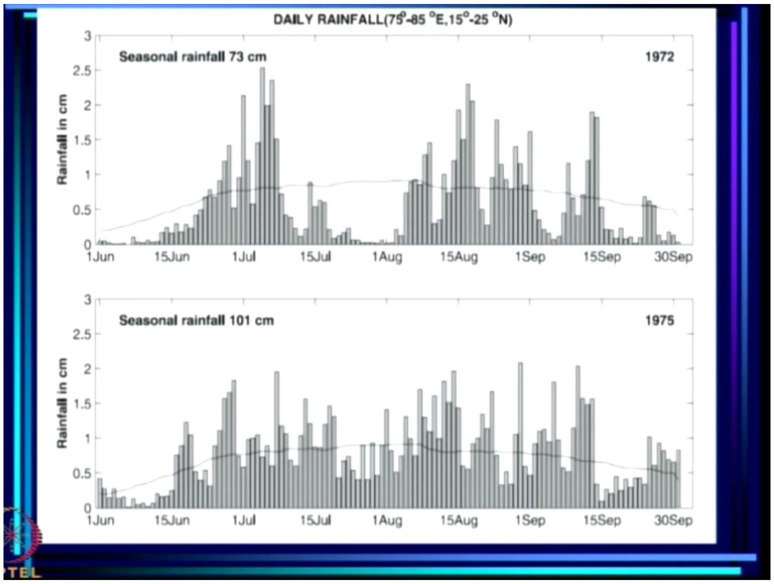

So this is the first feature. These are the active weak spells which we have of course discussed in great depth and this is the rainfall of our Central India you remember and this is the long break that occurred in 72, but notice that this is also in fact a drought year, but even in a good monsoon year, we do have fluctuations between active and weak spells. So active and weak spells are features which are found in every year, every monsoon season, but breaks of this kind do not occur in every monsoon season. We have already looked at that.

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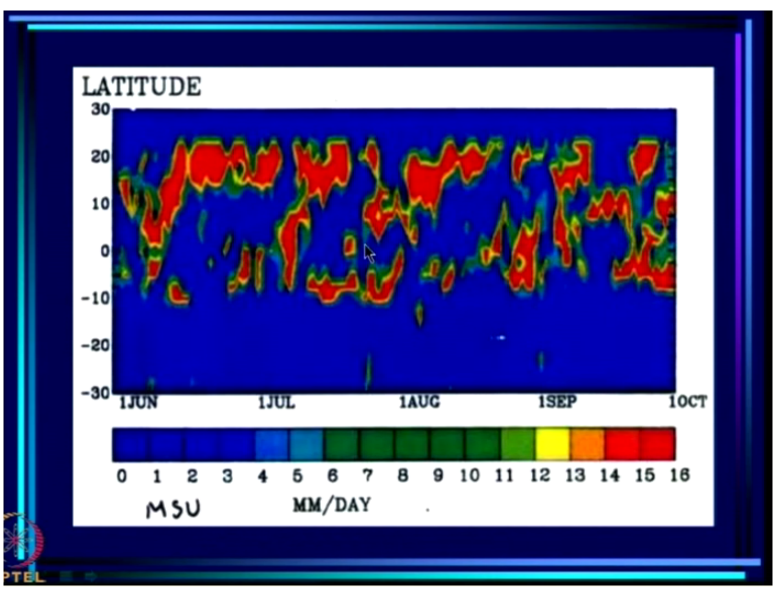

The other feature is northward propagations of the band starting from the equatorial region and moving northward. So this as you remember is from satellite MSU at 90 degrees for one specific year 1986. So, this is the other feature and you also see here active and weak spells here. This is a weak spell and this is an active spell and these are the northward propagations. So these are the 2 major features on the intraseasonal skills that we see.

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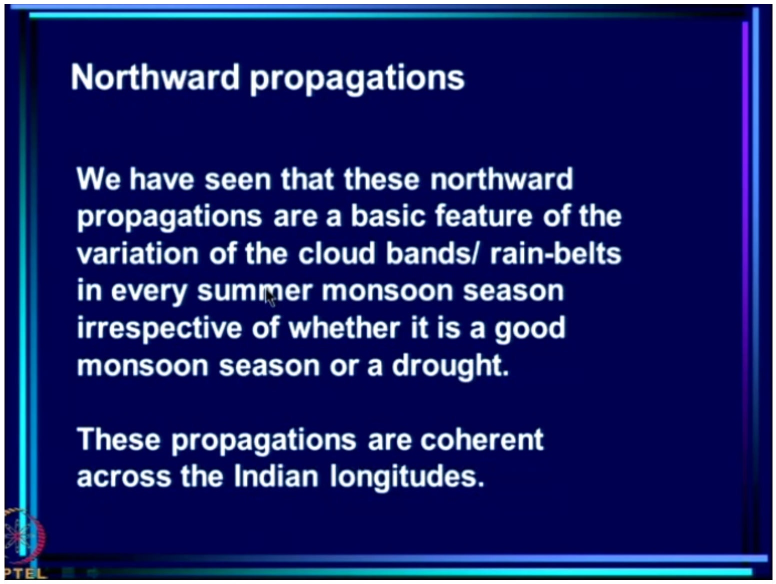

Now northward propagations we have seen are a basic feature of the variation of cloud-bands or rain-belts in every summer monsoon season irrespective of whether it is a good monsoon season or a poor monsoon season.

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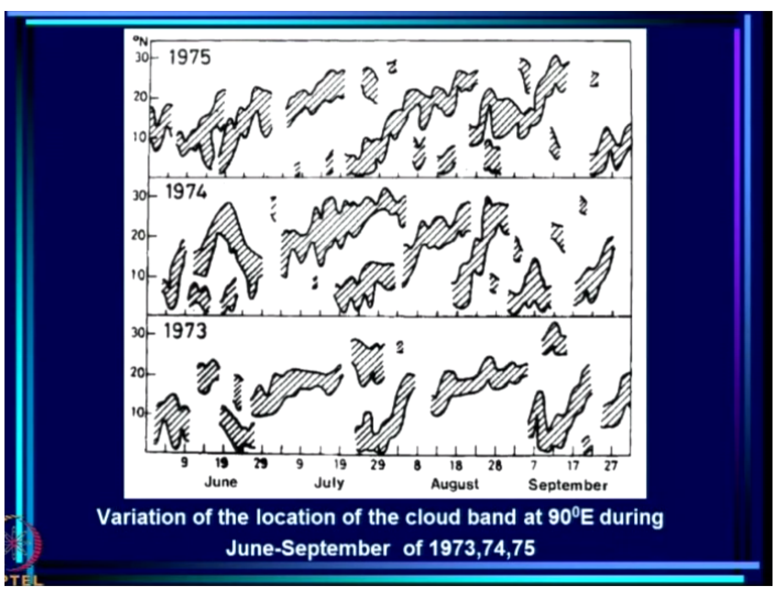

So you have 3 years 73, 74, 75. 74 was a drought. 75 was a good monsoon here and irrespective whether it is a drought or not these northward propagations always occur. This is of course at 90 degrees.

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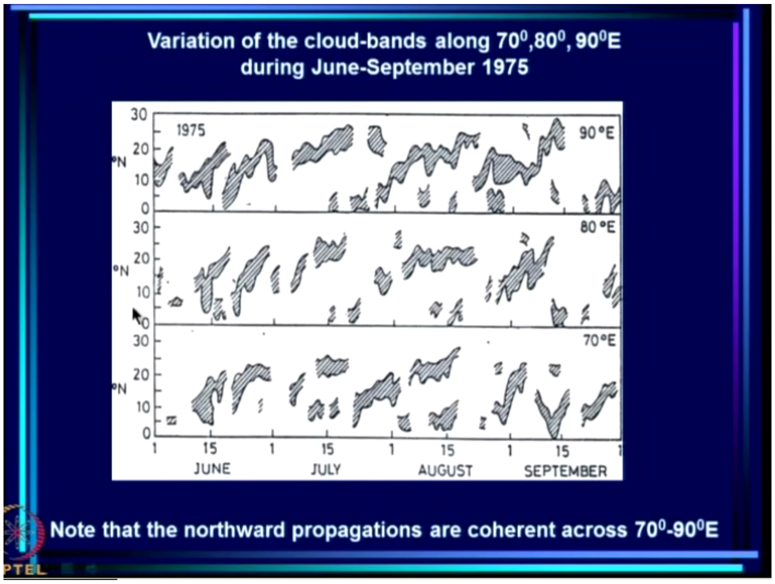

We also see if we look at just 75 and look across the Indian longitudes we see that these northward propagations are coherent across the longitudes.

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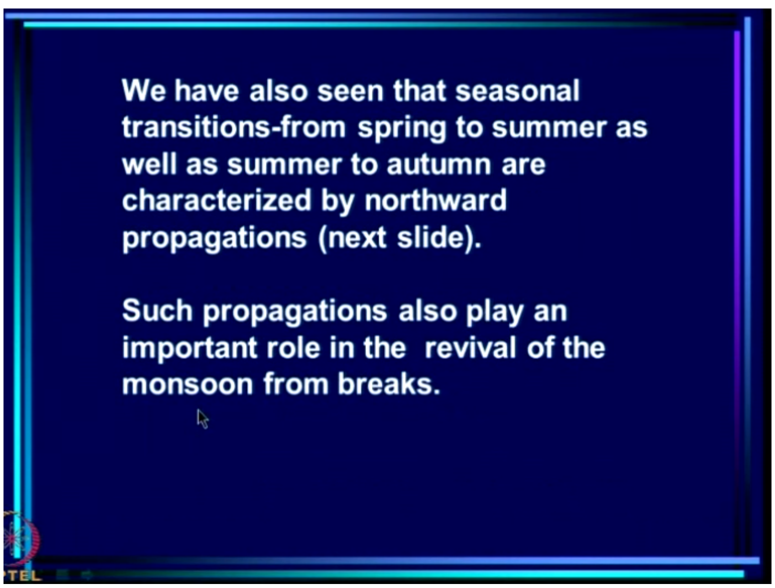

Now, we have also seen now this was during the season but we have also seen that seasonal transitions that is spring to summer as well as summer to autumn area characterized by northward propagations.

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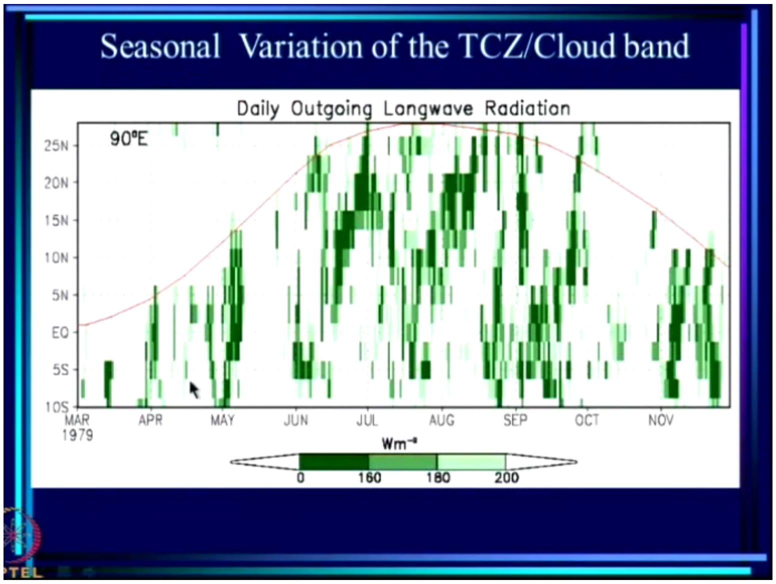

This is something we have seen. So this is the seasonal transition-from spring to summer and that is characterized by northward transition propagations and you can see that the post-monsoon season are the seasonal transition-from the summer monsoon to the fall are also characterized by northward propagation.

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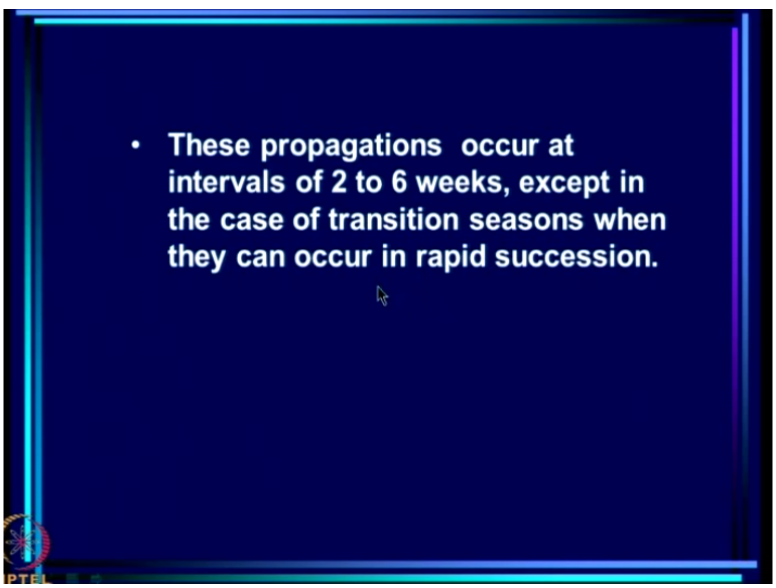

These propagations occur at intervals of 2 to 6 weeks except in the case of transition seasons when they can occur in rapid succession.

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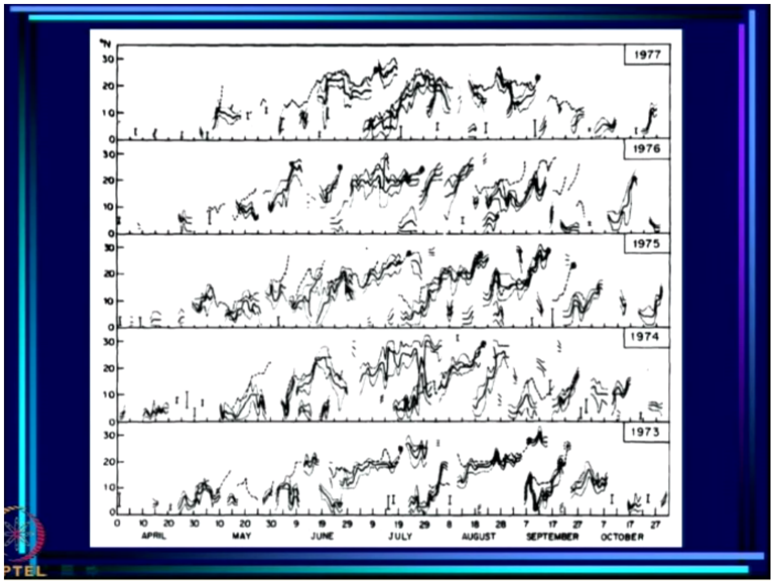

This is from the original paper by Sikka and Gadgil and what you can see is that by enlarge the period between 2 propagations is of the order of 40 days or so. This is one propagation; this is the other one. But occasionally you will see that they occur in quick succession like this one here. This is during the onset phase, say in 75, use of one propagation it (()) (04:09) got finished and another got generated in quick succession.

So often in transition phases you see these propagations occurring in quick succession like here and here, but otherwise typically the period between them is of the order of about 40 days.

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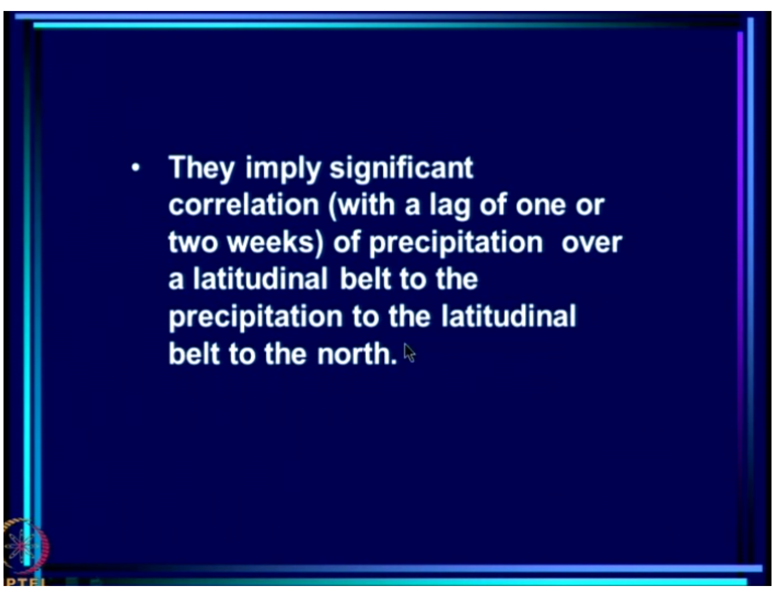

Now this implies you see that this band is moving northward from the equatorial Indian ocean across the Indian peninsula. So if the band is moving, this means that there will be a correlation between the south and north and that is seen here.

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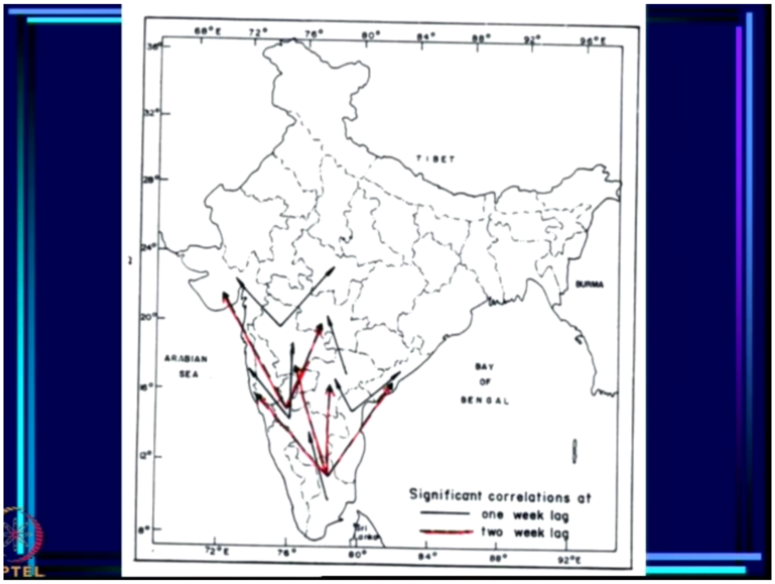

That if we look at correlation with lag so black arrows correspond to 1-week lag. Then a band that is here you will see this is correlated with this with a 1 week lag similarly this rainfall over here is correlated with this. Rainfall over here is correlated with this, rainfall here correlated with this, rainfall here correlated with this, which are just saying that these are all manifestations of the northward movement of the band.

Even with a 2-week lag you see of course rainfall here is correlated with this. Here also is correlated with this and here all are correlated with this because in 2 weeks it will amount but much more so typical length of arrows will be much more. So actually these northward propagations that we see are manifested as lag correlations in rain-belts or in rainfall over the subdivisions.

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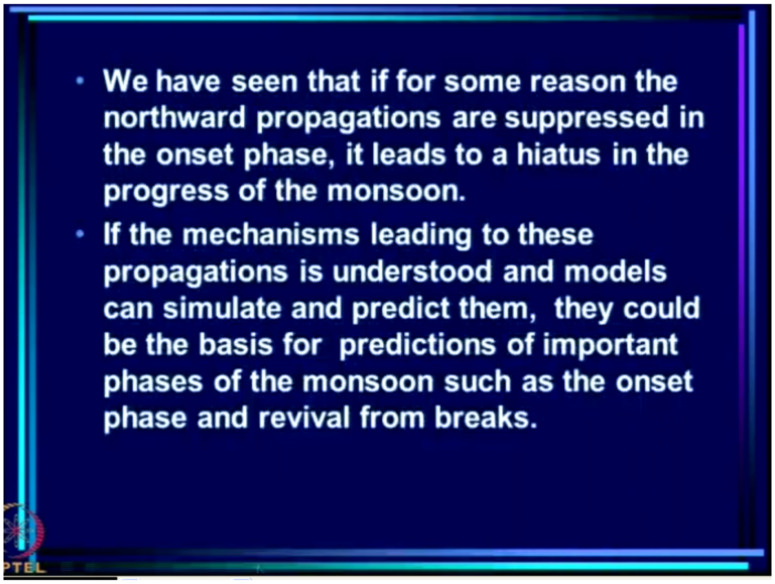

So it will be useful to if you can predict northward propagations because we would then be able to predict the rainfall. Now we have seen that if for some reason the northward propagations are suppressed in the onset phase it leads to a hiatus in the progress of the monsoon. If the mechanisms leading to these propagations is understood and models can simulate or predict them, they could be the basis for predictions of important phases of the monsoon such as the onset phase and revival from breaks.

So, we see not only during the intraseasonal variation between active and break do the propagation play a role particularly in revival from long breaks, but they are also important in the transition phases which we have seen and variability in the northward propagation if suppose it is suppressed in that transition phase we will see examples of this in fact then we have ah, then we have actually ah what is called a hiatus in the phase.

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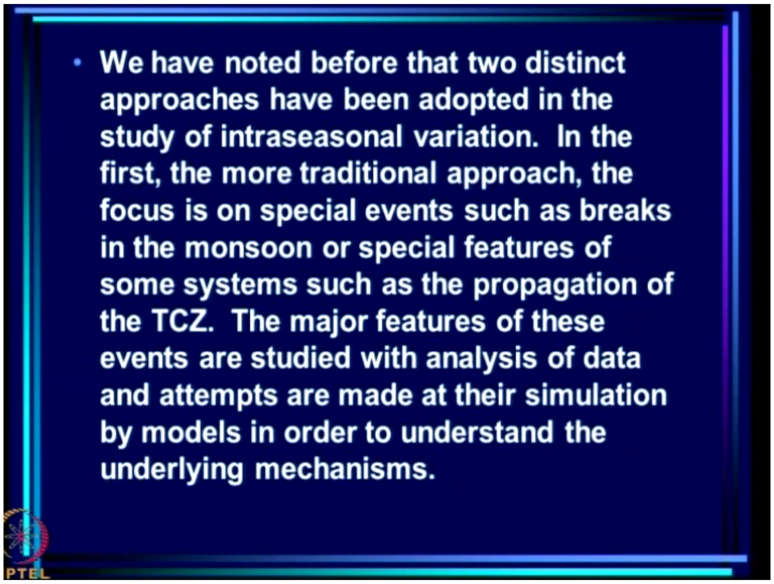

Can you just stop edit this for a minute? I will switch off my mobile and come. Okay, we will start again, okay. We have noted before that 2 distinct approaches had been adopted in the study of intraseasonal variation. In the first, the more traditional approach the focus is on special events such as breaks in the monsoon are special features of some system such as the propagation of the TCZ. The major features of these events are studied with analysis of data and attempts are made at simulations of these events by models in order to understand the underlying mechanisms.

So the focus in the first approach is on these events.

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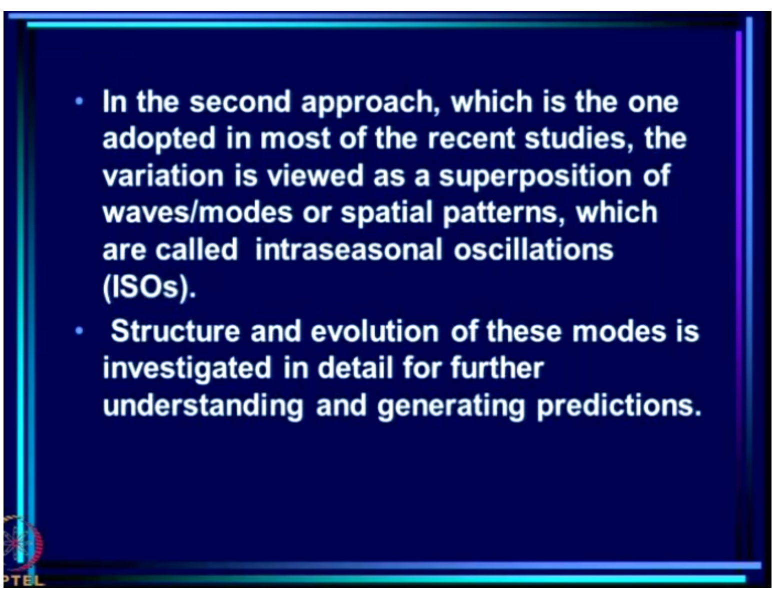

In the second approach, which is the one adopted in most of the recent studies, the variation is viewed as a superposition of waves or modes or spatial patterns which are called intraseasonal oscillations. Structure and evolution of these modes is investigated in detail for further understanding and generating predictions. So this is an alternative approach that people adopt.

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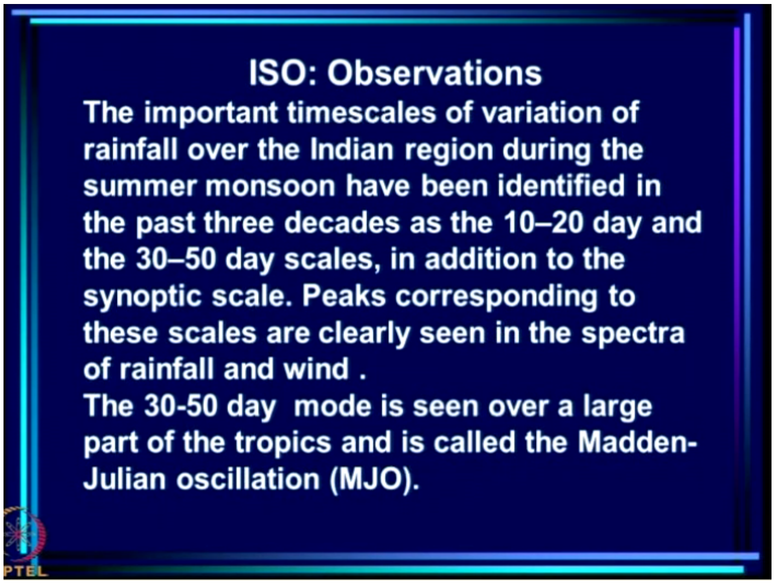

So, we have so far in our description of the event of active weak cycles are of northward propagation use the traditional approach. Now let us look at the second approach namely of intraseasonal oscillations. So what are the observations? The important time scales of variation of the rainfall over the Indian region during the summer monsoon have been identified in the past 3 decades as the 10 to 20-day or quasi-biweekly scale and 30 to 50-day scales in addition to this synoptic scale.

Peaks corresponding to these scales are clearly seen in the spectra of rainfall and wind and the 30-50-day mode is seen also.

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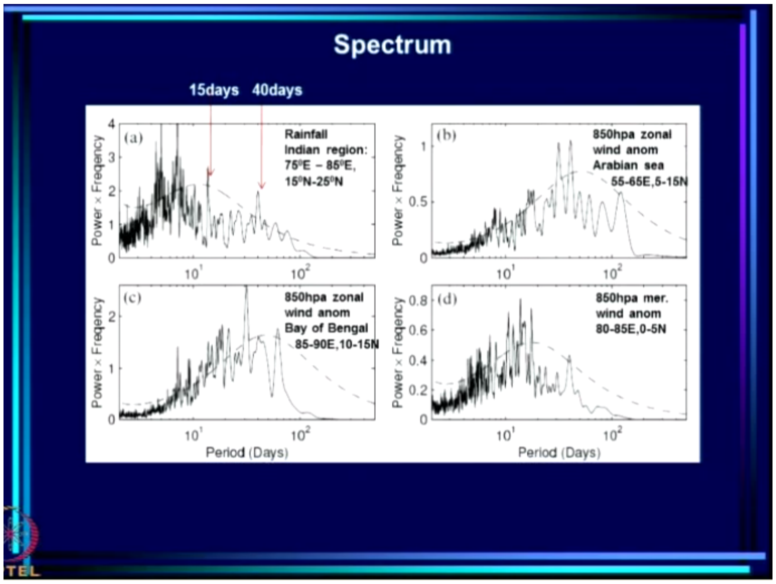

So you see here this is spectrum. This is rainfall over the central Indian region. This is from a paper by Goswami and what you see here is ah this is from 75 to 85 and 15 to 25 and this is a peak corresponding to 15 days. This is the peak corresponding to 40 days and all these correspond to the synoptic scale peaks corresponding to synoptic scale. This is as far as rainfall is concerned. Now if you look at the zonal wind over Arabian sea.

Then the picture is somewhat different. If you look at the Bay of Bengal zonal wind it is different and the wind anomaly, meridional wind anomaly also the modes are somewhat different, but the typical modes that are observed in rainfall are seen in this spectrum. Now, this 30-50-day mode, which we first encountered as a mode in, which northward propagations occur of the TCZ from the equatorial Indian ocean to the monsoon zone.

In fact, happens to be a mode which is seen over a large part of the tropics and is called the Madden-Julian oscillation. So this is a very important feature of tropical circulation and convection. The Madden-Julian oscillation or MJO. This is an oscillation on the scale of 30-50 days. Now what you saw were spectra here from Goswami's paper now what you see here.

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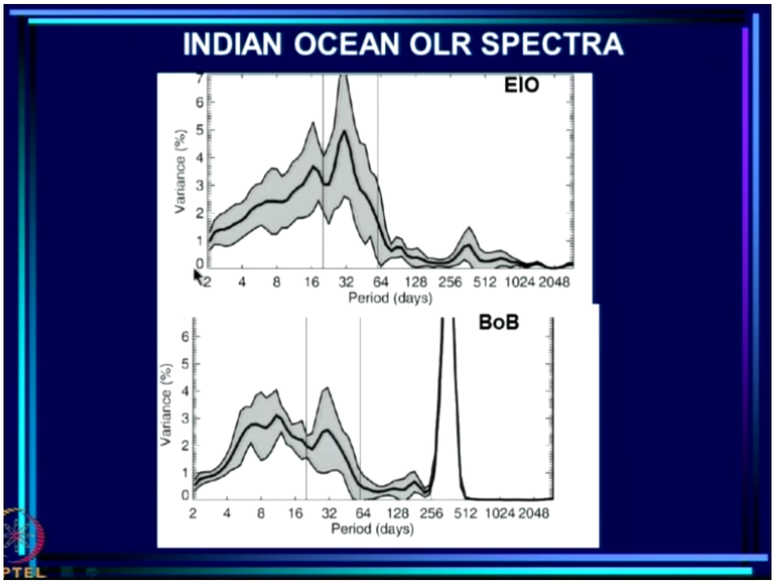

And spectra derived by Webster, and this is the eastern equatorial Indian ocean for which you see the variance. You see a very clear peak in the around say 30 days or so. Very clear peak in the spectrum and for the Bay of Bengal you have a peak around 32 days or so, but also another around 8 or 10 days. In fact, there is a lot of variance. All the way up to quasi-biweekly period over the Bay of Bengal. So these are spectra based on OLR.

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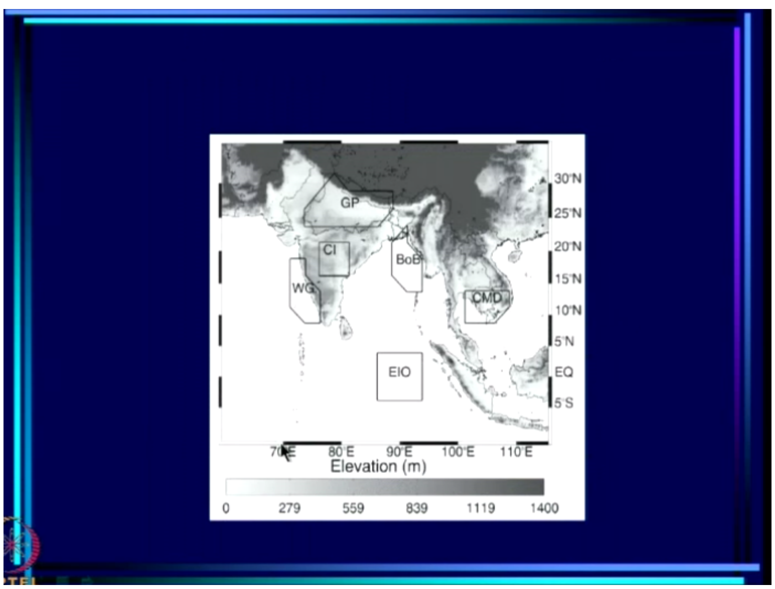

Actually for different regions Bay of Bengal, Eastern Indian Ocean or equatorial Indian Ocean, but the eastern part then this is the Western Ghats area this is the central Indian and this is the Gangetic plain so and this is Cambodia. So for these reasons Webster Ocean Webster have actually done

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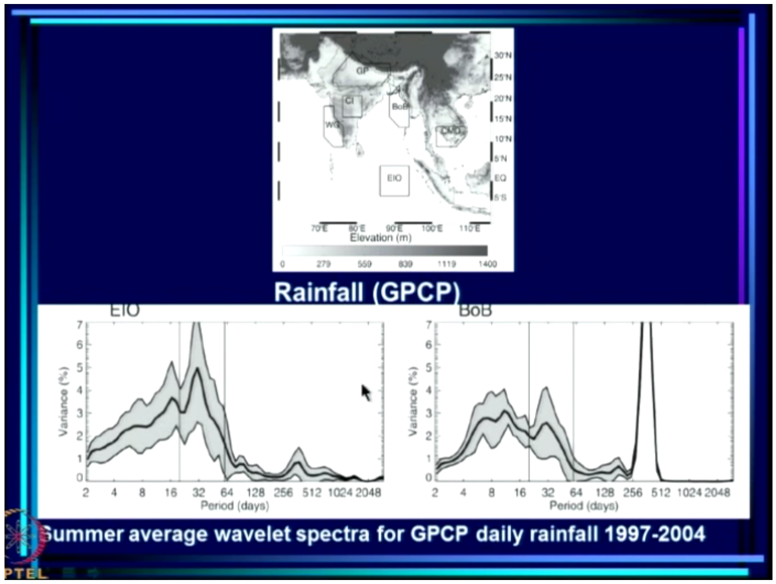

Frequency analysis and wavelet analysis and what you see here is somewhere wavelet spectrum for GPCP rainfall for different regions and the first is EIO which you had seen earlier the OLR spectrum. This is very, very similar. You see a very clear mode around 32 days or so. Most of the energy is in that mode. Now, if we look at Bay of Bengal and the region is shown here.

Then you see again a very similar kind of thing to what we saw earlier in the spectrum of winds that there is a peak here around 32 and a very broad peak going all the way from 4 days to about 10, 12 days or so. This is the characteristic spectra of this region.

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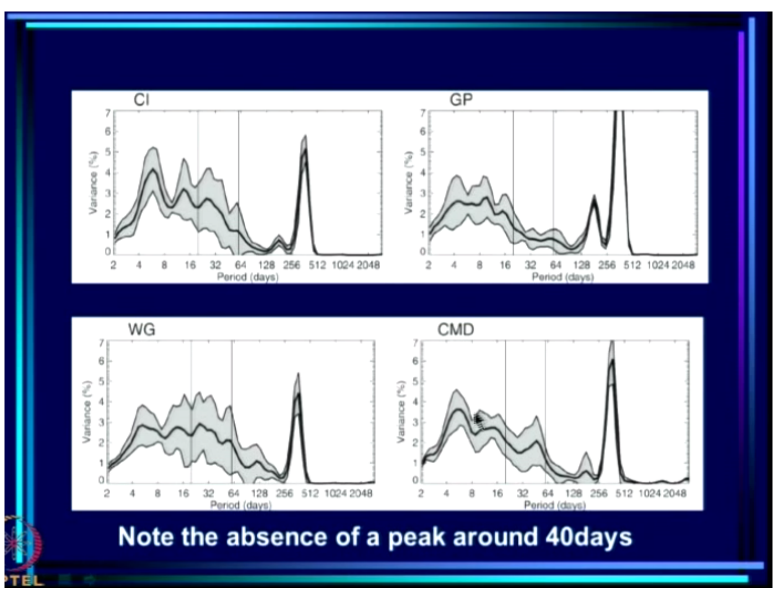

But you noticed that the spectra do vary from place to place. So although it may be useful to look at modes the weight is more than superposed in different regions is definitely different. So interpretation of these modes and the role they play at different places has to be investigated properly before we can see what the implications off of fields like rainfall.

Now this is central India and this is very interesting. This is very different for example from EIO where here the maximum variance seems to be in the synoptic scale and then there is a steady decline with not much variance in the 30 to 50-day mode. Same story for the Western Ghats region. Actually here it is much flatter than central India and you have variance in al frequencies up to about 2 months or so.

Now Cambodia again is somewhat similar to central India. In that you get a decreasing variance with increasing period very similar to Western Ghats and the Gangetic plain is more similar to western Ghats whereas central India and Cambodia are similar and neither of them have too much variance in the 30 to 50-day mode. This is the Gangetic plain and you see most of the variance is flat up to about 2 weeks and then decreases rapidly here.

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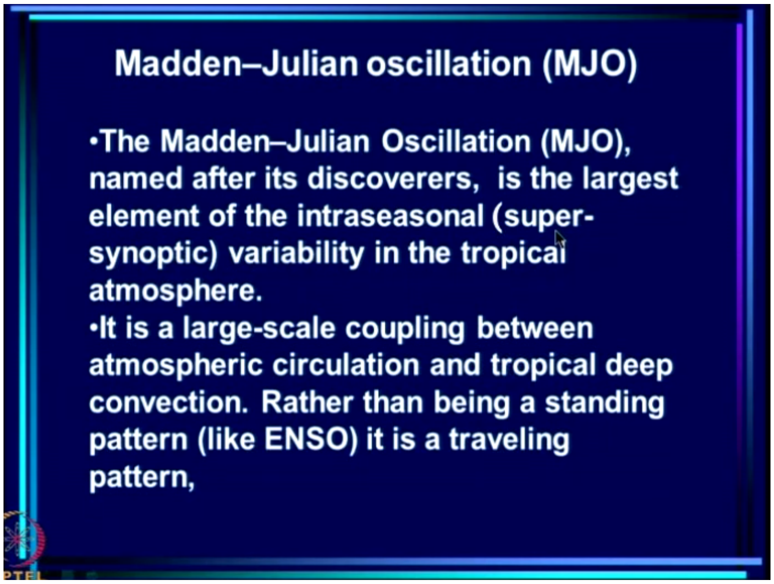

So this is to be born in mind when we look at the different modes. Now let me talk a little bit about Madden-Julian Oscillation because like ENSO on the interannual scale. Madden-Julian Oscillation is a very important phenomenon on the intraseasonal scale in the tropics. So Madden-

Julian Oscillation MJO named after its discoverers in the largest element of the intraseasonal, super-synoptic variability in the tropical atmosphere.

It is a large-scale coupling between atmospheric circulation and tropical deep circulation. Rather than being a standing pattern like ENSO it is a traveling pattern and

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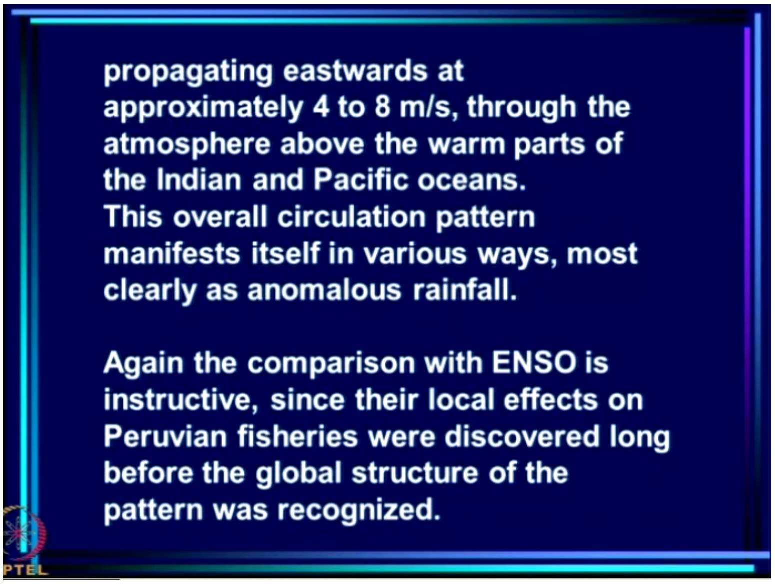

Propagating eastwards approximately at 4 to 8 meters per second, through the atmosphere above the warm parts of the Indian and Pacific oceans. This overall circulation pattern manifests itself in many ways most clearly as anomalous rainfall. Again the comparison with ENSO is instructive, because local effects on Peruvian fisheries were discovered long before the global structure of the pattern was recognized in ENSO whereas with Madden-Jullian oscillation it is the global pattern.

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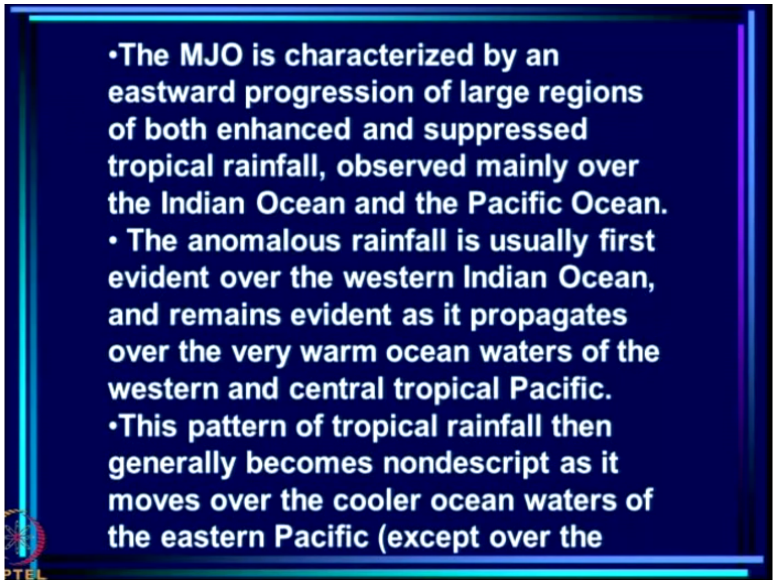

That has been first discovered. So the MJO is characterized by an eastward progression of large regions of both enhanced and suppressed.

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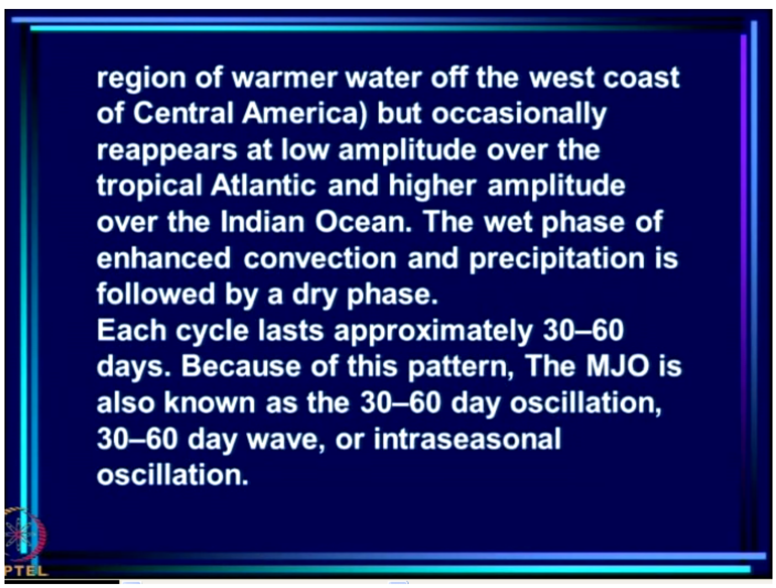

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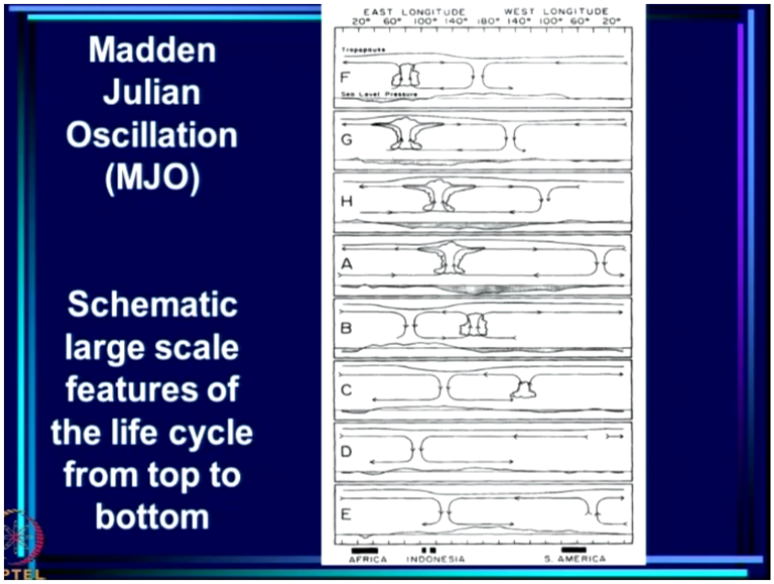

Convection and may be it will be good to look at this and then we go back and see what is happening. See this is going this is the way a cycle of a Madden-Julian oscillation evolves. Now this is 20 degrees east. This is 60 degrees east so Indian longitudes are around here and it goes right. This is the date line and it goes all the way round the globe till 10 degrees here and 10 degrees east. So that is on the coast of Africa.

So this is the equatorial region. MJO is an oscillation of convection over the equatorial region primarily and this is the typical pattern for northern hemispheric winter. So you have convection beginning somewhere near the Indian Ocean, western Indian Ocean. This is the convection here. Now you see convergence into the convection divergence a loft so this is 1 cell. This is the convection cell. The air that is ascending in the convection is descending here.

So you have wet here and dry here okay. Now, this system moves eastward with time so that the next will be here. It has got intensified then it is here is now over Indonesian region now it is over west pacific and now it has come close to the date line and just east of the date line is the last time it is seen as an active convection after that it disappears.

So, it is phenomena which involves eastward propagation of convection and the associated circulation from about the western equatorial Indian ocean to just past the date line about 140 degrees west. So the MJO is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall observed mainly over the Indian Ocean and the Pacific Ocean.

The anomalous rainfall is usually first evident over the western Indian Ocean and remains evident as it propagates over the very warm waters of the western and central tropical Pacific. This pattern of tropical rainfall then generally becomes nondescript as it moves over the cooler ocean waters of the eastern Pacific which is what we have seen except perhaps for region of warmer water off the west coast of Central America but occasionally reappears at low amplitude over the tropical Atlantic and higher amplitude over the Indian Ocean.

The wet phase of the enhanced convection and precipitation is followed by a dry phase. Each cycle lasts approximately 30 to 60 days. Because of this pattern, MJO is also known as 30-60-day oscillation or intraseasonal 30-60 intraseasonal oscillations. So, this picture is actually from the original paper by Madden and Julian who discovered this.

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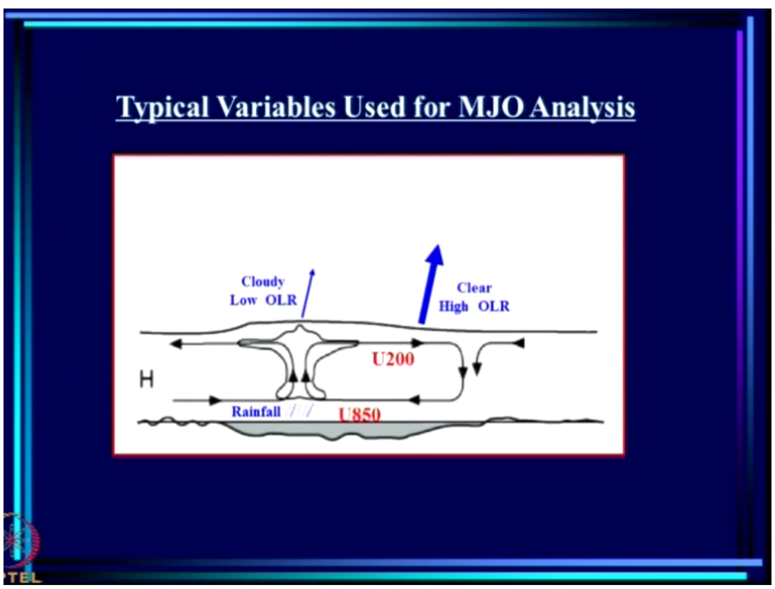

Now these are the typical variables used in MJO analysis. You have this cloud system here associated with rainfall and you have cyclonic vorticity here. This is the 850 then you have convergence here, diversions a loft, and this will imply that low OLR here because it is deep clouds and high OLR and clear sky is here where there is descending motion. So here you have upper level convergence and divergence at the lower level and the opposite holds here.

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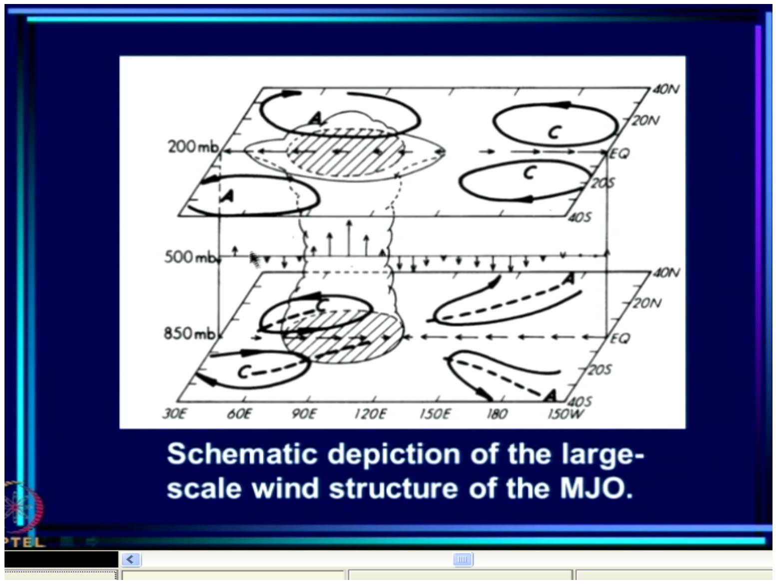

So this is then the schematic picture here you have cyclonic vorticity at the lower level over the region where it is raining, anti-cyclonic a loft so convergence here divergence a loft and the opposite holds over the region to the east where you have dry conditions and so you have convergence at upper levels and divergence at lower levels with no rain, no clouds.

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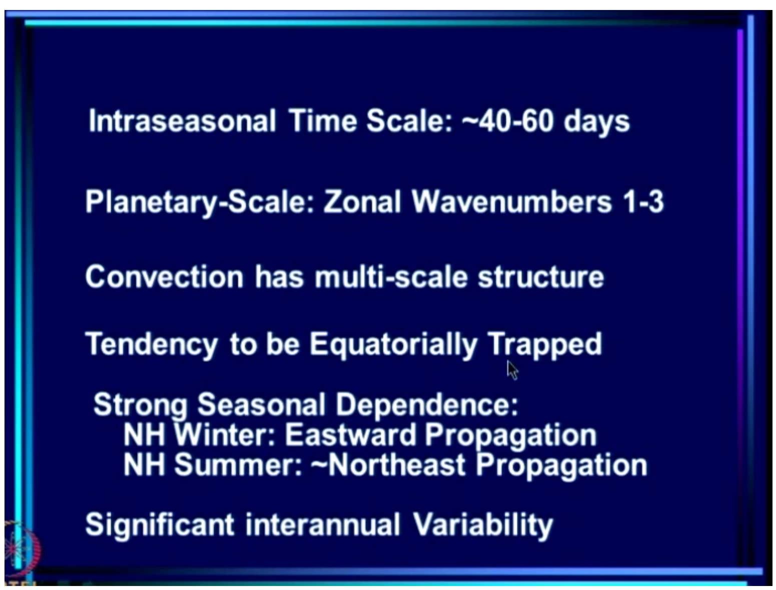

So this is the schematic picture that you have. So it is an intraseasonal time scale phenomenon 40 to 60 days. It is a planetary scale as you have seen. It goes all the way from about 50 degrees east to 140 degrees west almost half way round the globe. Convection has multiscales structure this is important and it has a tendency to be equatorially trapped however we have to remember that although the eastward propagation that you I just showed is a characteristic of northern hemispheric winter.

In northern hemispheric summer we have seen that there are northward propagations over the Indian longitudes under same time scale so this MJO can be thought of as having a northeastward propagation and there is significant interannual variability as well.

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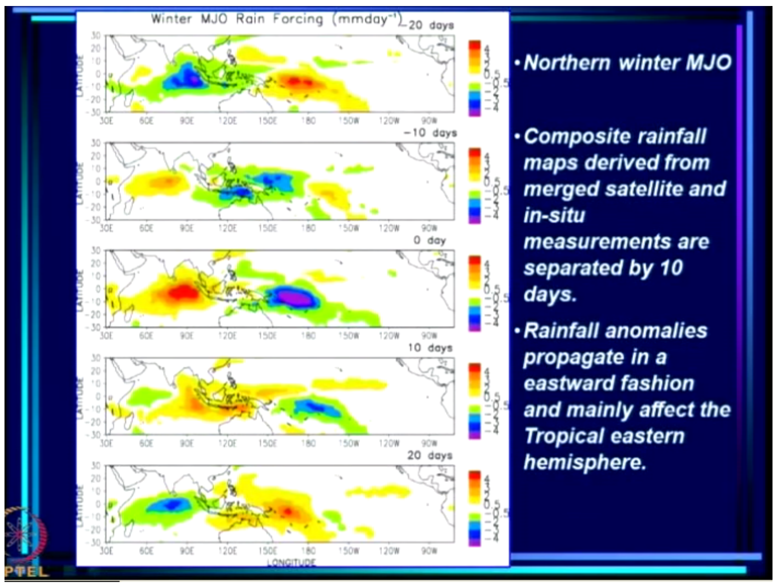

So let us now look at what the winter MJO pattern looks like and this is the rain forcing and what you have here these are composite. Composite rainfall maps derived from merged satellite in-situ and in-situ measurements separated by 10 days okay. So this corresponds to -20 days, -10 days, 0 day, 10 day, and 20 day and what you see here is these are negative anomalies of rainfall. These are positive anomalies of rainfall.

So you can see here that this is a positive anomaly of rainfall that has appeared. Now it has moved east from here to here and intensified. Now it moves further east here and is moving east here and now here it has moved all the way to the west Pacific. So you see a very clear eastward propagation here. If you want to look at dry conditions also dry anomalies also you will see they also move eastward from here up to here and another has formed here now.

So what you see here is a clear eastward propagation and see also that this is more or less restricted to the tropical eastern hemisphere. So you see the action is between around 50 east or so to about 140 east. From 140 east the other half of the tropical atmosphere is not affected by MJO.

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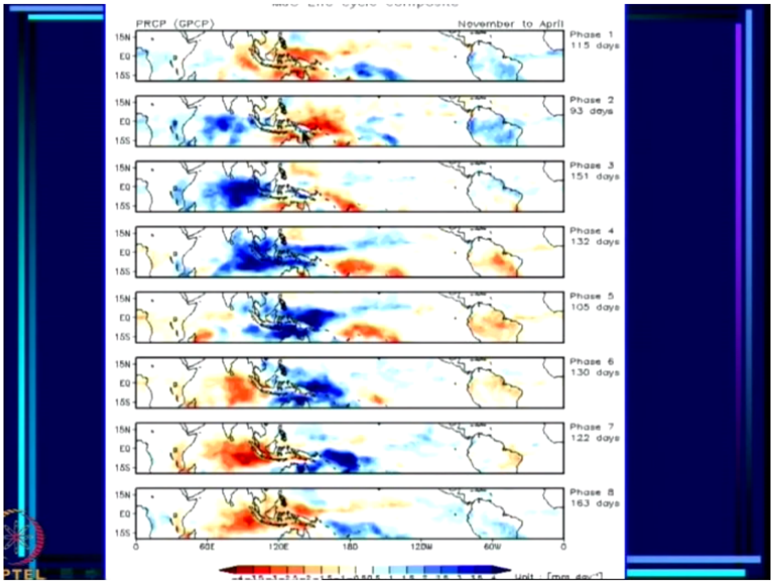

And this is an MJO lifecycle composite from GPCP again and you will see very similar things. This is rainfall and you see the rain band propagating very nicely and this is from November to April. These are the different phases of MJO as they say phase I, II, III. IV, V, VI and so on. Now I must mention that Madden-Julian oscillation has been extensively studied over the last 2 decades.

So what I will do in this lecture is give you only some introduction and it will not be possible to go into great detail. In fact, an entire course can be given now on intraseasonal variation and Madden Julian oscillation because there is that much literature that has been published in the last 10 and 10 or 20 years okay. Now this is the summer one and let us start again its composites of rainfall.

Let us start with here. Remember yellow is positive rainfall anomaly and blue is negative. So here a rain band has appeared and everywhere here there is deficit. Now the rain band moves northward but also eastward. You can see it has moved north, but also eastward and again it has moved north and intensified eastward and again further north and intensified eastward and now further north even further north, but it is very weak here and has become strong here.

This is what they consider as a northeastward propagation. But it is somewhat of a pigment of the imagination I believe because if you look at actual propagation you do not see too much of northeastward movements. It is much more a clean northward movement and eastward movement in the equatorial region okay.

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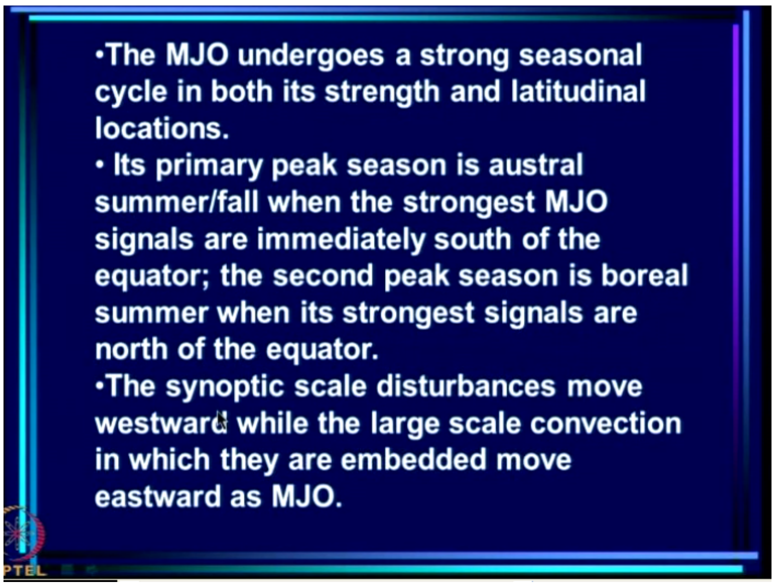

The MJO undergoes strong seasonal cycle in both strengths and latitudinal locations. Its primary peak season is austral summer or fall when the strongest MJO signals are immediately south of the equator. The second peak season is boreal summer when its strongest signals are north of the equator. The synoptic scale disturbances move westward while the large-scale convection in which they are embedded move eastward.

Now this is the thing that I talked about earlier that there is an interaction between different scales of convection and it is very interesting that in the larger scale convection synoptic scale convection is embedded and what we saw earlier was an organized convection on a much larger scale which moves eastward, but the individual synoptic scale disturbances.

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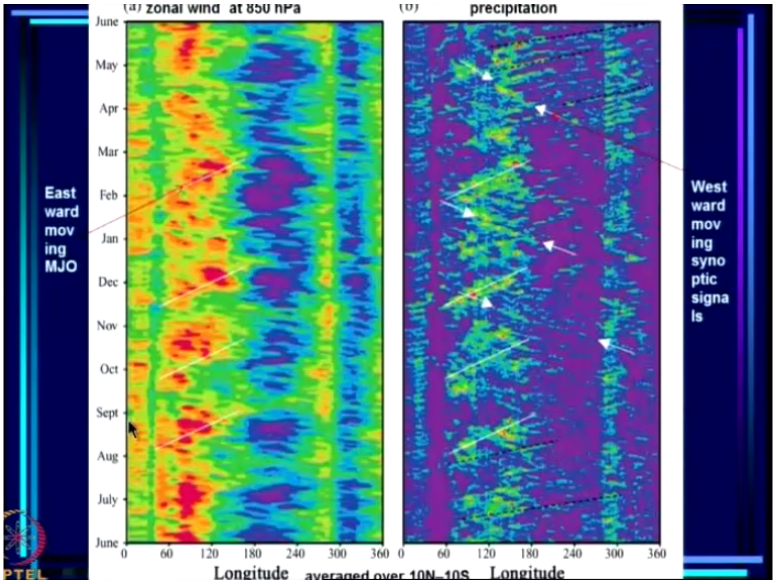

Actually move westward and we can see that and this is from (()) (25:16) paper. This is actually zonal wind at 850 hpa and this is the rainfall precipitation and this is all average from 10 south to 10 north and what you can see here is very clear eastward propagations here. You can see here clear eastward propagation and here as well so this is clear eastward propagation which characterizes the MJO.

This is the eastward propagation, but look at precipitation. Precipitation also you see very clear eastward propagation exactly at the same time. Remember this is time and this is latitude longitude so an arrow like this implies eastward propagation however an arrow which is at right angles to this would imply westward propagation and that is what you see here see these are individual systems which are moving to the west.

Which you can see here and here which are literally at a very large angle almost right angle to the eastward propagating systems and this is the westward propagation of the synoptic scale systems. So life is a little bit complicated because of this multiscale problem, but the large-scale convection certainly most eastward in MJO.

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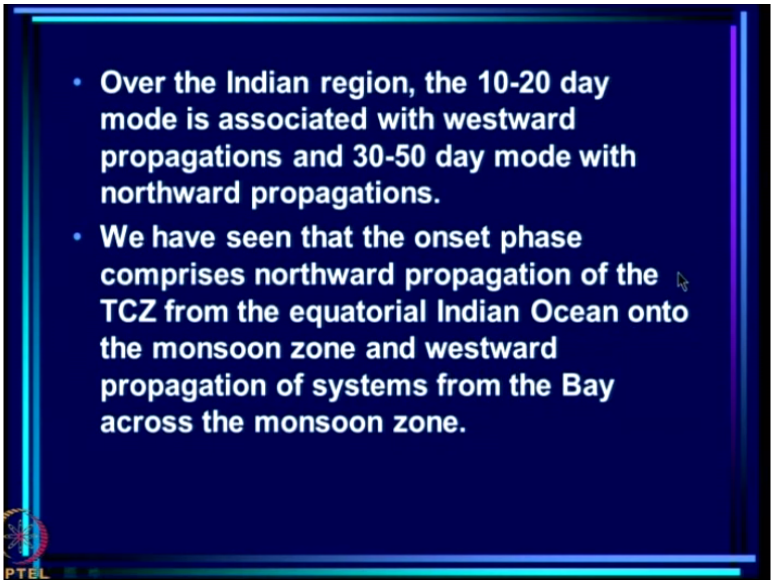

Now over the Indian region 10 to 20-day mode is associated with westward propagations and 30 to 50-day mode with northward propagations. We have seen that the onset phase comprises of northward propagation of the TCZ from the equatorial Indian Ocean on to the monsoon zone and westward propagation of systems from the Bay across the monsoon zone. This is what why we have seen very clearly in our lectures on the onset phase.

So the transition also involves both the modes in a way both northward and westward propagations.

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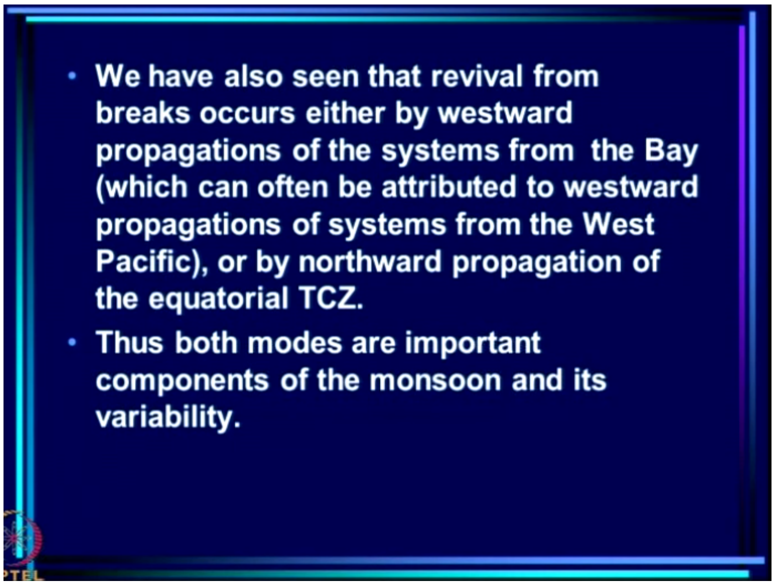

We have also seen that revival from breaks occurs either by westward propagations of the system from the Bay which can often be attributed to westward propagations of systems from the West Pacific or when northward propagations of the equatorial TCZ. Thus, both modes are important components of the monsoon and its variability and this has to be born in mind because people have got carried away with MJO in the 30 to 50-day mode which involves northward propagation and not paid as much attention to the westward propagation quasi-biweekly mode which plays and equally important role in the monsoon.

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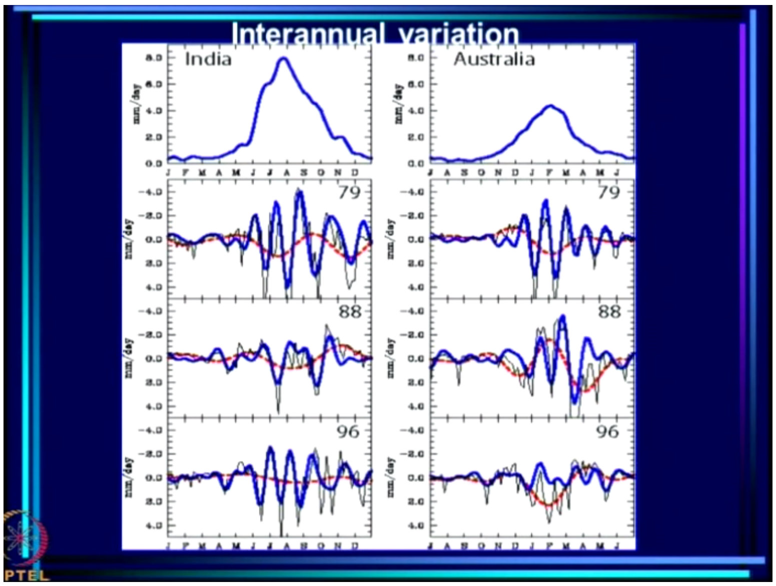

Now this is just to illustrate that actually the modes have considerable interannual variation and you see that here 79 has very large amplitude fluctuations 88, much smaller amplitude, 96 higher frequencies than 88, and so on and so forth and that is the characteristic of the tropic, the eastern hemisphere wherever MJO occurs okay.

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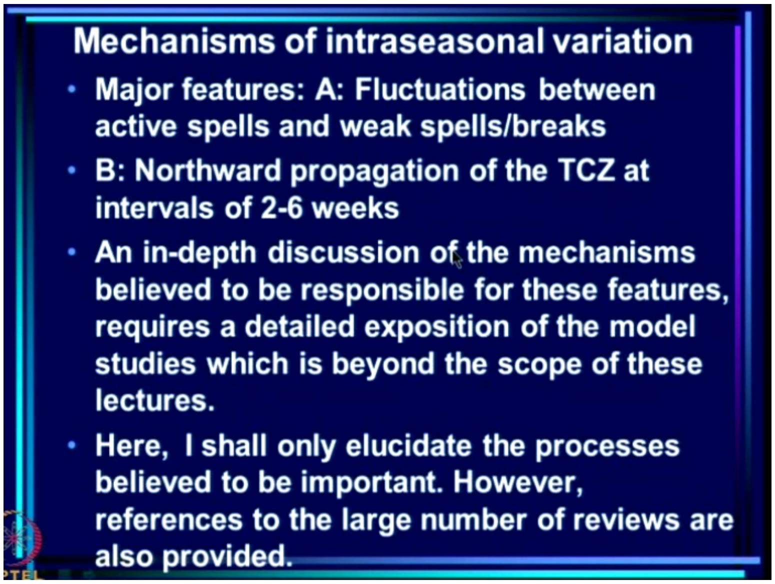

So, much about the intraseasonal oscillation and the intraseasonal variation. Now so we have some idea of the nature of these variation and oscillations. Question is what are the mechanisms that lead to that. So the major features of the mechanisms are over the Indian region are fluctuations between active spells and weak spells or breaks and northward propagation of the TCZ at intervals of 2 to 6 weeks.

An in-depth discussion of these mechanisms believed to be responsible for these features requires a detailed exposition of the model studies which is beyond the scope of these lectures because in these lectures I have really not referred to models at all. So here I shall only elucidate the processes believed to be important, but at the end references to the large number of reviews are also provided so that people who are interested in going in depth in the mechanisms can refer to those papers okay.

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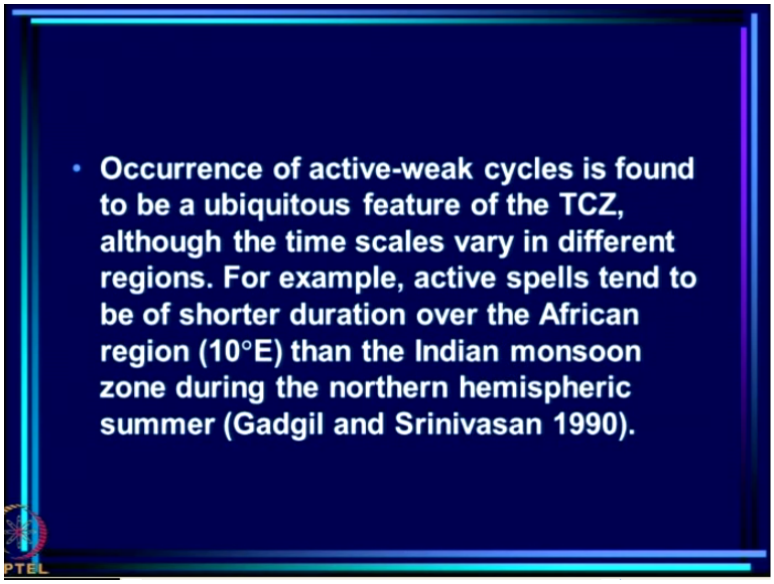

Now, occurrence of active-weak cycles is found to be a ubiquitous feature of the TCZ although the time scales vary in different regions that is to say overall the monsoonal regions of the world where TCZ occurs it fluctuates okay, but the periods of active spells and weak spells vary from place to place. For example, active spells tend to be of shorter duration over the African region than the Indian monsoon zone during the northern hemispheric summer.

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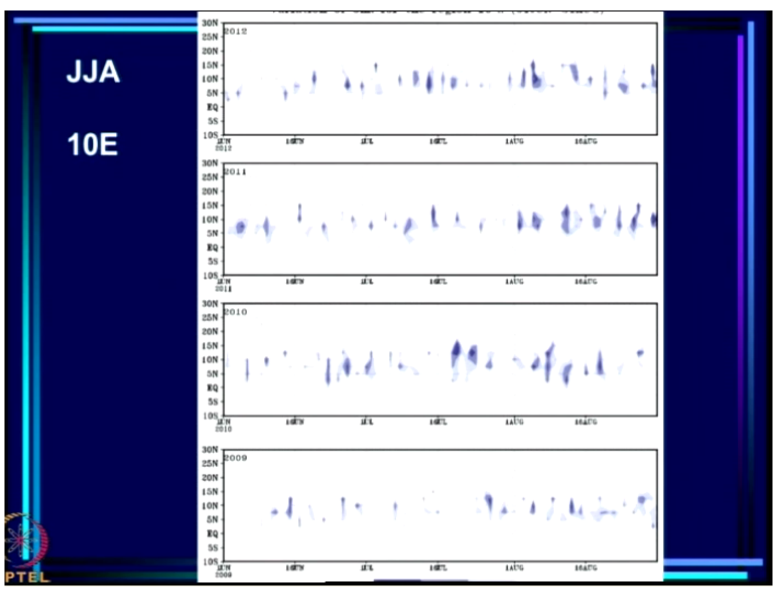

And we will now see examples of this and what you see is for different years. Again the OLR low LR regions are plotted so this is 2009, 2010, 2011, and 12 and this is all in the African region then east for JJA and what you see is that typically only for a few days' things are active and it is a highly fluctuating phenomena with a high frequency of fluctuation compared to the Indian region. This is the African case.

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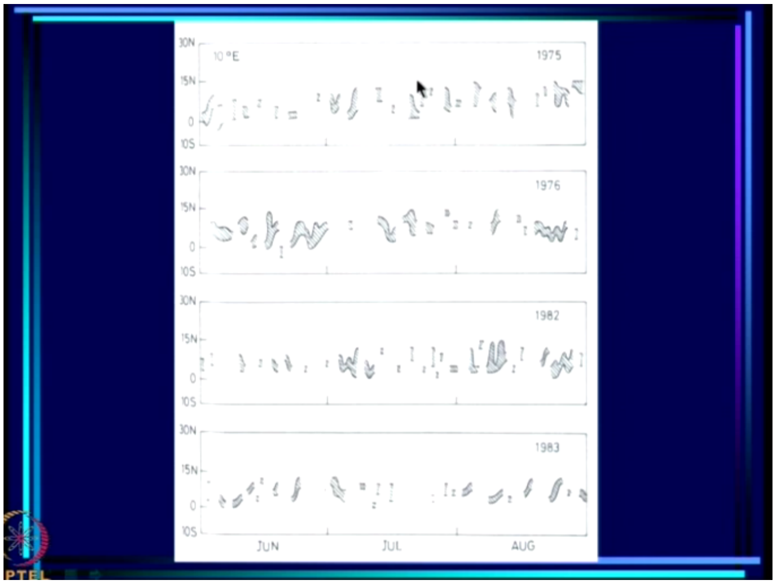

And this is what we had in our paper where we have drawn actually the bands, cloud-bands and what you see here is again there is a considerable variation from here to here. See in 76 you got much longer active spells over the African region then in 75 and you got very big dry spells in 83 here for example. So there is considerable interannual variation, but the typical scales.

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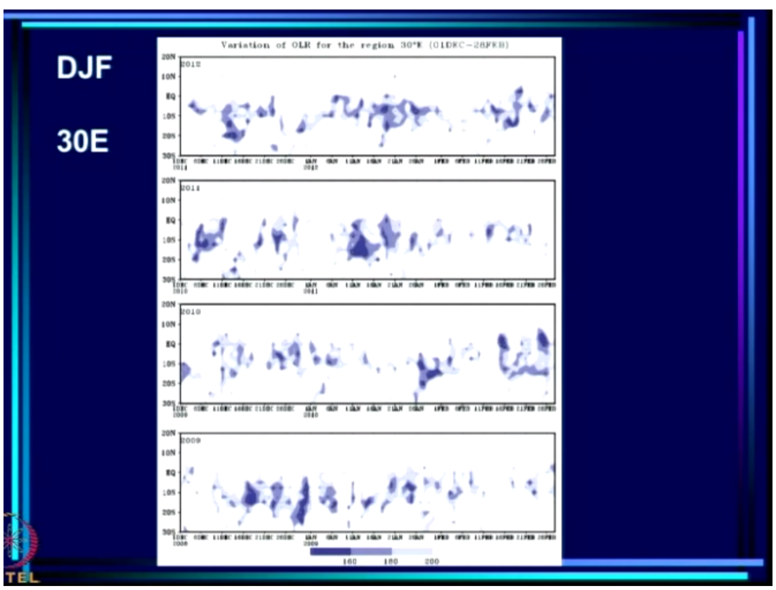

Time scales of active and weak spells vary a great deal from region to region. Now if you go to Africa, southern Africa for December, January, February that is northern winter again you have fluctuations between active spells and weak spells or breaks, but these happen to be characterized by much longer time scales. Then the one over West Africa at 10 east.

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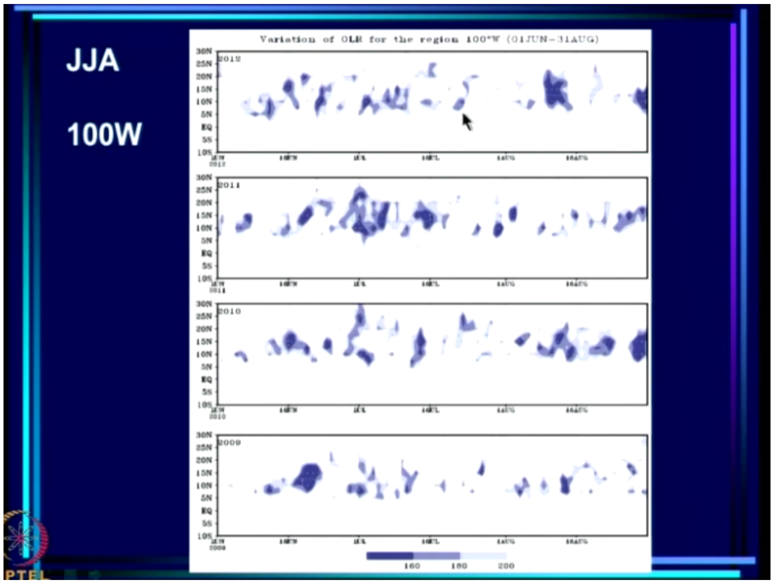

Now this is the variation over 100 west and this is over the specific region and over South American region and again you see that the time scales are somewhat different, but the fact that you will never have a cloud-band persisting through a season is a characteristics of all regions.

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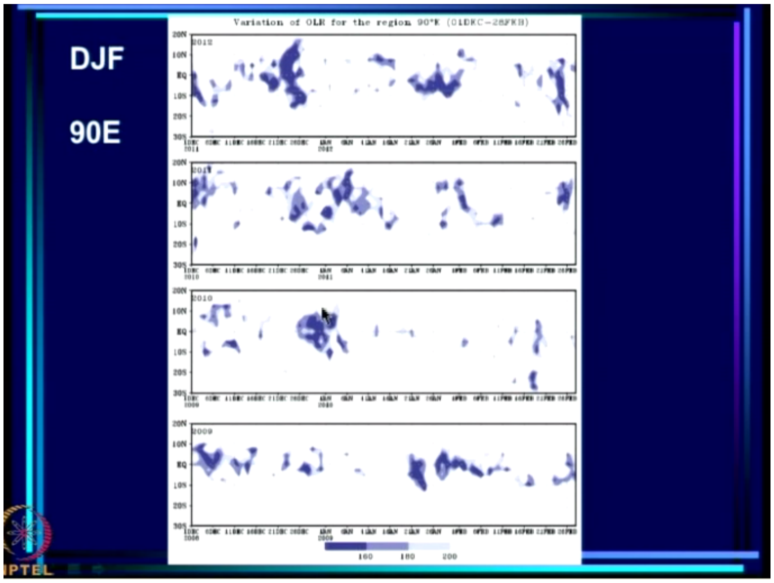

Now this is 90 degrees east and December, January, February, so this is the Indian Ocean and again you see a great deal of variation from year to year and fluctuations are always there. This is

70 west so this is south America. South America you seem to have much more much longer active periods and less of a fluctuation compared to say Africa.

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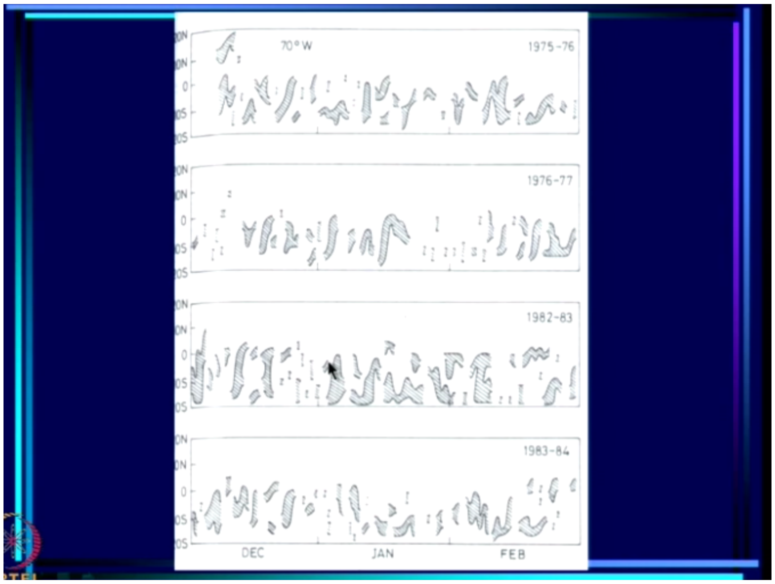

And this is again the same thing that you tend to get longer active periods, but there are occasions in which you get large breaks also.

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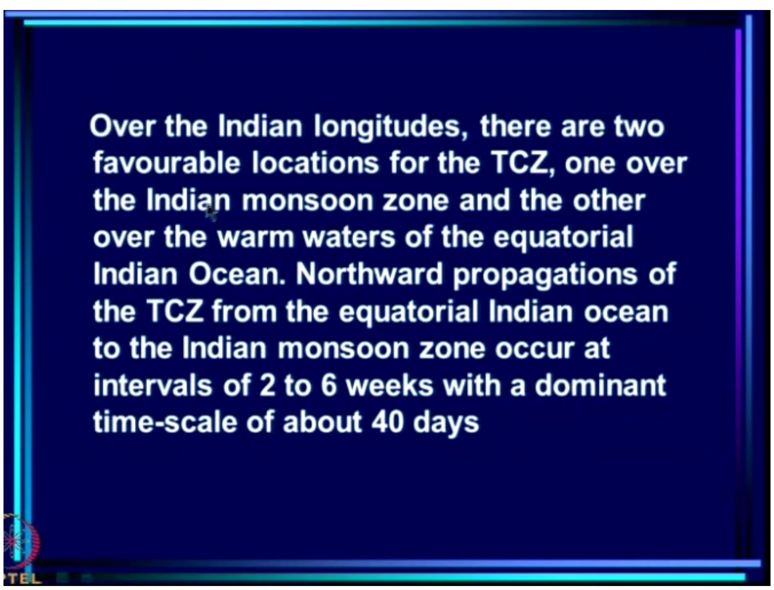

So no matter where you go every monsoonal region there are fluctuations in the TCZ and therefore active spells and weak spells and they are characterized by different time skills. now over the Indian longitudes there are 2 favorable locations for TCZ one over the Indian monsoon zone and the other over the warm waters of the equatorial Indian ocean in our summer. So, northward propagation of the TCZ from the equatorial Indian Ocean to the Indian monsoon zone occur at 2 to 6 weeks with a dominant time-scale of 40 days.

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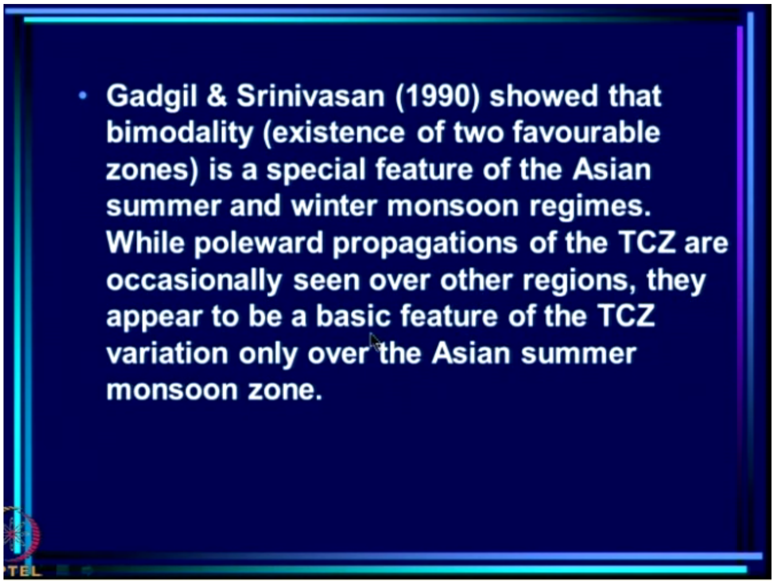

Now we looked at satellite data and we showed that bimodality that is existence of 2 favorable zones is a special feature of the Asian summer and winter monsoon regimes. So this feature that we seen over the Indian region is not seen everywhere. It is the special feature of Asian summer and winter monsoon regime while poleward propagation of the TCZ are occasionally seen over other regions. They appear to be a basic feature of the TCZ only over the Asian summer monsoon zone.

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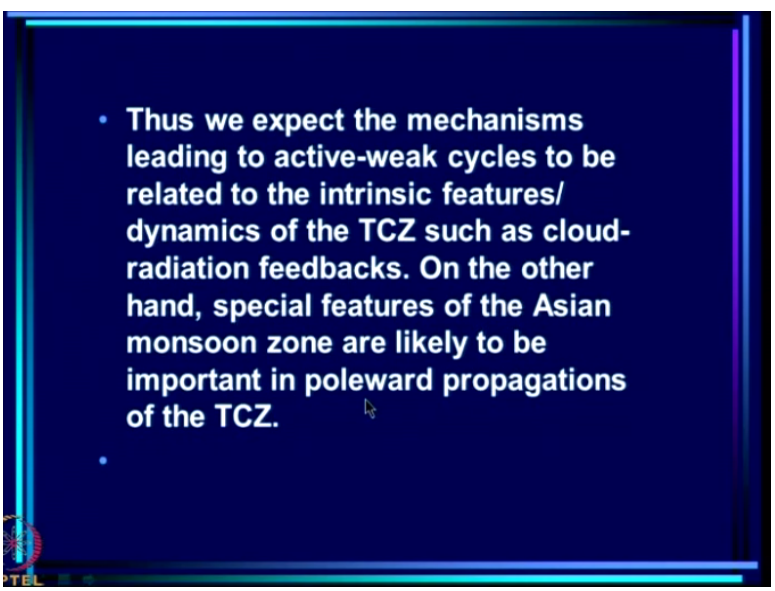

Thus we expect the mechanisms leading to active-weak cycles to be related to the intrinsic features or dynamics of the TCZ such as cloud-radiation feedbacks. Why is that because they are over every zone, every region over which the TCZ occurs we see fluctuation. So they must be related to some intrinsic feature of dynamics of the TCZ such as cloud radiation feedback. On the other hands special features of the Asian monsoon zone are likely to be important for poleward propagations of the TCZ.

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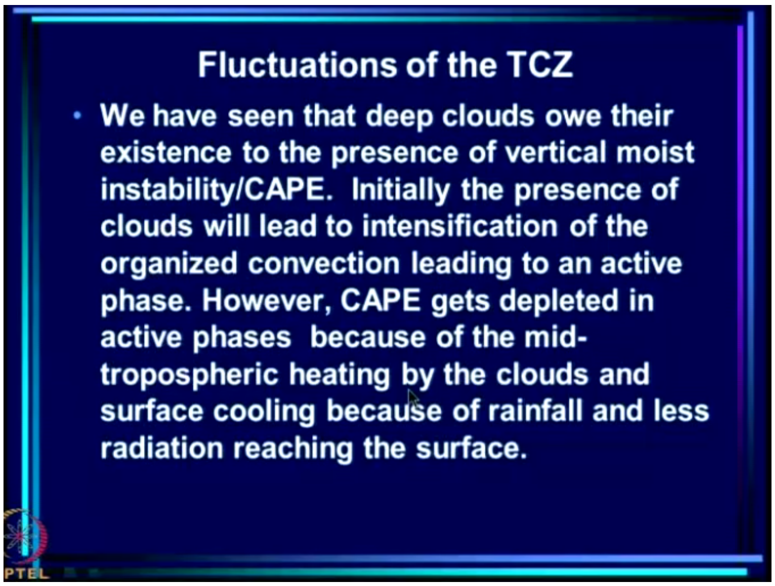

So let us look at what can lead to fluctuations of the TCZ. We have seen that deep clouds over their existence to the presence of vertical moist instability which we called CAPE. This is the available potential energy, convect available potential energy CAPE which is the measure of that instability. Initially the presence of clouds we lead to intensification of organized convection leading to an active phase.

However, CAPE gets depleted in active phases because of the mid-tropospheric heating by the clouds and surface cooling because of rainfall and less radiation reaching the surface. So what is happening is that the instability which is the atmosphere is slowly getting eaten up by convection because mid-tropospheric heating occurs so and also cooling of the surface occurs.

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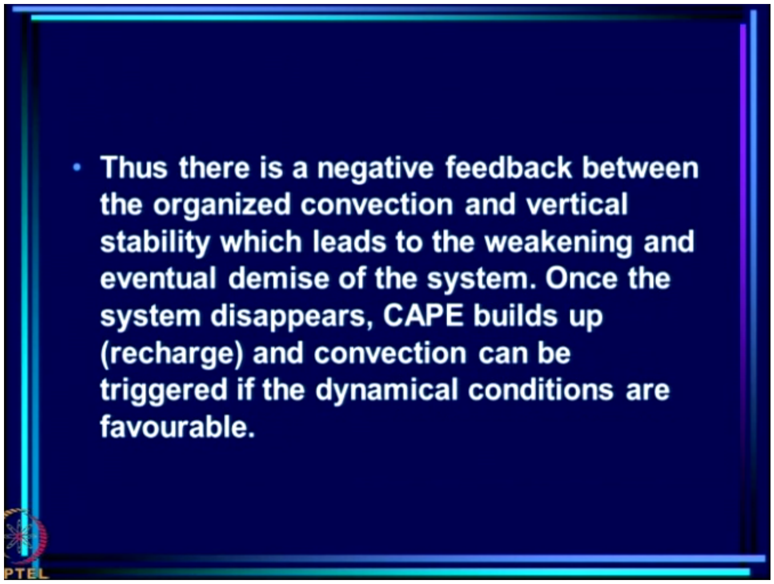

Thus there is a negative feedback between the organized convection and vertical stability which leads to the weakening and eventual demise of the system. Once the system disappears again CAPE builds up which is the recharge and convection can be triggered if the dynamical conditions are favourable.

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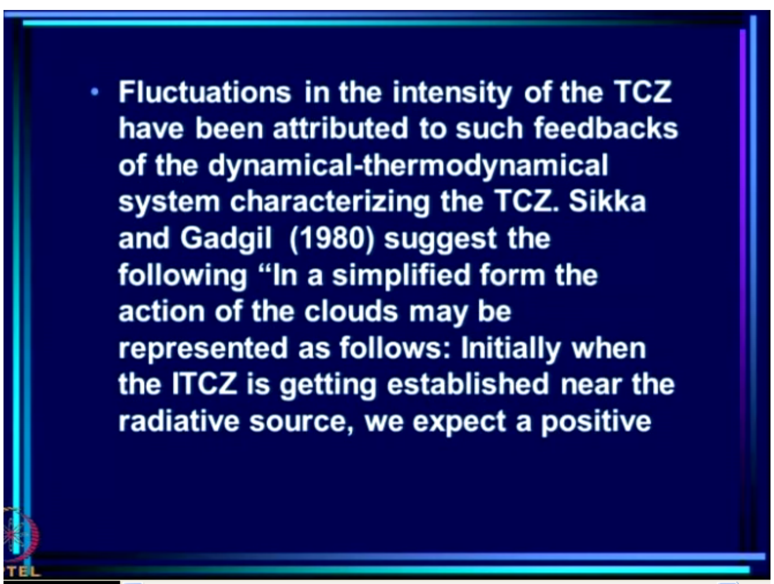

Now fluctuations in the intensity of the TCZ have been attributed to such feedbacks of the dynamical-thermodynamical system characterizing the TCZ. In the paper by Sikka and Gadgil in 1980 they talked about the fluctuations of the TCZ and they suggest the following that in a simplified form the action of clouds may be represented as follows: Initially when the ITCZ is getting established near the radiative source, we expect the positive feedback from clouds.

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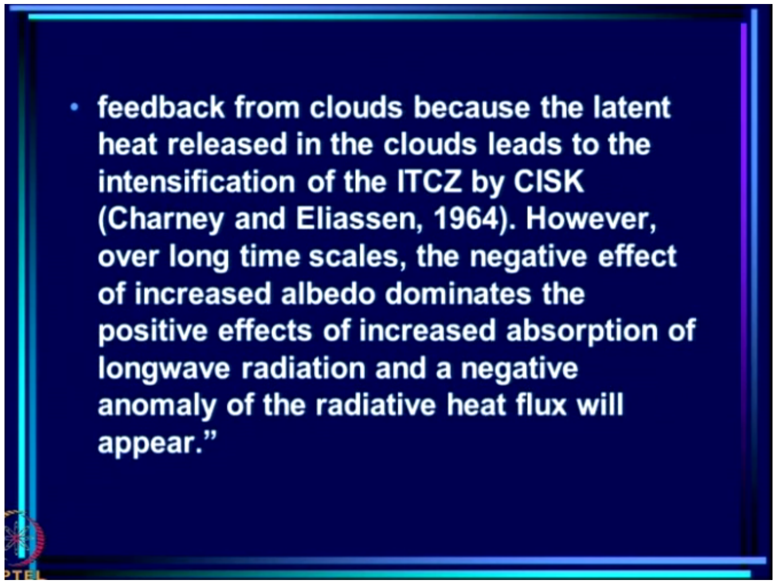

Because the latent heat released in the clouds leads to the intensification of the ITCZ by CISK. So initially we will see that clouds release heat and we have already looked at conditional instability of the second kind, the release of heat by clouds leads to intensification of the cyclonic vorticity and which in turn leads to intensification of the convergence and more clouds. So initially there is a positive feedback between the clouds and the cloud system okay.

However, over long time scales the negative impact of the increased albedo dominates the positive effects of increased absorption of long wave radiation and a negative anomaly of radiative heat flux will appear.

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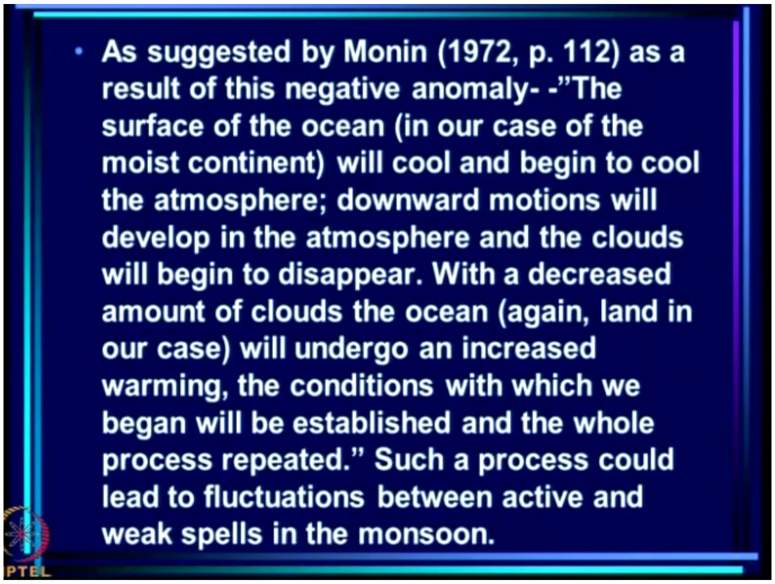

In fact, Monin has a very nice description of how are TCZ would oscillate over the ocean. He says the surface of the ocean in our case the moist continent will cool and begin to cool the atmosphere. Downward motions will develop in the atmosphere and the clouds will begin to disappear.

With the decreased amount of clouds, the ocean again land in our case, will undergo an increased warming. The conditions with which we began will be established and the whole process will be repeated. Such a process could lead to fluctuations between active and weak spells in the monsoon. So there are feedbacks which are negative feedbacks which can lead to these kinds of fluctuations.

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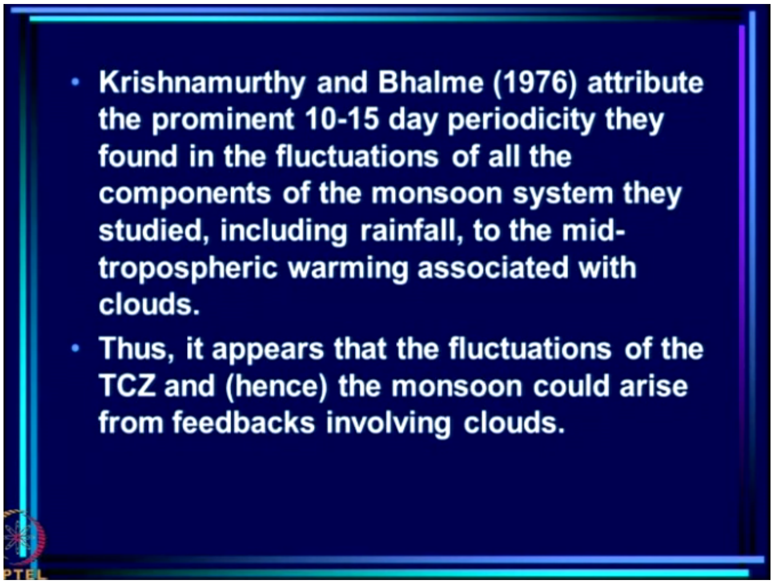

Now Krishnamurthy and Bhalme attribute the prominent 10 to 15-day periodicity they found in the fluctuations of all the components of the monsoon system they studied, including rainfall, to the mid-tropospheric warming associated with clouds. Thus it appears that the fluctuations of the TCZ and hence the monsoon could arise from feedbacks involving clouds.

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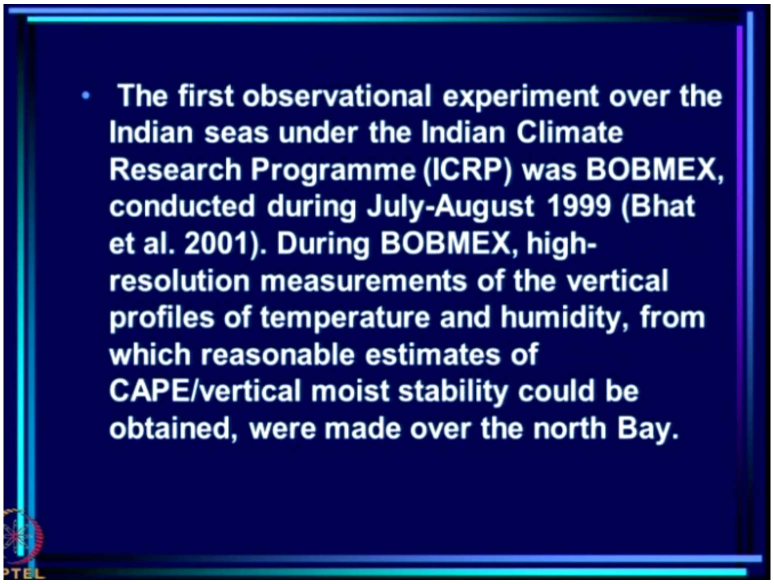

The first observational experiment over the Indian seas under the Indian Climate Research Programme was BOBMEX conducted during July-August 1999. This was under the leadership of Bhat. During BOBMEX, high-resolution measurements of the vertical profiles of the temperature and humidity, from which reasonable estimates of CAPE and vertical moist stability could be obtained were made over the north Bay.

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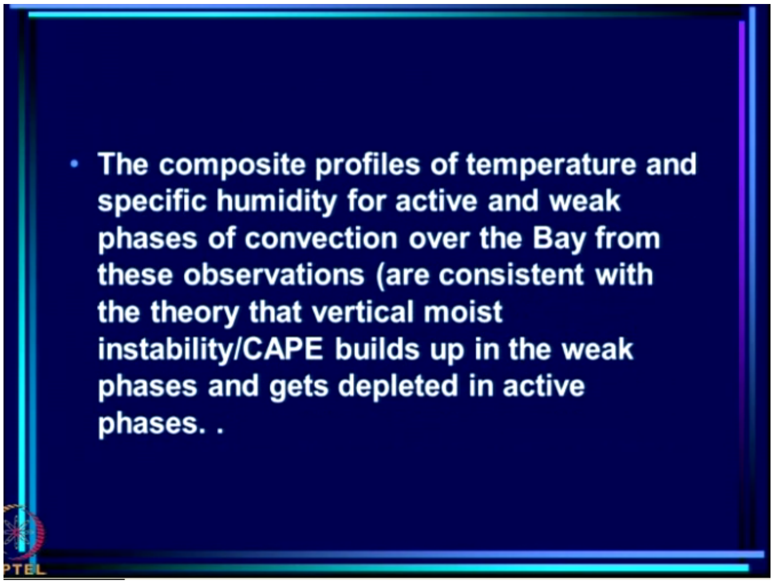

The composite profiles of temperature and specific humidity for active and weak phases of convection over the Bay from these observations are consistent with the theory that vertical moist instability builds up in the weak phases and gets depleted in active phases.

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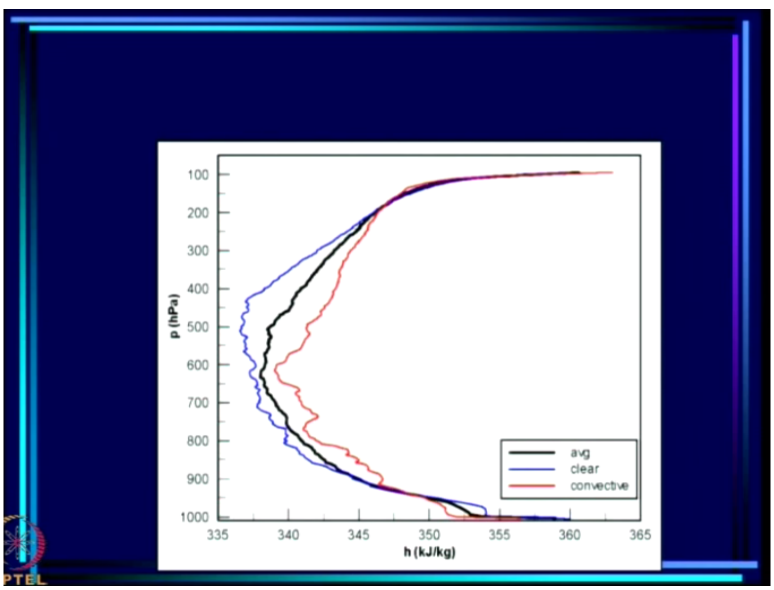

So you have here the profile over the potential temperature. You see here that this is the convective phase and this is an average and this is a clear phase. So what is happening is that once the cloud starts building up you see here warming. This is the warming of the mid troposphere that Krishnamurthy and Bhalme and others talked about and there is also cooling of the surface. So what happens is that the stability, instability decreases.

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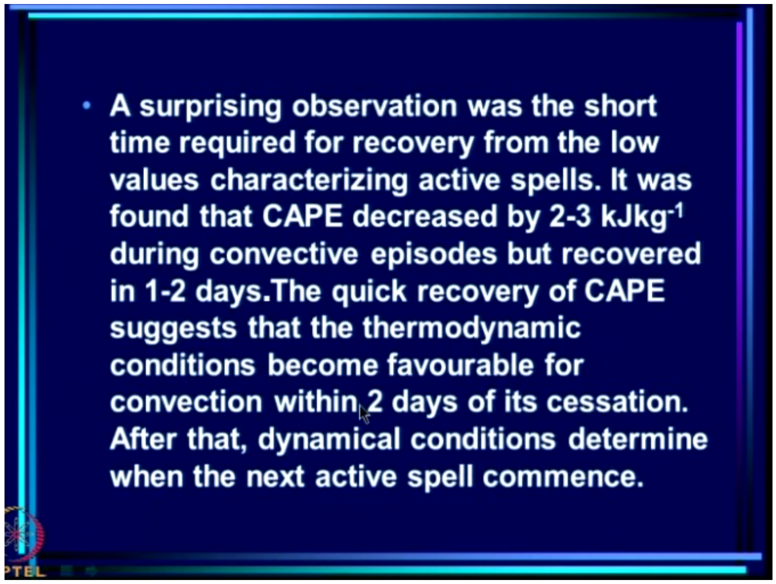

A surprising observation was short term required for recovery from low values characterizing the active spells. In fact, this was totally unexpected. It was found that CAPE decreased by 2 to 3 kilowatt Joule per kg per gram during convection convective episode, but recovered in 1 or 2 days. The quick recovery of CAPE suggests that the thermodynamic conditions become favorable for convection within 2 days of its cessation.

This is for the Bay of Bengal and may actually explain why is it that the Bay of Bengal is one of the most fertile oceans as far as genesis of cloud systems is concerned. They occur at genesis occurs at very high frequency over the Bay and this quick recovery of CAPE may have something to do with it.

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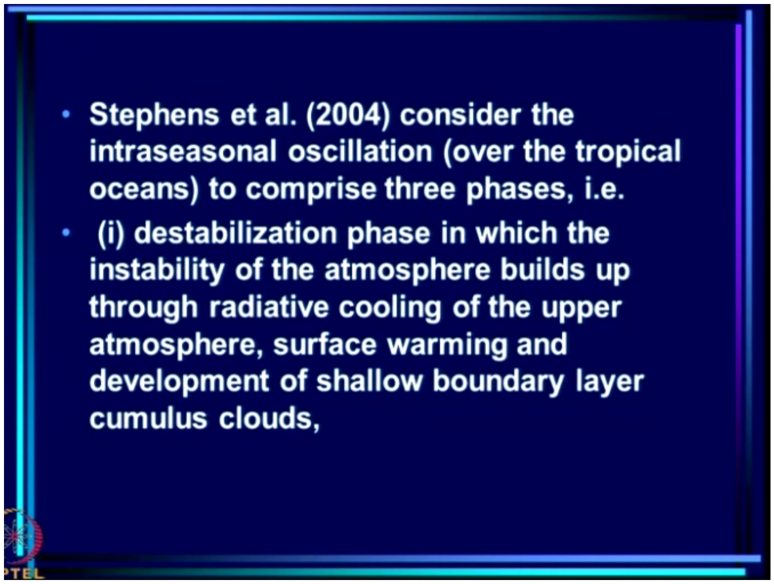

Now, this is the feedback on the vertical moist instability. Now similar theories have been proposed for the MJO which again is an oscillation which involves convective dynamic feedbacks and they consider the 3 phases occur one is the destabilization phase in which the instability of the atmosphere builds up through radiative cooling of the upper atmosphere, surface warming, and development of a shallow boundary layer cumulus clouds. So this corresponds to what we call the weak phase.

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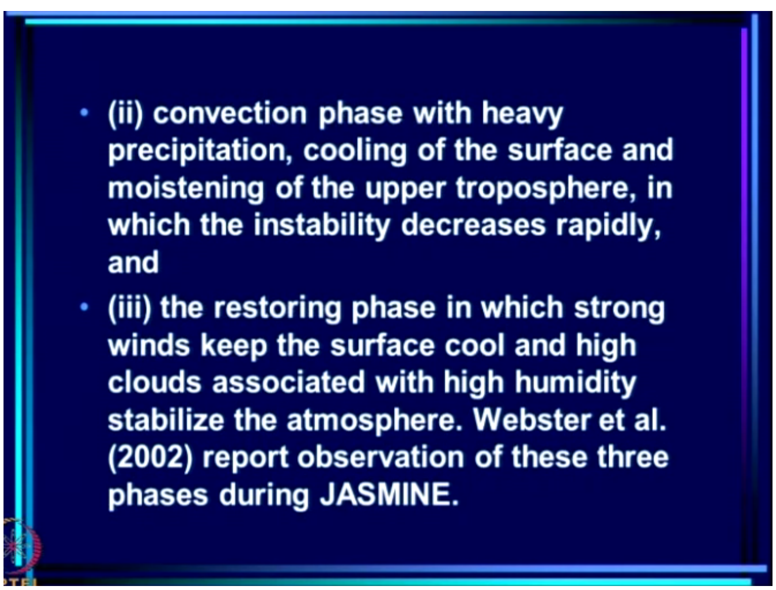

Then convective phase occurs with heavy precipitations, cooling of the surface, and moistening of the surface, of the upper troposphere in which the instability decreases rapidly and the restoring phase in which strong winds keep the surface cool and high clouds associated with high humidity stabilize the atmosphere. In fact, so you have 3 phases of this and feedbacks similar to what I discussed earlier have been proposed.

And there was another observational experiment called JASMINE and in that they reported that operated in the intraseasonal oscillation in fact involved these 3 phases; destabilization, convection, and the resorting phase.

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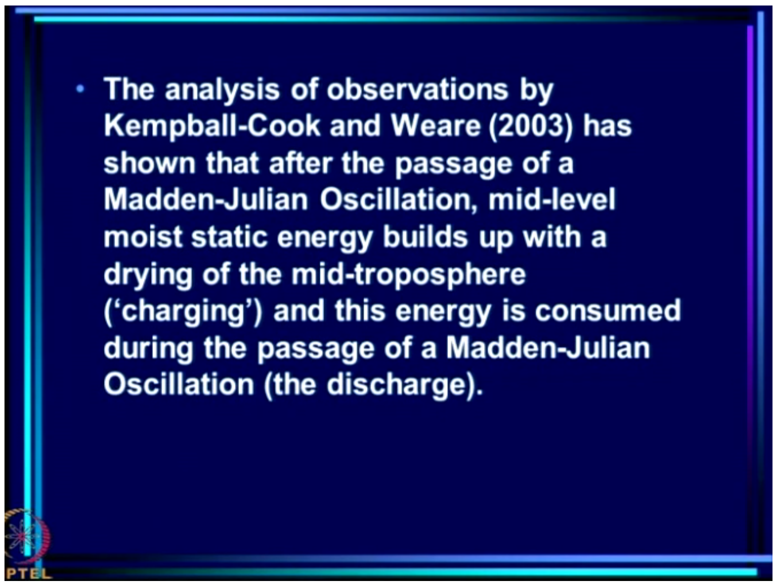

Now analysis of observations by Kempball-Cook and Weare has shown that after a passage of Madden-Julian Oscillation, mid-level moist static energy builds up with a drying of the mid-troposphere and this energy this is the charging and this energy is consumed during the passage of a Madden-Julian Oscillation. This is the discharge.

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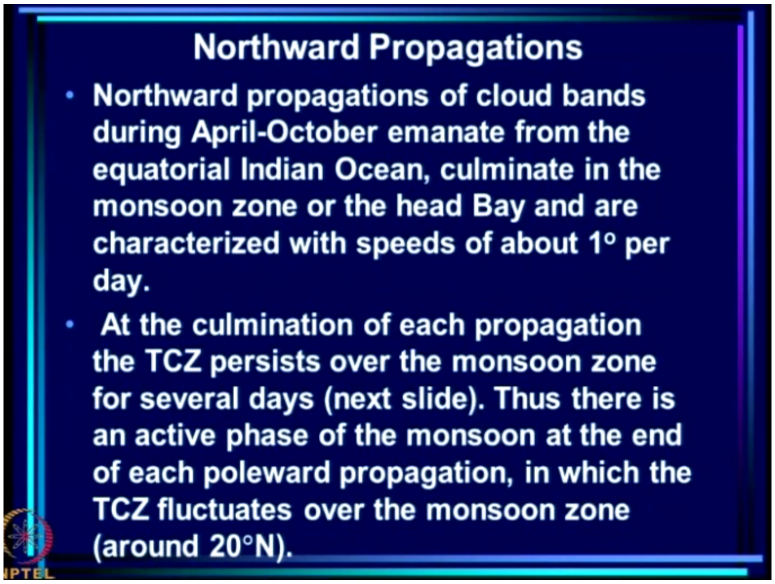

So you can see that throughout very, very similar kind of things have been proposed and details of this can be found in many studies, but whether these feedbacks help us to actually predict the fluctuations has is yet to be determined. northward propagations. So we think we know something about how the fluctuations of the tropical convergence zone occur. Northward propagations.

Northward propagations of cloud-bands during April to October emanate from the equatorial Indian Ocean culminate in the monsoon zone or the head Bay and are characterized with speeds of about 1 degree per day. At the culmination of each propagation the TCZ persists over the monsoon zone for several days.

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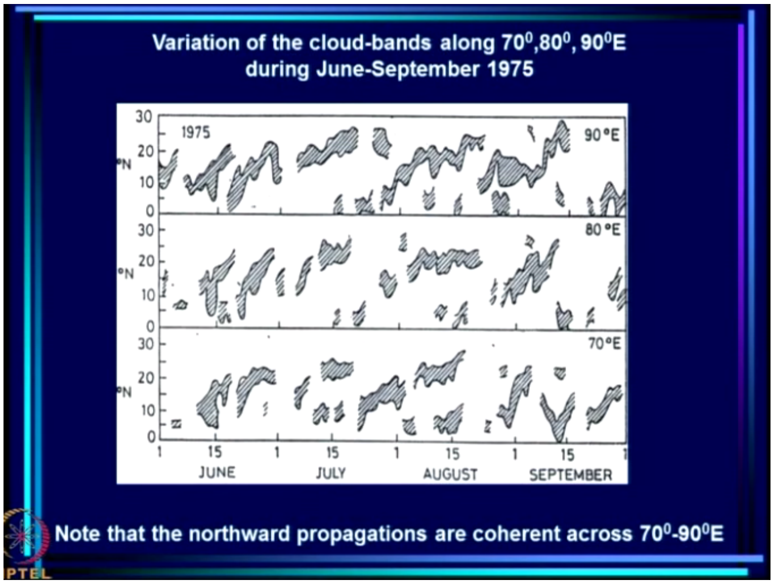

This is something we have seen that we have this is the culmination for example here. These are quick propagations. Then this is the culmination at the end of the onset phase and you can see that the TCZ fluctuates in the same place with of course some fluctuations in the intensity, but it is around the same region here. Similarly, here at the end of the northward propagation it just occurs here and similarly here and so on and so forth.

So at the culmination of each propagation the TCZ persists over the monsoon zone for several days. Thus there is an active phase of the monsoon at the end of each poleward propagation in which the TCZ fluctuates around the monsoon zone of 20 degrees north or. So you can see it fluctuates around 20 degrees north or so.

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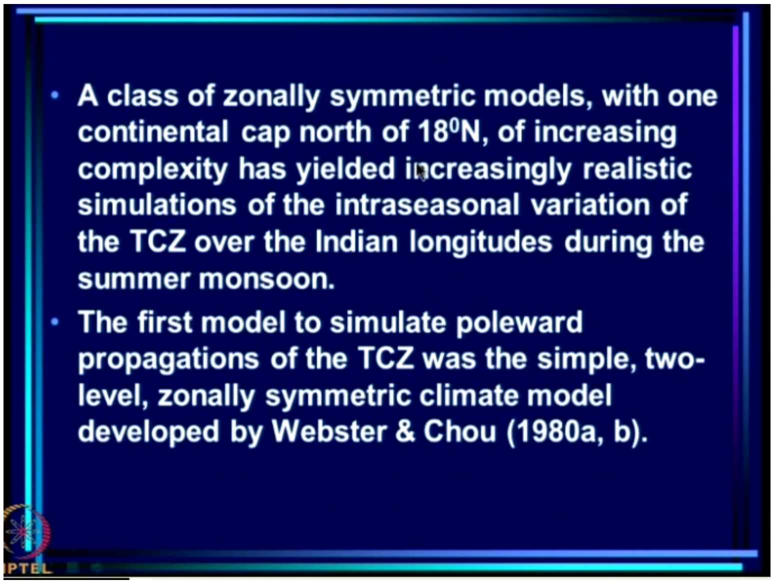

Now, this phenomenon was explained by a class of zonally symmetric models which are very, very simple models with 1 continental cap north of 18 degrees. So, zonally symmetric means it is a sphere in which there is no variation with longitude right. The atmosphere does not vary with longitude at all. It varies only with latitude and the continent is a cap north of 18 degrees north okay.

Now, but these models actually were a hierarchy with increasing complexity and they have yielded increasingly realistic simulations of the intraseasonal variation of the TCZ over the Indian longitudes during the summer monsoon. See the first model to simulate poleward propagations of the TCZ was the simple 2-level zonally symmetric model developed by Webster and Chou.

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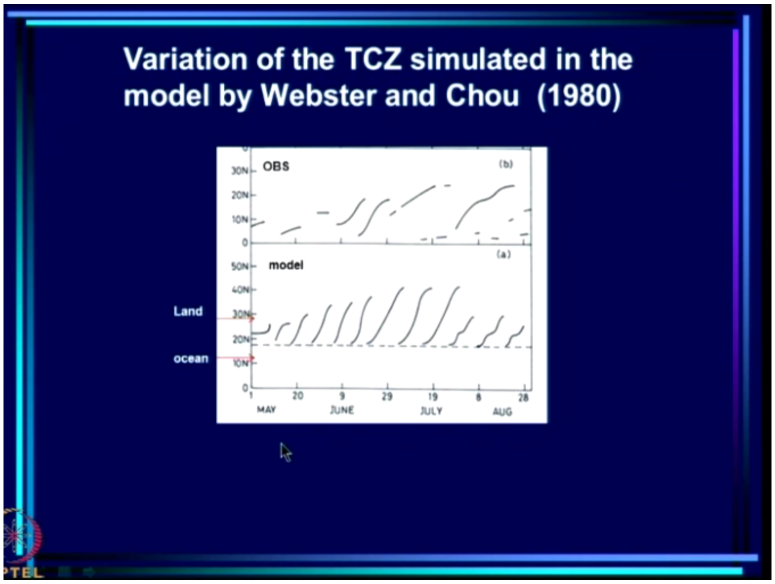

And what it did is the following. Now what we are seeing here is only the axis of the rain-belts and this is the observation for 1975 at 90 degrees east and this is what the model showed. Remember that the model has continent up to 18 degrees beyond 18 degrees north. So from the northern pole till 18 degrees is a continental cap and this is the ocean and what you can see is it generates lot of northward propagations.

In fact, fall too frequently. Secondly, while remember now southern tip of India is around 8 north so the observed propagations actually originate from the equatorial Indian ocean not from land, but in the model they all originate at the land ocean boundary and occur at very frequent intervals.

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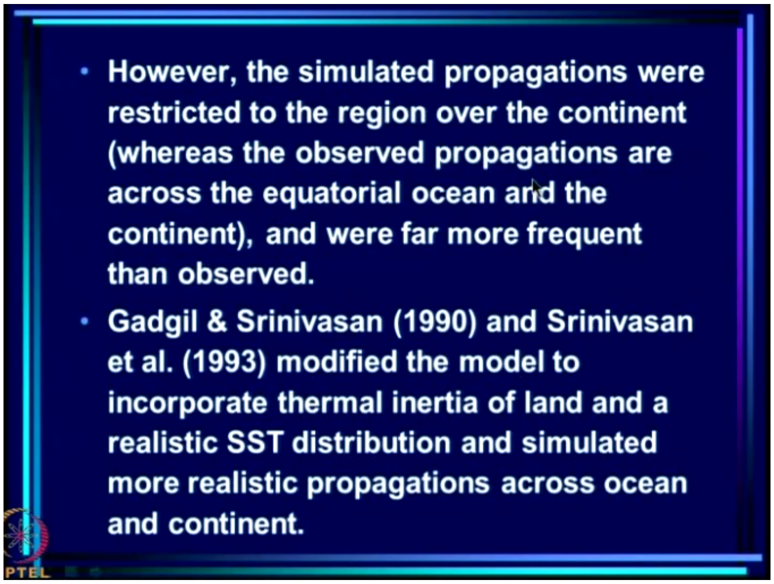

So the simulated propagations were restricted to the region over the continent whereas the observed propagations are across the equatorial ocean and the continent and were far more frequent than observed okay. So this was a problem with this model and then we started working on this and what Srinivasan released is that one has to incorporate the thermal inertia of land and which should also have a realistic SST distribution. Once these 2 were incorporated

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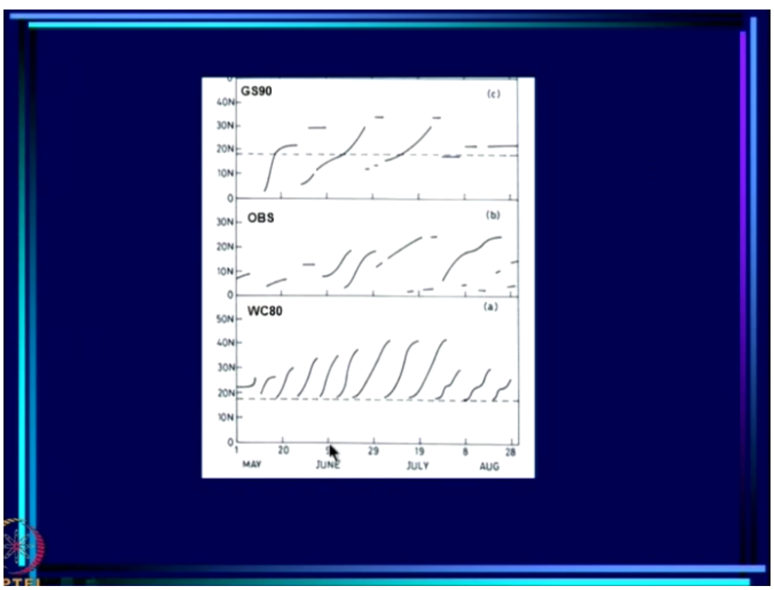

Then we got somewhat more realistic propagations. now this again is the observed one. This is the old thing with the simple model. When you incorporate thermal inertia of land then you see that the propagations have become less frequent much less frequent than these okay and you are also with realistic SST. You are also getting genesis over the ocean which also means that propagations are not restricted to land any more.

They occur over both ocean and land okay. So the next complexity in the model told as that.

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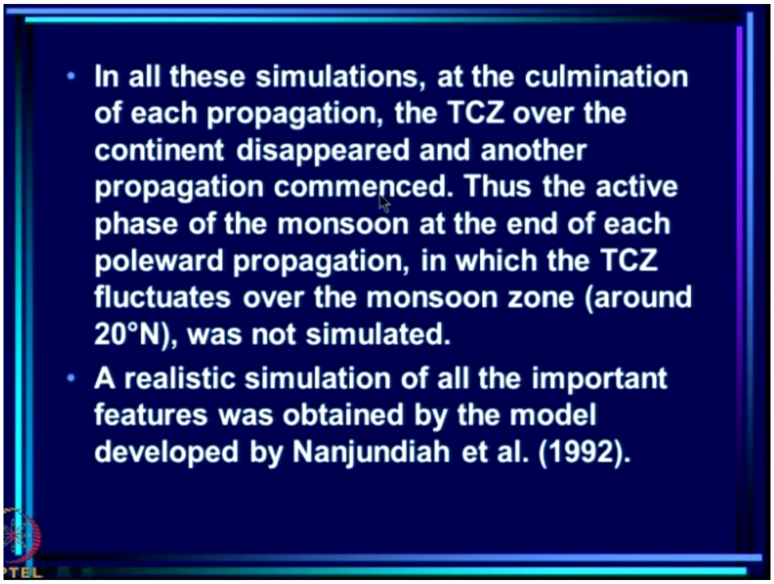

Now in all these simulations at the culmination of each propagation, the TCZ over the continent disappeared. You can see it just moves north and disappears. That is true with all these, but if you look at observations actually there is this active spell here which occurs at the culmination of northward propagation which is not simulated in any of those. Thus the active phase of the monsoon at the end of each poleward propagation in which the TCZ fluctuates over the monsoon zone around 20 northwards not simulated.

A realistic simulation of all important features was obtained by the model developed by Nanjundiah et al.

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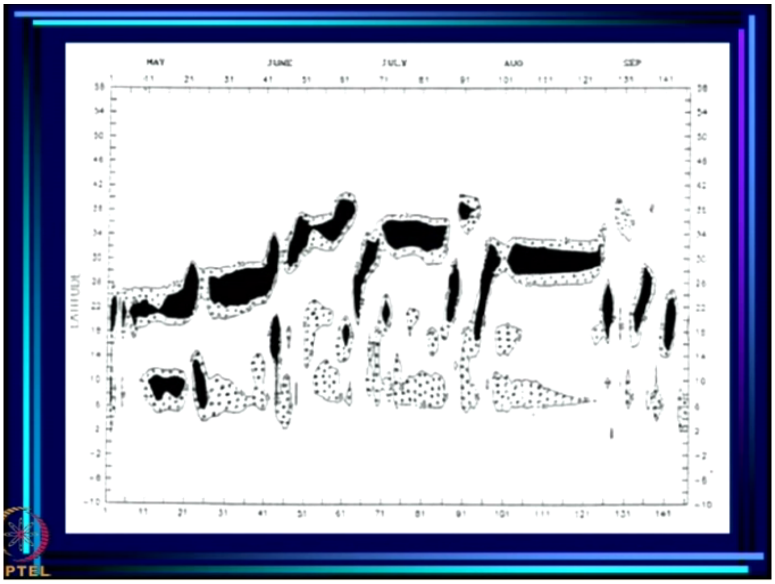

Which was more complicated and what you see here is in fact you see very clearly 2 favorable zones and you see very nice propagation and most important is at the end of the propagation there is a very clear active spell which was absent in all the earlier models.

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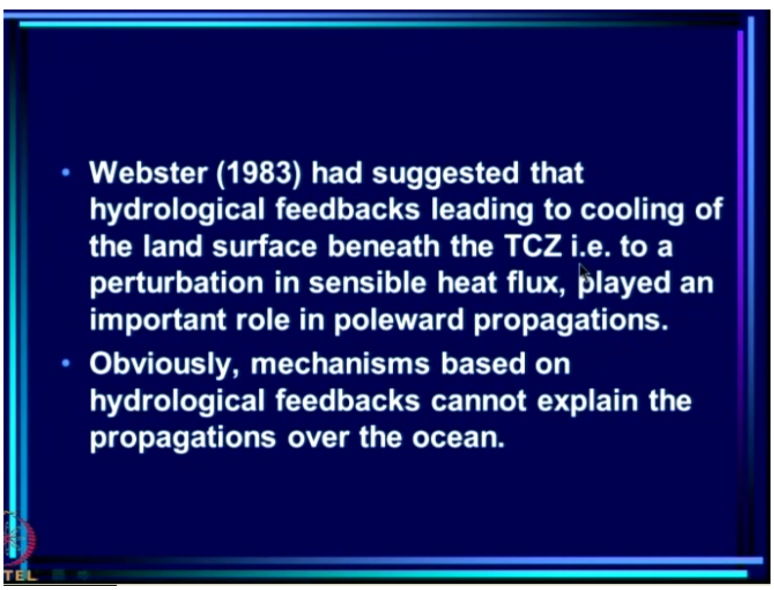

So now Webster had suggested that hydrological feedbacks leading to cooling of the land surface beneath the TCZ that is to a perturbation in the sensible heat flux, played an important role in poleward propagation. Obviously, the mechanisms based on hydrological feedbacks cannot explain propagations over the ocean. Also we did an experiment in which we switched off the sensible heat flux totally and still the propagations occur.

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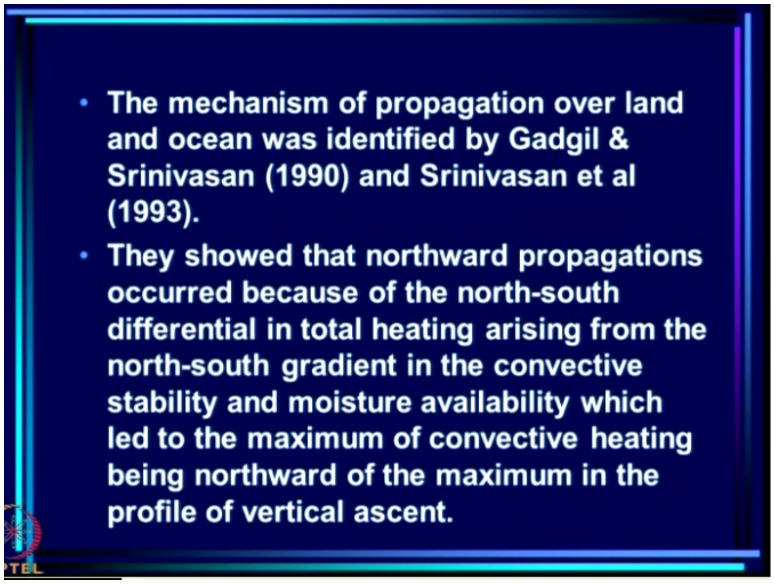

So that suggested that Webster had not got the story write. The mechanism of propagation over land and ocean was identified by Gadgil and Srinivasan and Srinivasan et al and they showed that northward propagations occurred because of the north-south differential in total heating arising from the north-south gradient in the convective stability and moisture availability which led to maximum convective heating being northward of the maximum.

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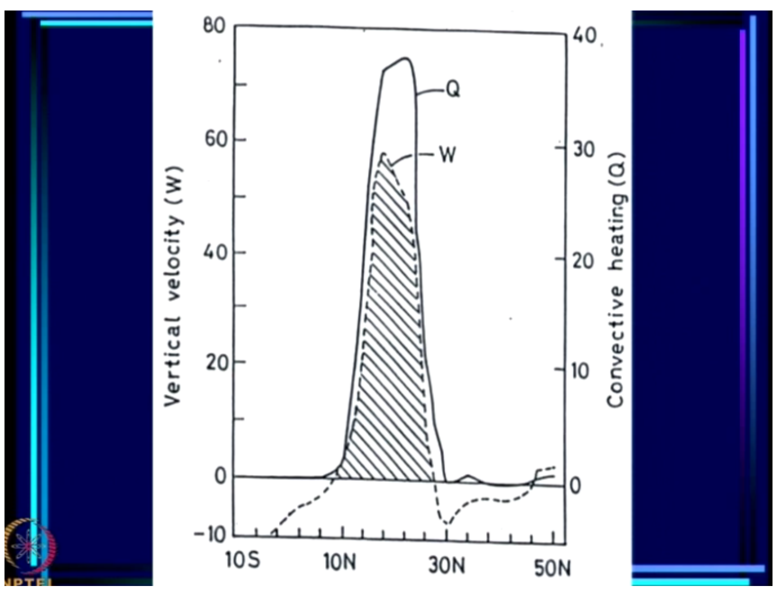

So what happens is this is W, vertical velocity and vertical velocity is maximum here, but the convective heating associated with the system is actually maximum slightly to the north of where its W is maximum where the rain is. Now if that happens then there is more heating to the north and lower pressure will occur to the north and the rain system will move to the north. So this is the mechanism of poleward propagations.

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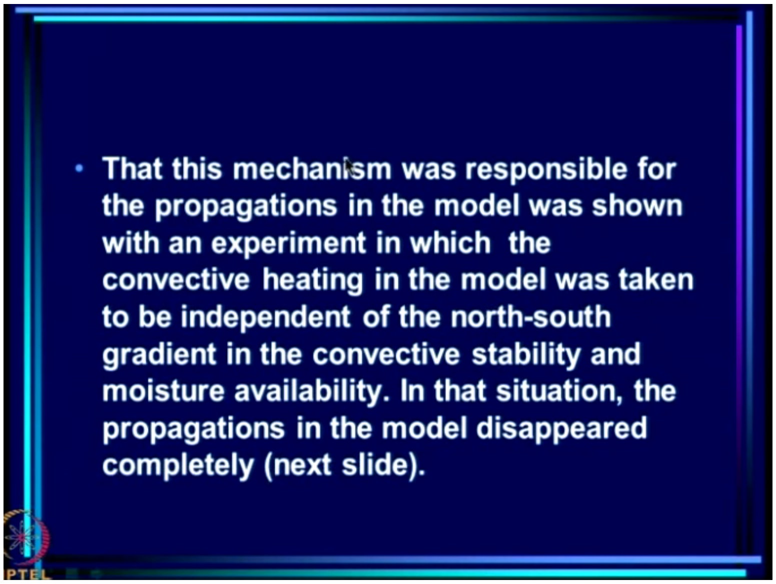

That this mechanism was responsible for the propagations in the model was shown with an experiment in which the convective heating in the model was taken to be independent of the north-south gradient in the convective stability and moisture availability. So what we do is to test whether indeed it is this gradient of instability that is responsible we change the model to say that this kind of radiant has no longer effects the convection in the model.

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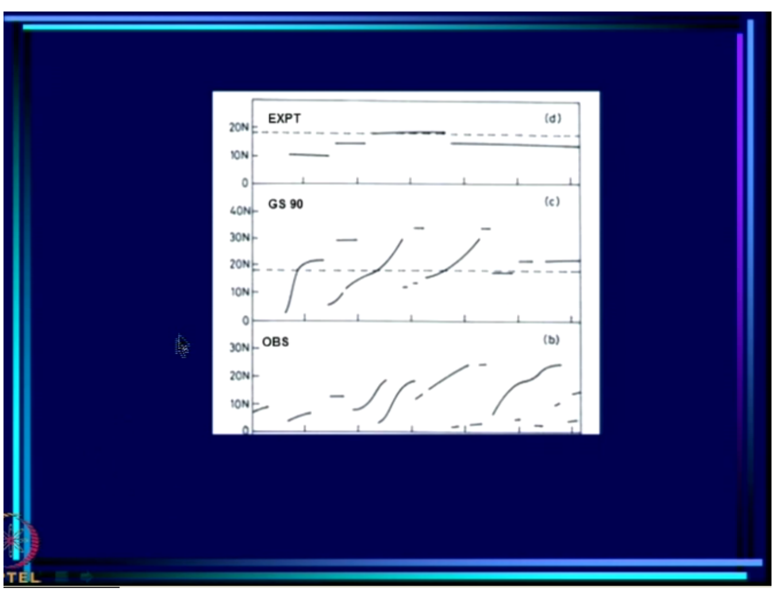

And in that experiment what you saw was that there were no propagations at all. So another this is the advantage of working with model that one can propose theories and they can be verified with model experiments.

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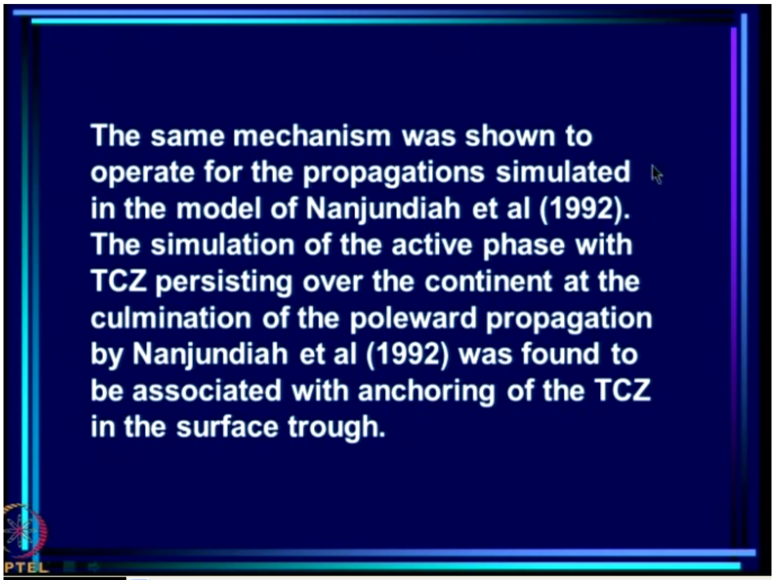

Now same mechanism was shown to operate for propagations that simulated in the model of Nanjundiah et al simulation of the active phase with the TCZ persisting over the continent at the culmination of the poleward propagation was found to be associated with anchoring of the TCZ in the surface trough which is very interesting because this is exactly what is observed.

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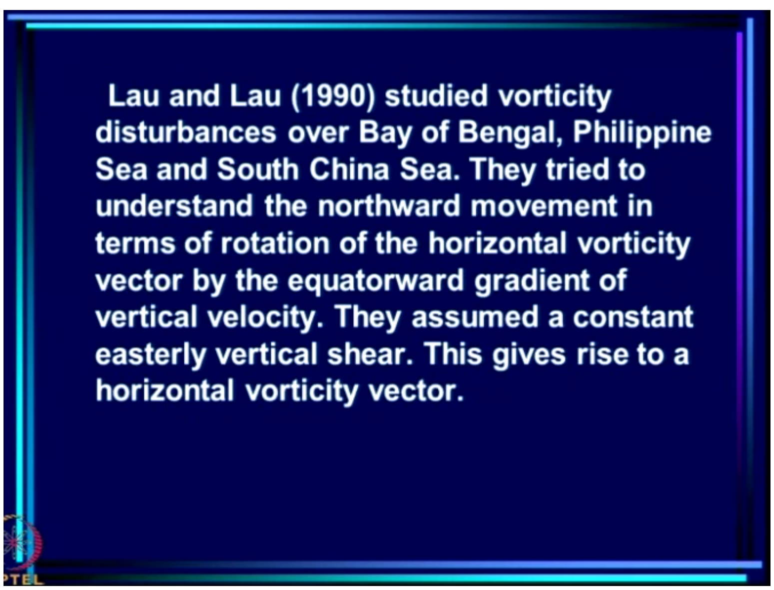

Now there are alternative theories like Lau and Lau who studied vorticity disturbances in the Bay of Bengal, Philippine sea and South China sea and they tried to understand northward movement in terms of rotation of the horizontal vorticity vector by the equatorward gradient of vertical velocity and I do not want to get into detail of this.

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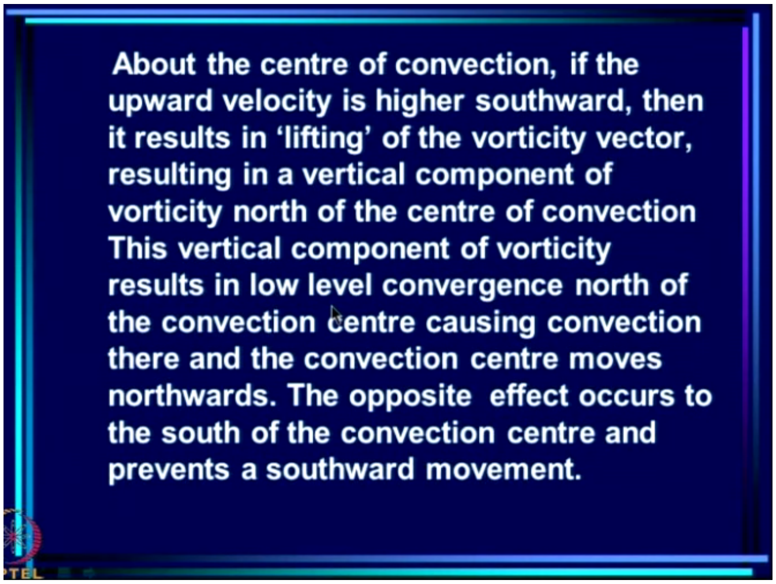

People who are interested can look at the paper, but they basically say that about the center of convection if the upward velocity is higher southward then it results in lifting of the vorticity vector which results in vertical component of vorticity not of the center of convection and this results in low level convergence to the north. So this is another mechanism by which you could get convergence to the north of the rain-belt where the rain-belt has to move.

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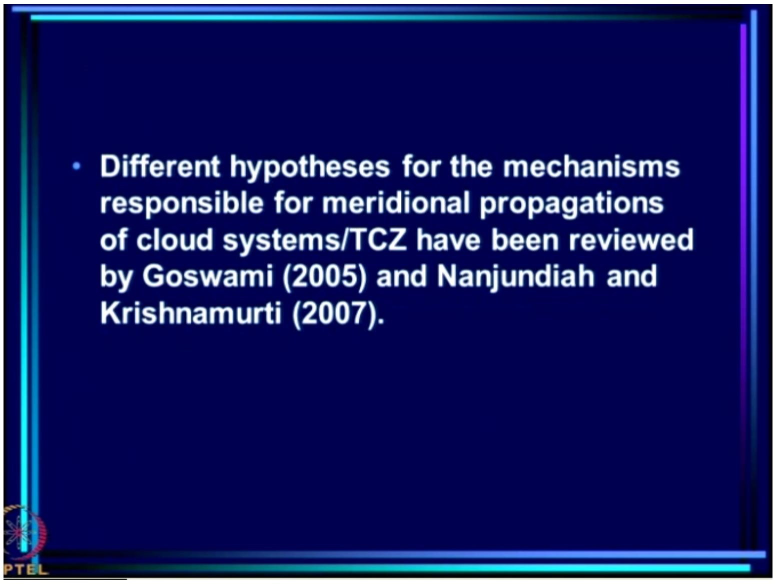

In face different hypotheses for mechanisms responsible for meridional propagations have been reviewed in these 2 papers.

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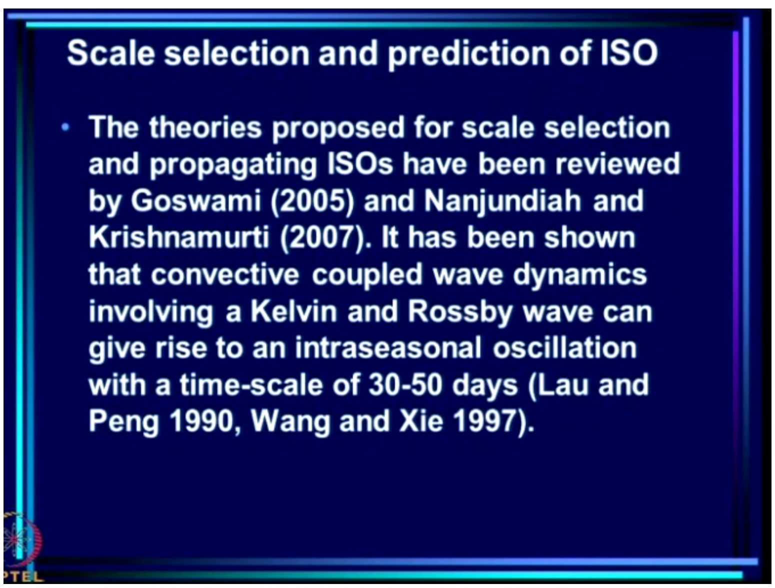

Now there are also studied on scale selection and prediction of intraseaonal oscillations. Again this is something that we are not equipped to go into in this lecture series because we have not discussed in detail about Kelvin wave and Rossby waves and so on, but there are major review papers for people who are interested.

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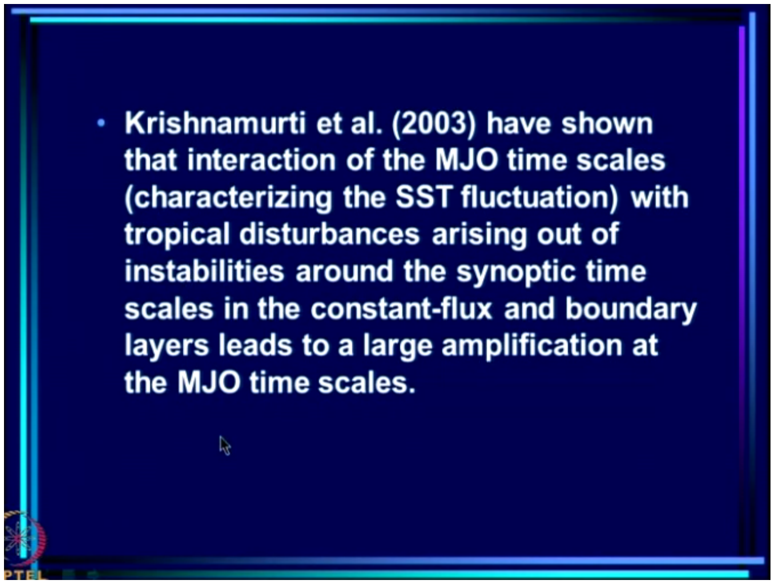

I should also mention that Krishnamurti et al have shown that interaction of the MJO time scales characterizing the SST fluctuation with tropical disturbances arising out of instabilities around the synoptic time scales in the constant-flux and boundary layers leads to a large amplification at the MJO time scales. So this is an interesting idea of scale interaction how synoptic scale systems can have given intensification of the MJO time scale.

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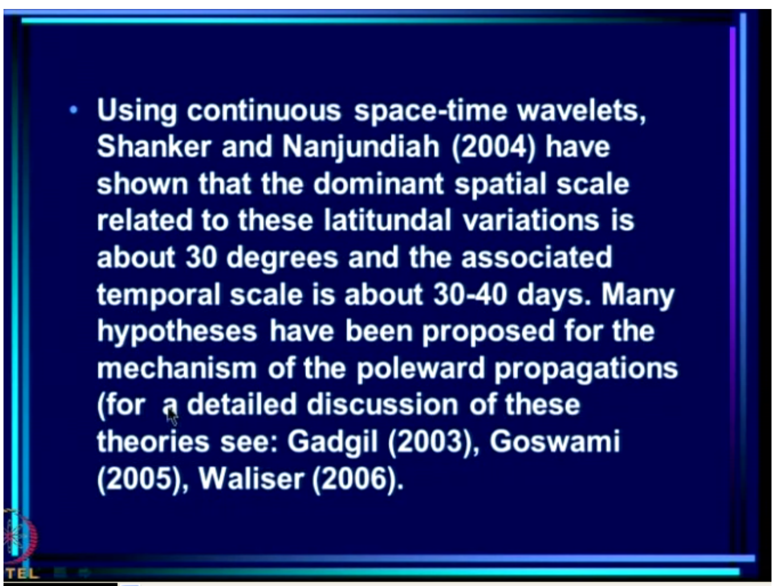

And using continuous space-time wavelets Shanker and Nanjundiah have shown that the dominant spatial scale related to these latitudinal variations is about 30 degrees and the associated temporal scale is 30 to 40 days. So many hypotheses have been proposed for these propagations.

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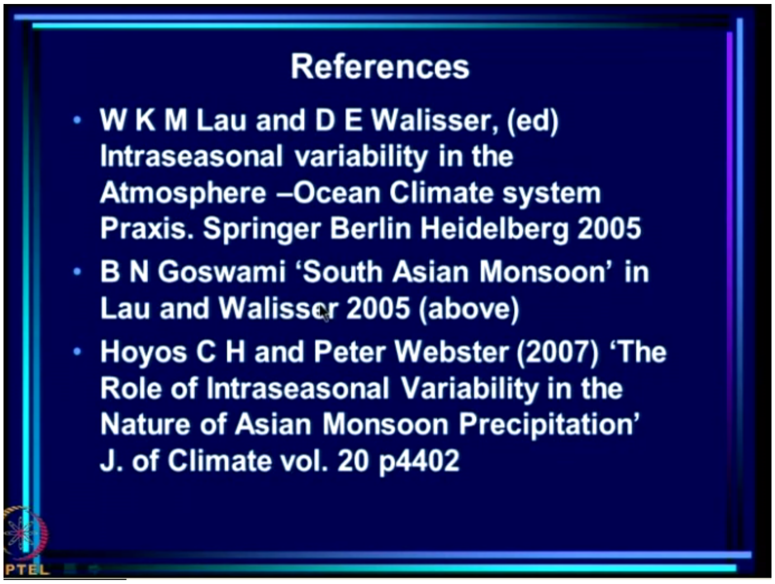

And they are all discussed in various details. So what I have tried to do here is to give you a flavor for the kind of processes that may be important in the 2 major features that we saw of intraseasonal variation over the Indian region active weak spell fluctuations and northward propagations. Thank you.

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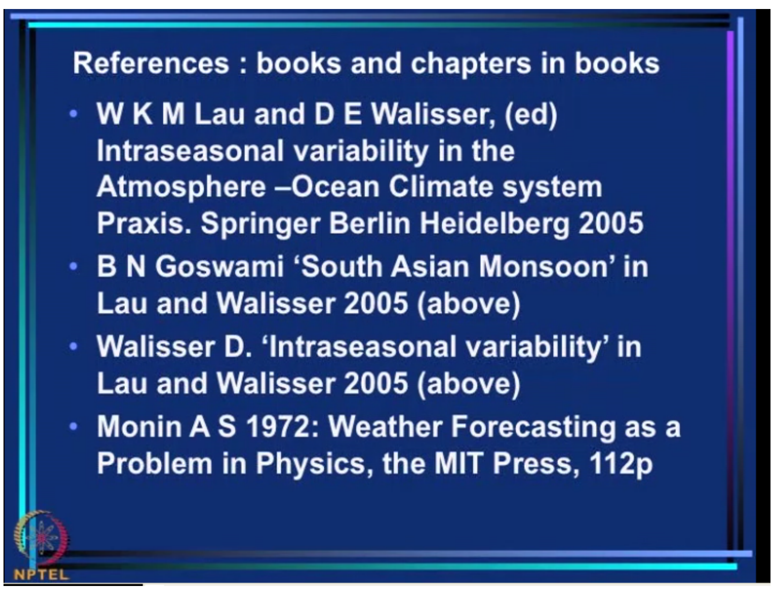

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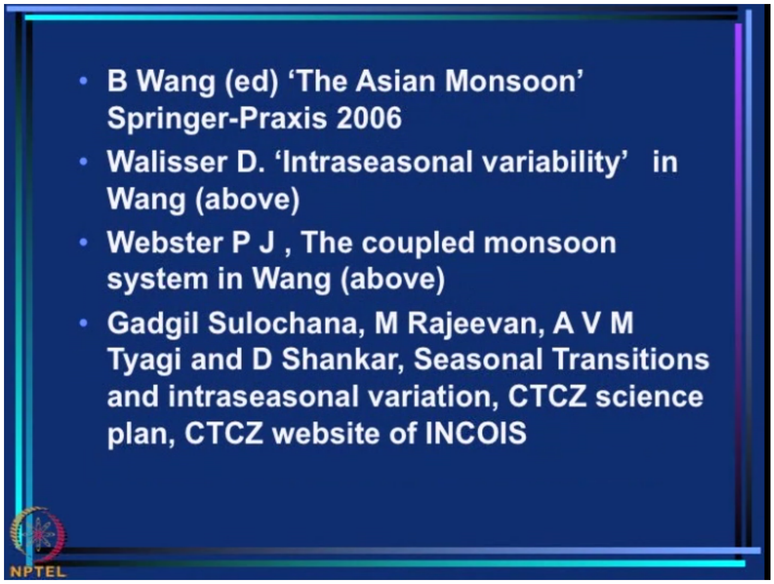

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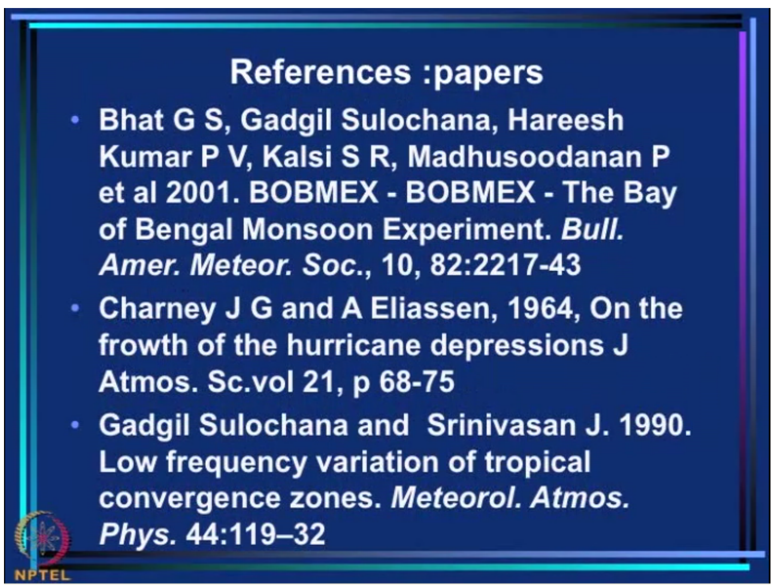

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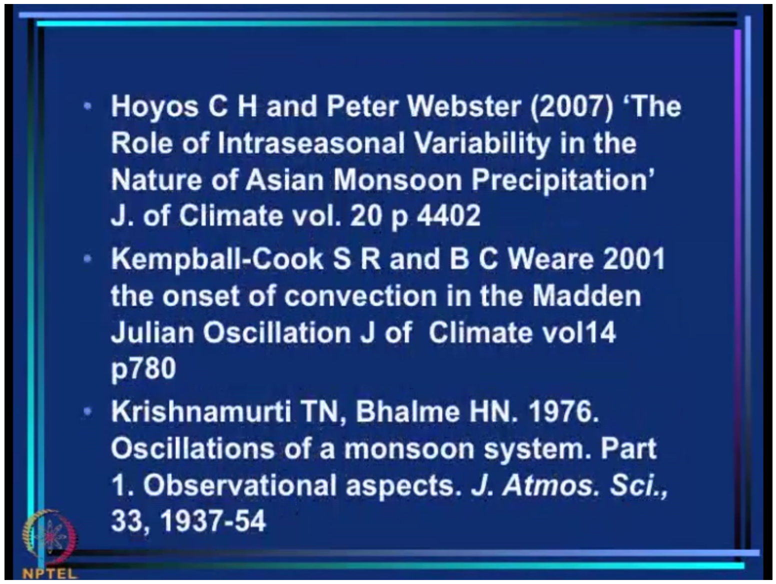

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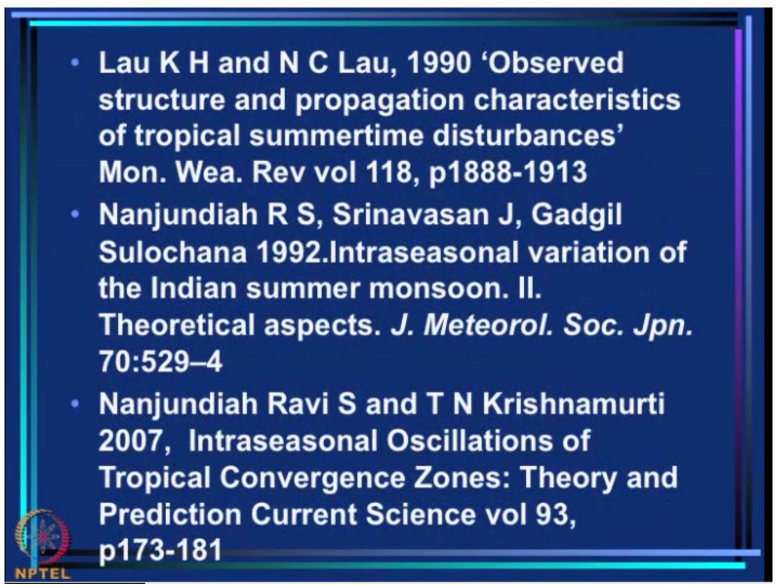

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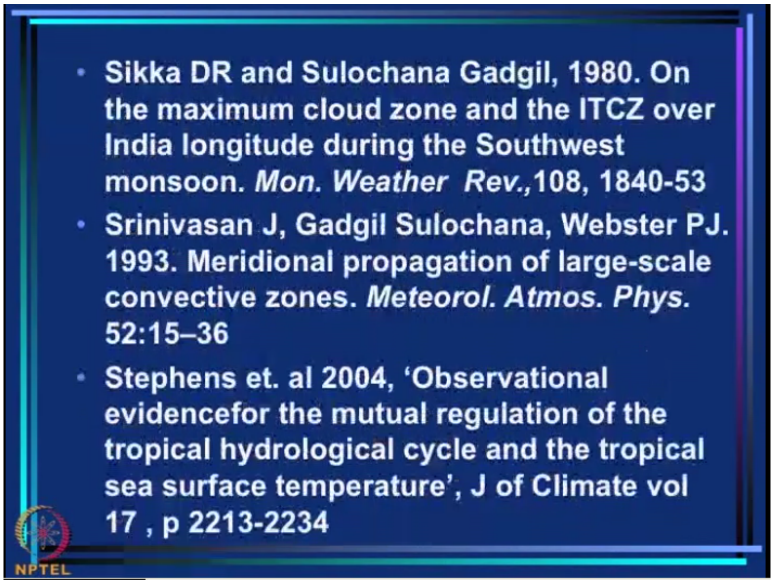

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