The Monsoon and Its Variability
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Lecture – 14
Heat Lows and the TCZ

So, today we are going to talk about heat lows. These are systems that are typical of the Sahara Desert or Rajasthan desert and so on and the TCZ and the interrelationship and as you know TCZ is responsible for most of the large-scale rainfall in the tropics.

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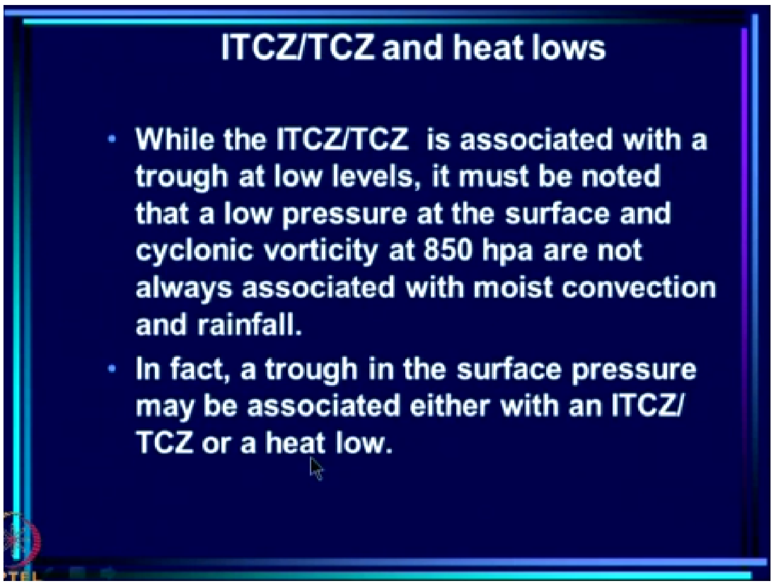

Now, while the ITCZ or TCZ is associated with a trough at low levels, it must be noted that a lot of pressure at the surface and cyclonic vorticity at 850 HPA are not always associated with moist convection and rainfall. So, having a cyclonic vorticity at 850 millibar particularly are necessary conditions but are not sufficient condition. In fact, a trough in the surface pressure may be associated either with an ITCZ or TCZ which is moist convective system giving rain or a heat low.

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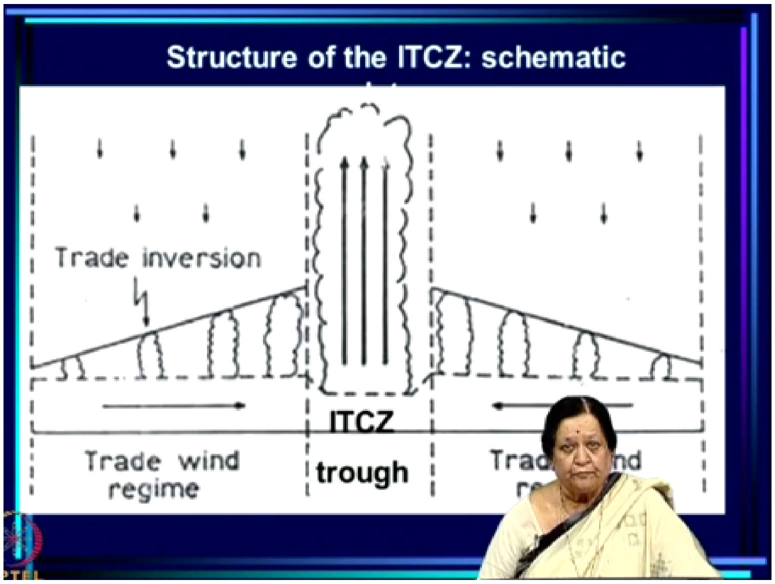

Now, see this our schematic of the ITCZ which we have seen earlier and we imagine that the ascending limb of the Hadley cell which is the inter-tropical convergence zone, convergence coming from 2 hemispheres actually is located over the tough region. This is how we had visualised the ITCZ; and then, there is of course ascent throughout the troposphere and moist convection and rainfall.

Now, what we are saying is that a trough may be associated with the ITCZ as we see but may not can be associated with an ITCZ. It may not be associated with a deep circulation of the kind you see here where air is arising above the trough right up to the top of the troposphere and sinking in the surrounding regions. See this kind of deep circulation may not always characterise a tough. In fact, it may be heat trough.

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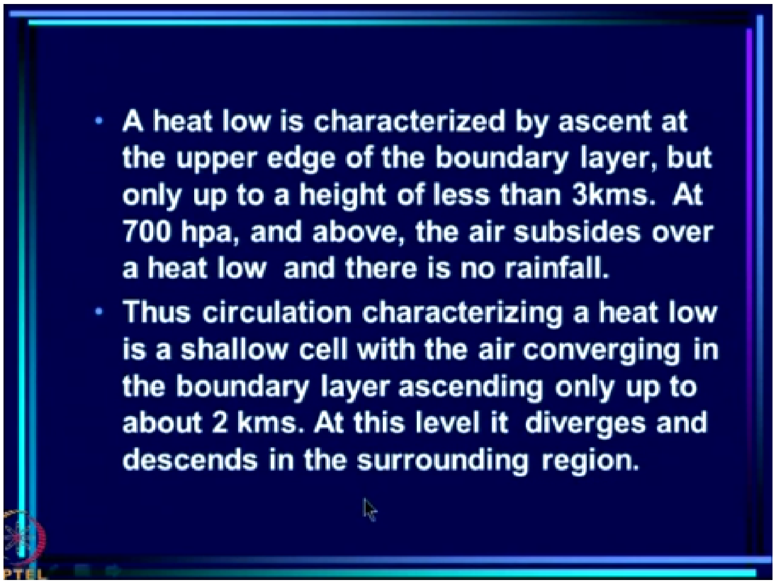

Now, what is the difference between the TCZ and heat low. A heat low is characterised by ascend at the upper edge of the boundary layer, just like the ITCZ or TCZ but only up to a height of < 3 km, i.e., to say at 700 HPA and above the air subsides over heat low and there is no rainfall. So, the ascent is restricted to the lower 2 km or so, ascent of air which is arising in the tough region and there is no rainfall.

Thus, the circulation characterising a heat low is a very shallow cell with the air converging in the boundary layer ascending only up to about 2 km. At this level, it diverges and sinks in the surrounding region, okay.

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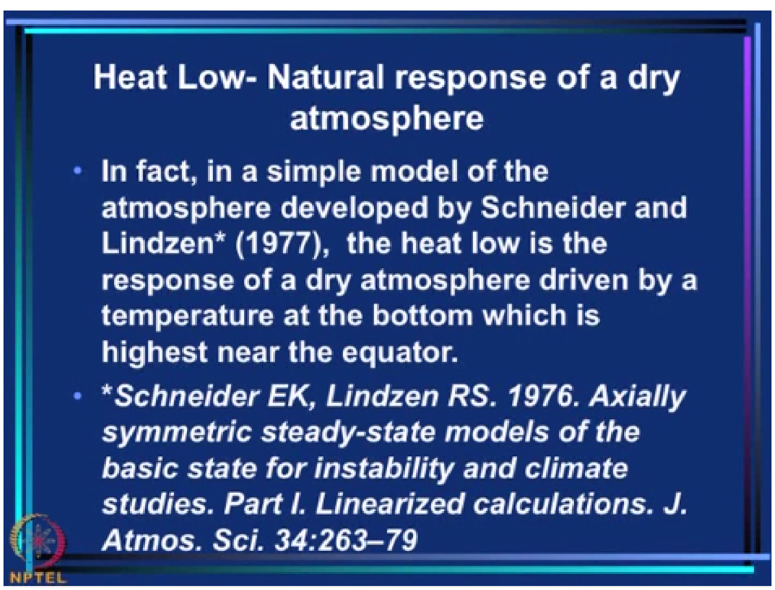

In fact, it turns out that if we look at a simple model of the atmosphere which is heated from below by specifying a temperature condition for which the temperature is maximum at the equator and decreases on either side towards the poles, then the solution that one gets is very much like a heat low.

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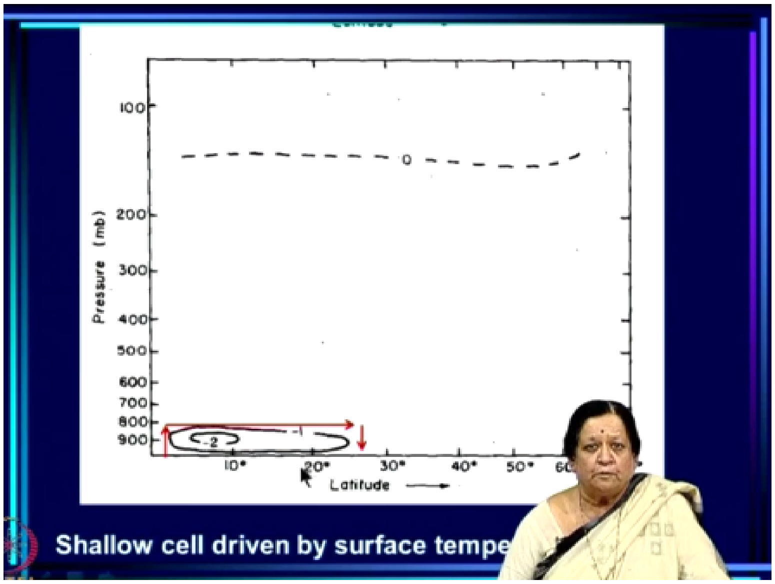

This is from a model by Schneider and Lindzen and it is interesting to see that this is for realistic profiles of temperature and so on variation with high but for a dry atmosphere. Now, this is very important. For a dry atmosphere, if you have heating from below or a temperature specified such that its maximum here and decreases with latitude, the response is yes, you do get ascent over the region where the temperature is maximum but it does not rise to beyond 2 km, only 800 HPA or millibar and then it actually spreads, diverges and then sinks.

So, the cell is very shallow as opposed to the cell earlier which was very deep you see. This cell is very deep because you have ascent throughout the troposphere and then you have divergence in the upper troposphere and sinking. As oppose to that, the cell when gets as a heat low is a very, very shallow cell driven by surface temperature gradient.

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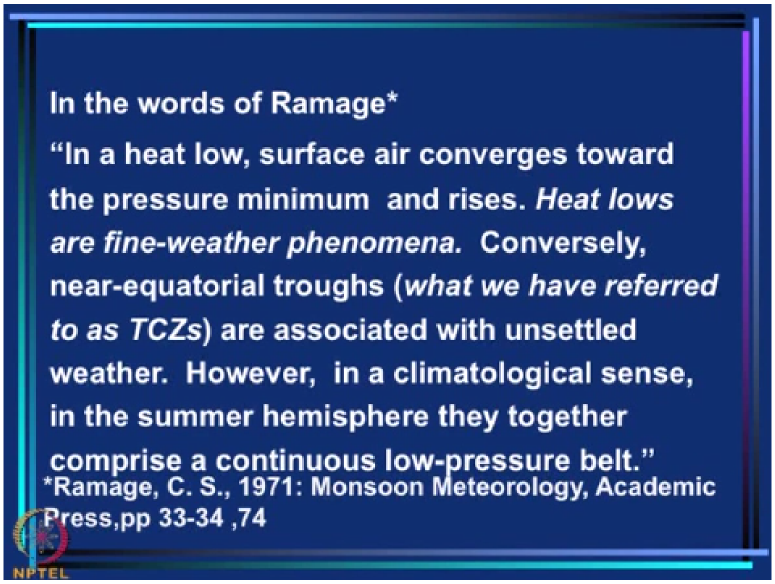

Now, Ramage talks about a heat low as follows. In a heat low, surface air convergence towards the pressure minimum the trough and rises. Heat lows are fine weather phenomena conversely near equatorial trough which is what we have referred to as TCZs are associated with unsettled weather. Unsettled weather the Englishman uses for rain. However, in a climatological sense in the summer hemisphere, they together comprise a continuous low-pressure belt.

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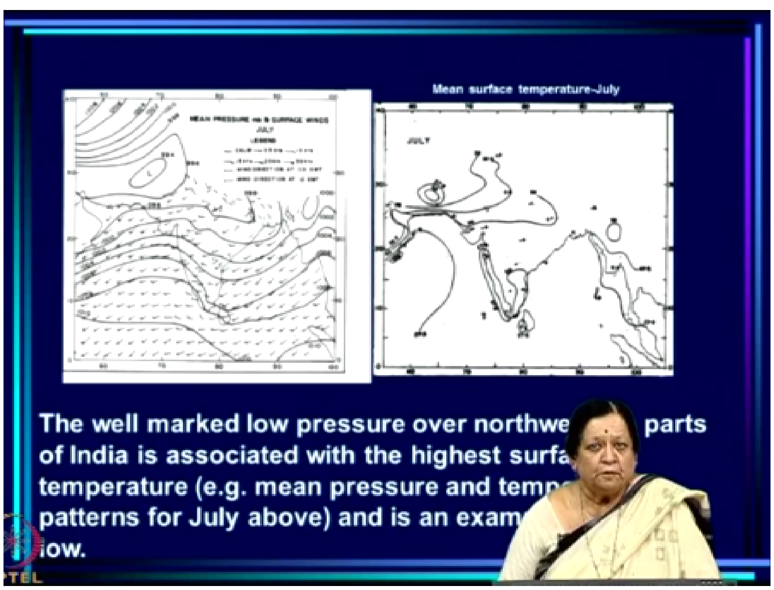

Now, let us see an example of this. This is something you have seen before. This is the mean pressure and wind for July and what you see is that the minimum pressure occurs here over the north-western parts of India, this is the minimum pressure and this is the monsoon trough with the pressure minimum going all the way from here and dipping into the bay here. Now, this is the mean surface temperature and that is very high over here.

It is maximum here and the temperature also decreases. So, this low pressure is associated with the highest temperature here. So, the well-marked low-pressure over north-western parts of India is associated with the highest surface temperature. Example, mean pressure and temperature patterns for July above and is an example of a heat low. So, this is a heat low, the temperature is very high and there is a low-pressure region here.

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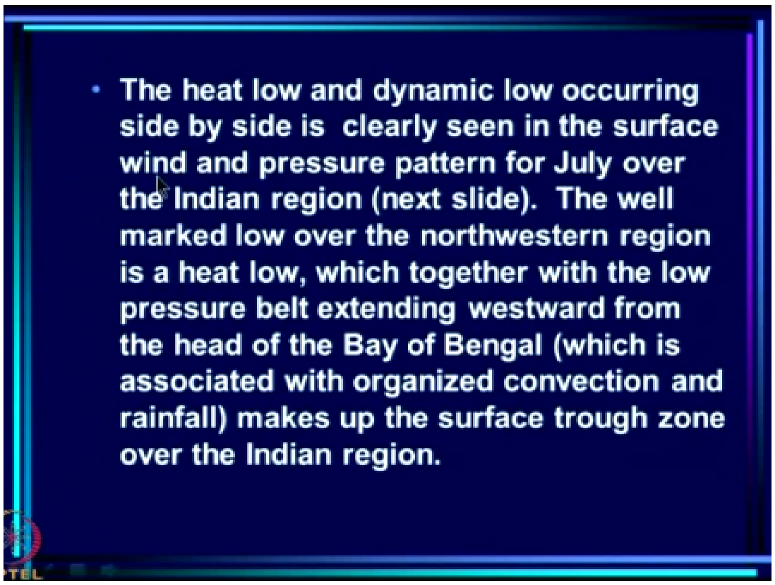

Now, Ramage said that often heat low and dynamic low occur side by side.

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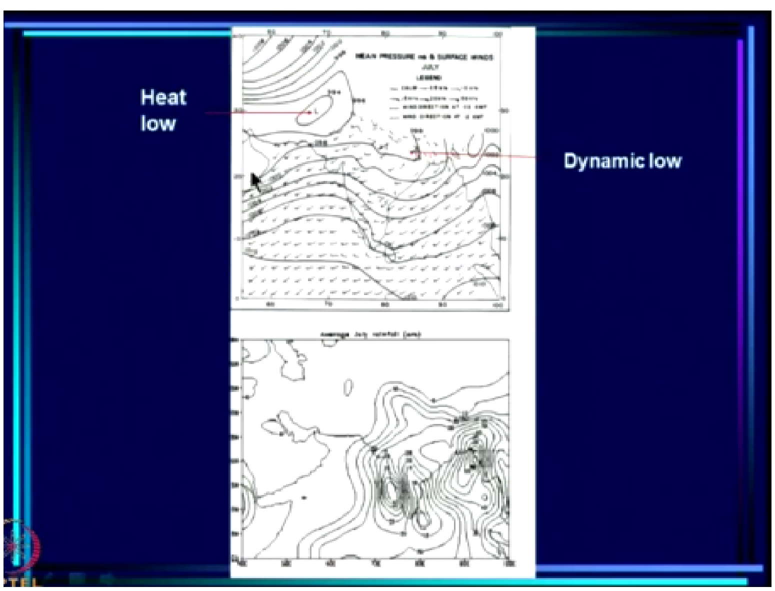

Now, this you see here. If you see the entire surface pattern of pressure pattern and winds, then this is a heat low but this is a trough also. This is also where the pressure is minimum and this is what we call a dynamic low in contradistinction to a heat low and you see here this in the average rainfall now for the same month and you see there is no rain over the heat low region here. There is hardly any rain here.

Most of the rain occurs in the monsoon zone on this side, the large-scale monsoon rainfall and that is associated with this dynamic low. So, there are 2 kinds of systems associated with the low-pressure region; one is a heat low and one is a dynamic low, okay. So, we have now seen that the heat low and dynamic low occurring side by side is clearly seen on the surface when pressure pattern here.

You can see here they are lying side by side. This is the dynamic low and this is the heat low. This is what Ramage had described and the clever the well-marked low over the north-western region is a heat low which together with the low-pressure belt extending westward from the head of the Bay of Bengal which is associated with organised convection and rainfall makes up the surface trough zone over the Indian region.

So, this is the surface trough zone over the Indian region going all the way from here to here, part of it is dynamic low and lying side by side is the heat low. This is what Ramage meant.

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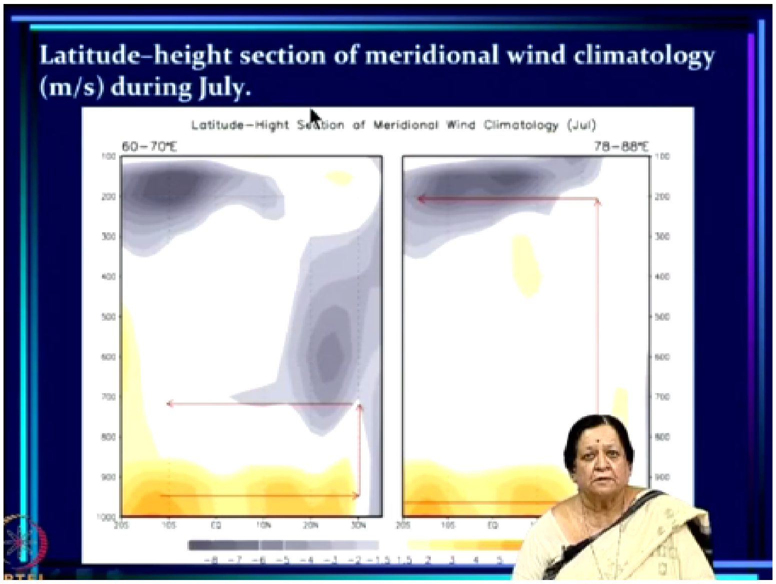

Now, you can actually see that also in the latitude height section of the meridional north-south wind climatology for July and what you see here is 60 degrees East to 70 degrees East average. You can see right here now this is 70 degrees and this is 60 degrees. So, 60 to 70 average is around this region here, okay. This other one is 78 to 88. So, that is just around here 78 to 88. This 10-degree belt here. So, this is representative of a dynamic low, this is of the heat low.

So, this is the heat low what we had said and see what is happening. Now, yellow means the flow of the wind is northward and grey means it is southward and white it is not really high-speed, it is within 1.5 meter per second. So, what you see here is northward flow up to the monsoon trough, up to almost the foothills of the Himalayas going upward here and returning here. So, this is a very shallow cell which is lower than 700 millibar, okay.

One the other hand, if you go to the dynamic low, you see that there is northward flow here and the southward flow begins only at a very high level above 300 millibar. So, you have a very deep cell here. This is the dynamic low which is the deep cell like a TCZ and this is the heat low which is the shallow cell. Now, this is for July climatology mind you, but this dynamic low can actually disappear and get converted to a heat low during intense dry spells right in the middle of the monsoon.

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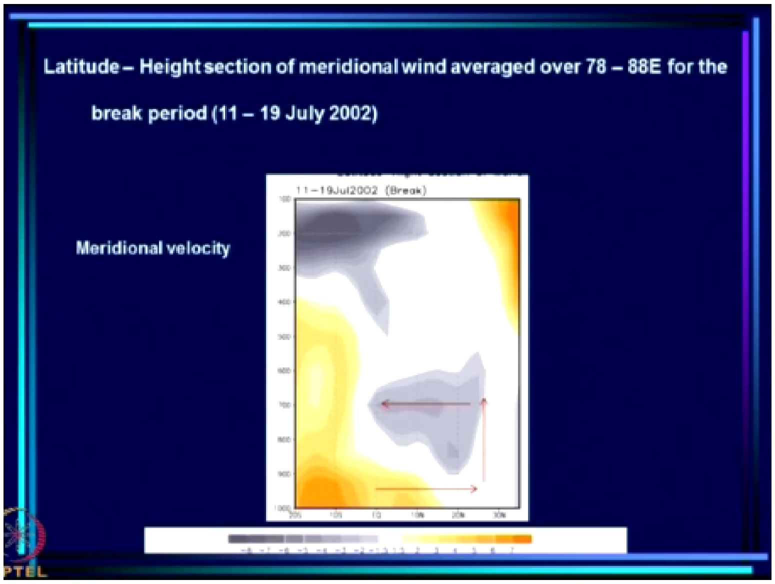

These are called breaks of the monsoon and in this break let us see what happened. This is the same thing 78 to 88 East, the same thing that we had seen before but now you see what has happened. What you have got is a heat low kind of a structure with southward flow right from about 2 km or so. So, you have a very shallow cell generated over a region which was a dynamic low.

And one of the challenging problems in monsoon meteorology is to understand how the transition from a heat low to dynamic low occurs and how the reverse transition from a dynamic low to heat low occurs. Now, this happens within a season when you have transition from break to active you will get conversion of heat low to the dynamic low that you saw earlier and active to break implies convergence from dynamic low to heat low of this kind. A very similar thing occurs in the onset phase of the monsoon as we shall see.

We have seen that in April-May, there is a heat low over the subcontinent and by July the dynamic low gets established that is what we call the CTCZ and that establishment is also a conversion of heat low to dynamic low. So, this transition between these 2 phases is extremely important to understand what are the factors that lead to it, may understand the transitions and can be actually model them and predict them. This is actually an outstanding problem in monsoon metrology today.

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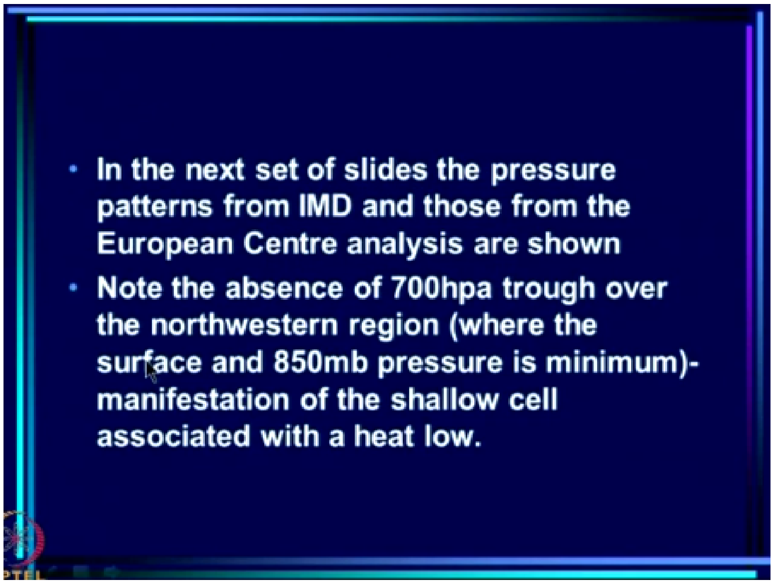

Now, in the next set of slides the pressure patterns from IMD and those from the European Centre Analysis are shown and we will have to see what a heat low is by looking at absence of 700 millibar trough over the heat low, okay which shows that the thing is shallow.

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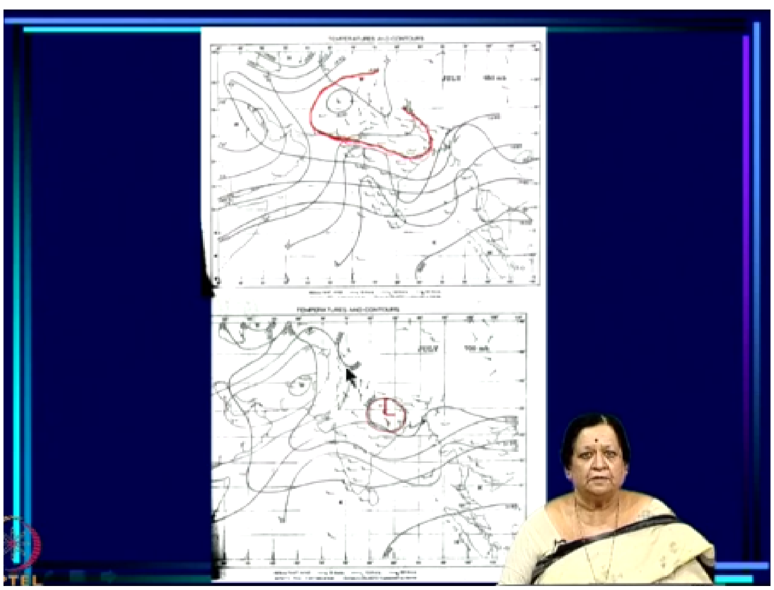

Now, what you see on top here is 850 millibar, that is 1.5 km above the sea level and what you have is a nice trough region here with minimum pressure here still just where the surface low was. So, this is at 1.5 km, you still have a very clear-cut trough zone over the region which extends all the way across the monsoon trough, but if you go to 700 millibar what you find is that the low-pressure region is constrained to the eastern part here.

So, this is low but this is not low. So, this low has not extended to 3 km. This is suggesting that the cell is indeed shallow.

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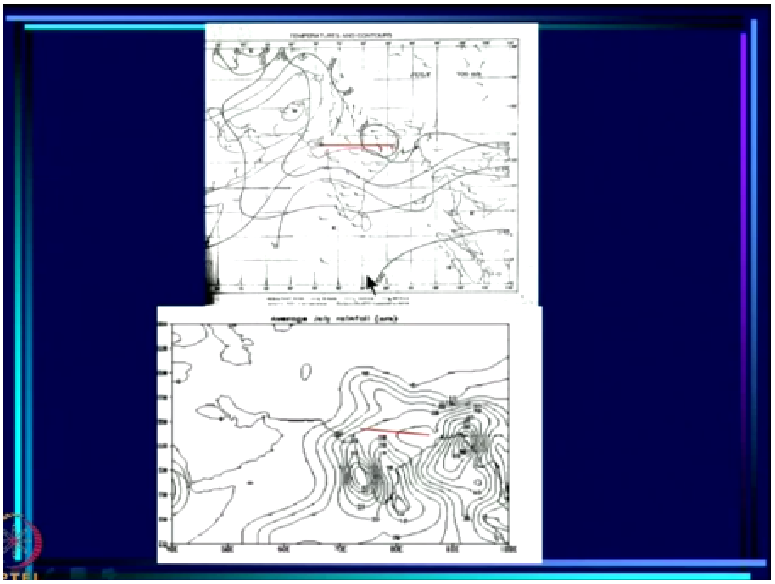

You can see here that if you look at the July rainfall here July 700 millibar, then July 700 millibar trough axis actually coincides with the axis of the non-ornographic rain. See, this we call ornographic rain because Western Ghats have contributed to it. The large-scale non-orographic rainfall axis actually coincides with the 700 millibar trough axis, okay and notice that here it is to the south of what the surface low was.

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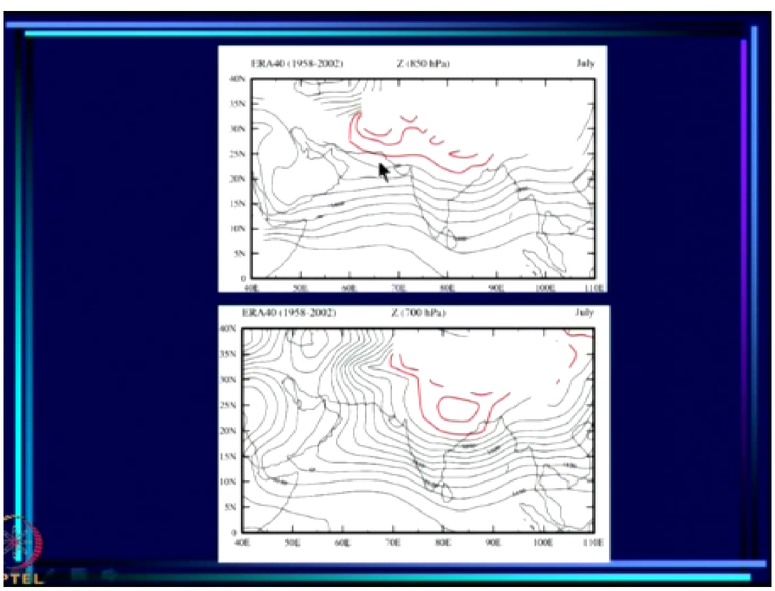

Now, let us see this is from the European Centre Analysis and this is at 850 again for July and what you see on top is for 850 HPA and this is the low-pressure region here. We have cut out the Himalayas because they are above the level we are looking at. Then, this is 700 millibar. You see now the trough zone is restricted to this part of India and the heat low does not form a part of the trough at all. So, it is very clear that the low-pressure associated with a heat low does not extend to 3 km or so, it is all below that.

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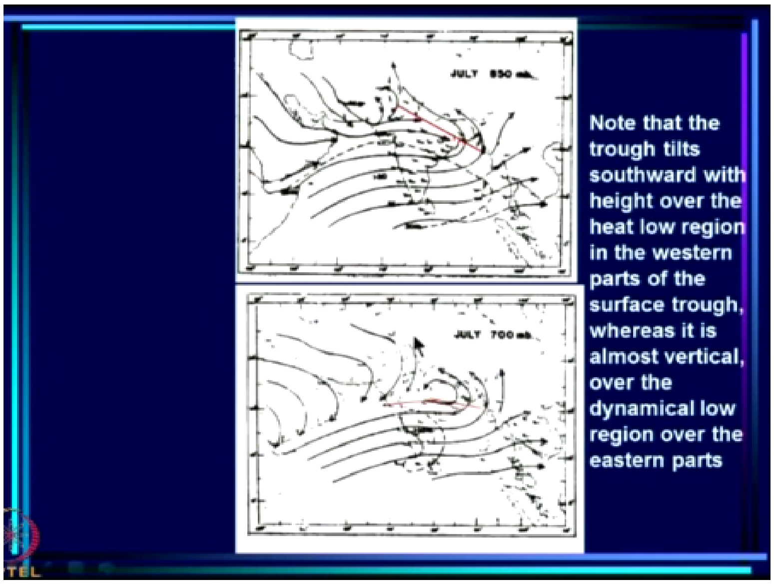

If you now see the 850 millibar streamlines as well as the 700 millibar, this is another indication of where the trough is. You can see at 850 millibar you have something like this very similar to the low-pressure zone we had and at 700 it is much more zonal, okay. Now, what it appears is in both the cases in the eastern part, this is dipping into the head of Bay of Bengal and so is this, okay.

So, in the eastern part there is not much variation with height of the trough location, but over the Western part as you go higher and higher there is a tilt towards the south. This we will come back to. So, what we are saying is that the trough tilt southward with height over the heat low region, okay because this is where the active convection is occurring, remember 700 millibar and that does not occur over the heat low region.

So, the trough tilt southward with height over the heat low region in the Western parts of the surface trough, whereas it is almost vertical over the dynamic low region over the Eastern parts, this is a point to note and we will come back to this as I say because of several issues raised about how vertical the system TCZ is.

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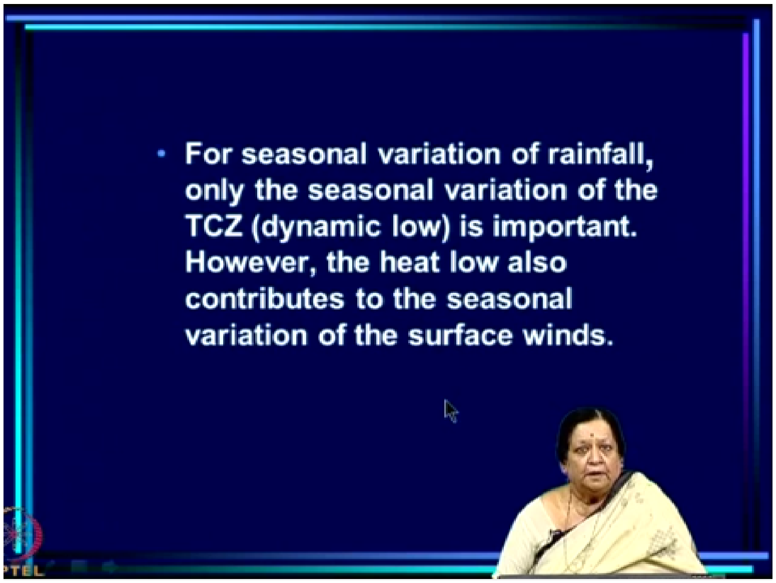

Now, for seasonal variation of rainfall, only the seasonal variation of the TCZ is important, okay. If you are interested in seasonal variation of rainfall, which is what most of the people living in the monsoonal regions of the world are, then only the seasonal variation of dynamic low is important but the heat low also contributes to the seasonal variation of surface winds because surface winds do depend on the pressure gradients and therefore on the heat low as well.

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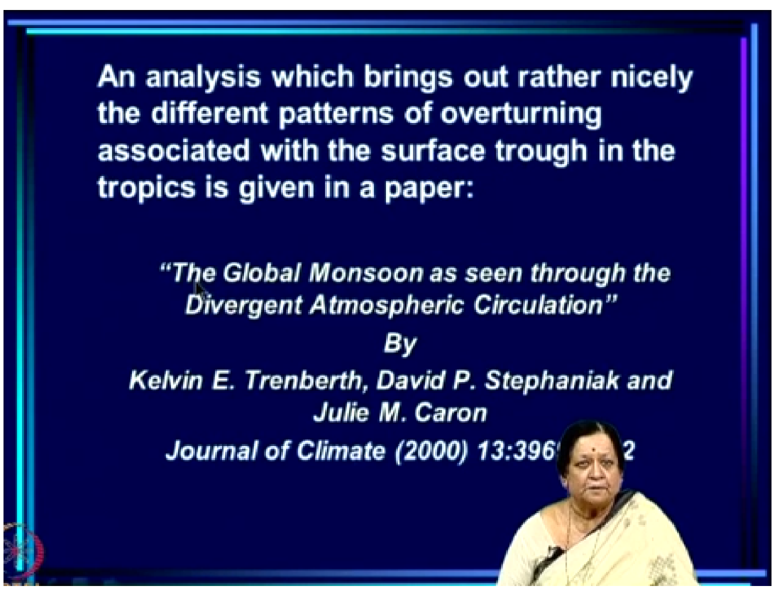

So, these are 2 very important entities or systems that we have to look at in the tropics, heat low and dynamic low. As I said, they are fixed in space or time and they vary depending on the phases of the monsoon and an analyses which brings out rather nicely the different patterns of overturning associated with the surface trough in the tropics is given by this very nice paper by Trenberth et. al. on the global monsoons as seen through divergent atmospheric circulation.

Divergent atmospheric circulation means the kind of vertical circulation we have been doing as cell circulation in the north-south and vertical plane.

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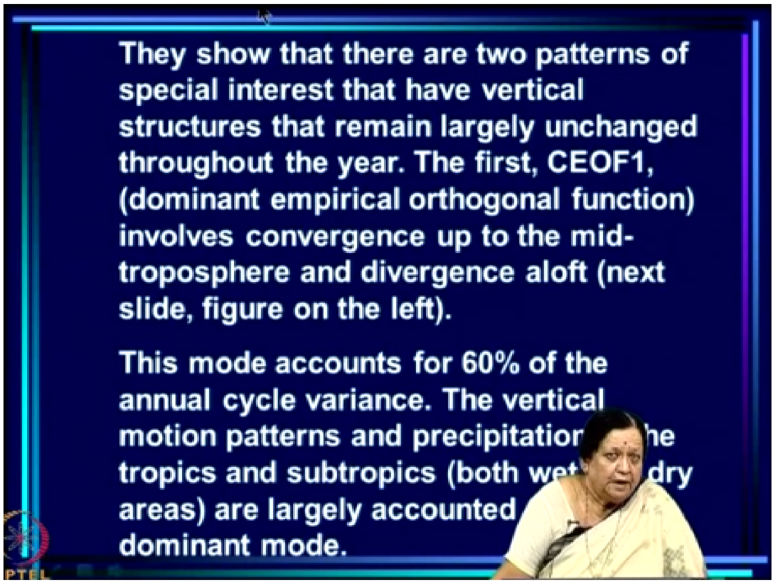

Now, what do they show. They show that there are 2 patterns of special interests that have vertical structure that remained largely unchanged throughout the year. The first which is what they call CEOF1. This stands for an empirical orthogonal function one. This is a pattern which can explain a lot of variation of the system. At some point, we will go into what EOFs are, but just understand that this is the dominant pattern, okay.

Dominant pattern of variation of this divergent wind field which he is looking at, and it involves convergence up to the mid-troposphere and divergence aloft, okay.

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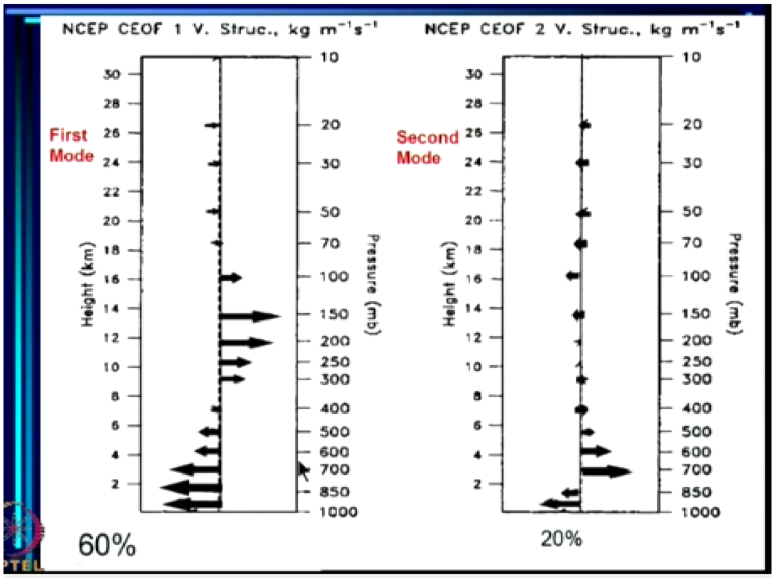

This is this mode here. Now, this is the first mode that you see and see this is height in kilometers and this is pressure in millibar. So, you can see that up to about 400 millibar or up to a height of well over 7 km, there is convergence. This stands for convergence, okay. Left-hand side stands for convergence of air and arrow to the right stands for divergence in this. So, you have air converging right up to mid-troposphere and diverging aloft.

This is the first mode and this accounts for 60% of the variance of the divergent fields. So, this is the most important mode. In fact, as I mentioned you know like we had in the description of the TCZ, this involves convergence up to the mid-troposphere and divergence aloft, okay and the vertical motion patterns and precipitation in the tropics and subtropics both wet and dry areas are largely accounted for by these dominant modes.

So, if I am interested in precipitation in the tropics, this is the critical mode to look at. But there is one more mode and this is the second mode, okay that they found and they actually nowhere in their paper mentioned a heat low but to us it is very clear that the second mode has convergence restricted to below 2 km, okay and divergence aloft. So, this it corresponds to very many shallow cell which does not extend beyond 2 km and this is the shallow cell which occurs and this is exactly what we have described as a heat low.

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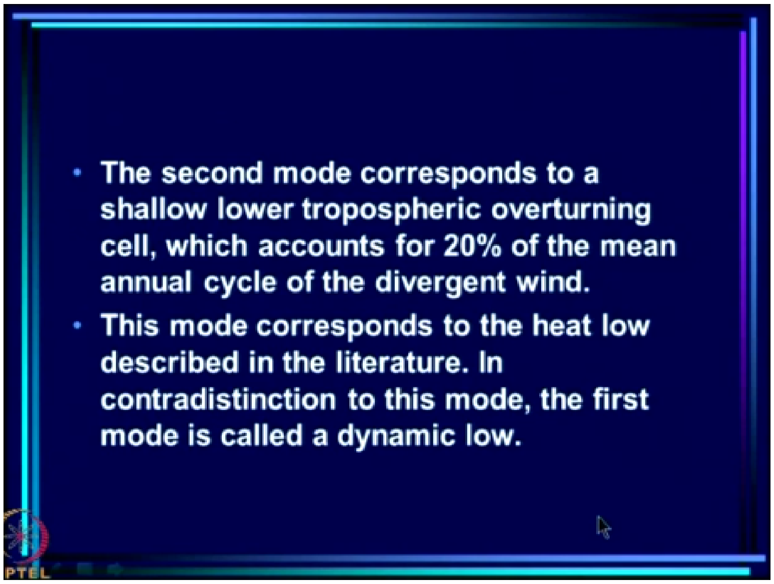

So, the second mode corresponds to a shallow lower tropospheric overturning cell which accounts for 20% of the mean annual cycle of the divergent wind. This mode corresponds to the heat low described in the literature. In contradistinction to this mode, the first mode is called dynamic low simply to distinguish it from the heat low.

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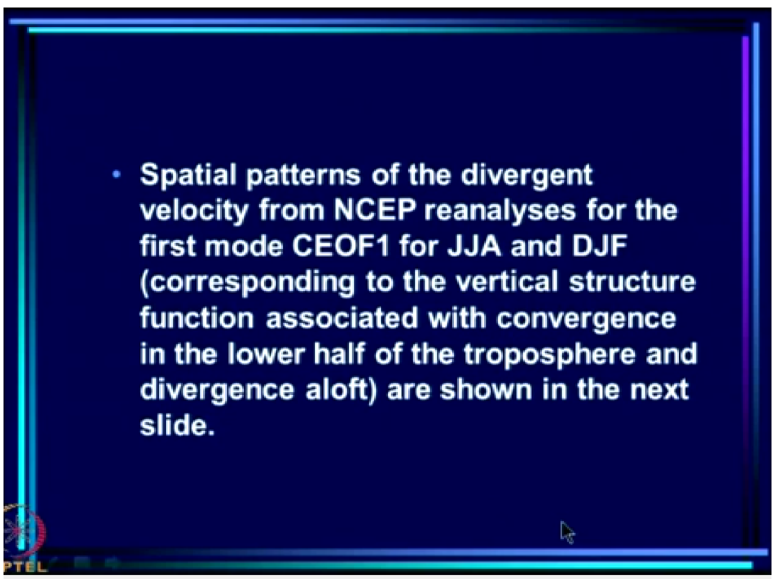

Now, irrespective of which analyses one takes and there are 2 popular ones, NCEP reanalysis and ECMWF reanalysis. The first mode of JJA and DJF, this is the 2 season; June, July, August corresponding to northern hemispheric summer and December, January, February corresponding to Northern hemispheric winter and Southern hemispheric summer.

So, reanalysis for the 2 seasons JJA and DJF corresponding to the vertical structure function associated with convergence in the lower half of the troposphere and divergence aloft are shown in the next slide.

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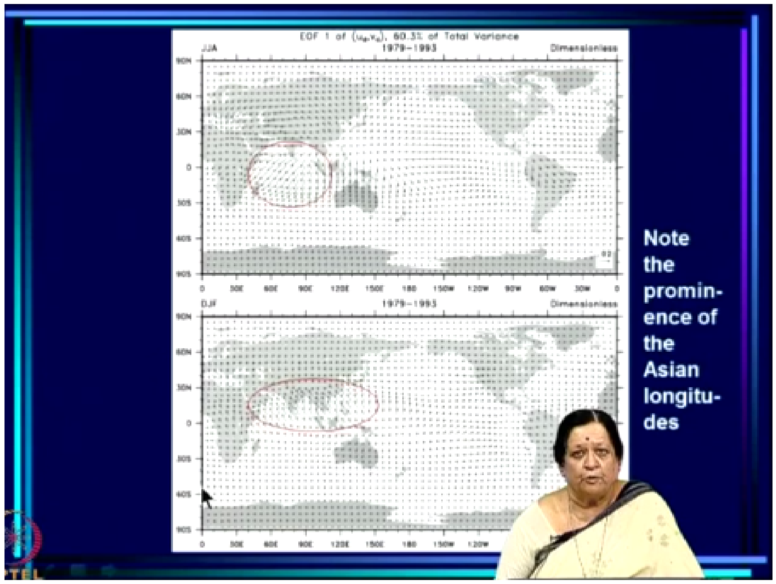

So, first we will look at dominant mode, okay which corresponds also to our TCZ mode. Now, this is EOF1 of JJA and this is EOF1 of DJF and it may be difficult for you to see the arrows but you can just see that they are very much larger in the region marked with red and this is none other than the Asian region. So, Asian region is dominant in the case of both DJF and in the case of JJA.

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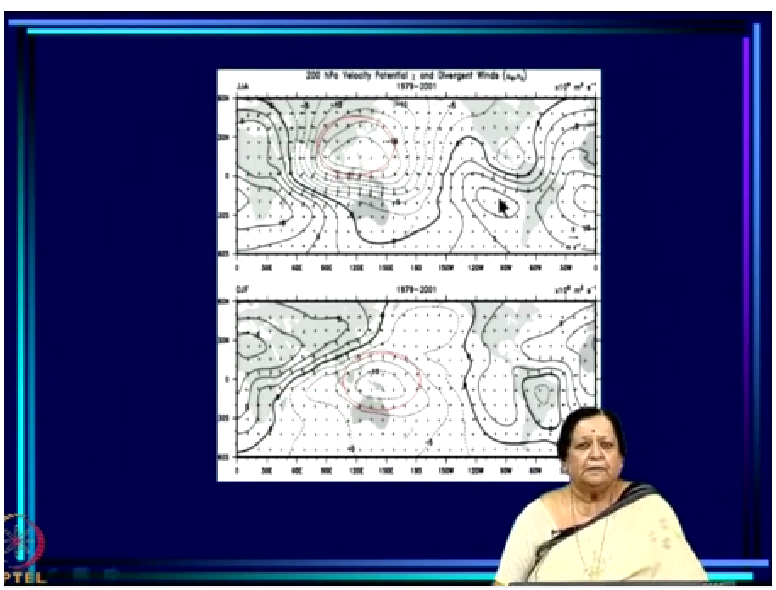

This is a divergence pattern at 200 millibar plotted by Krishnamurthy for 1979 and you can see that this is the major divergent thing. So, now remember we are in the upper troposphere. So, air has as to now go out from where it was brought from down by the TCZ and this is high-pressure that gets built and from here air is diverging. Again, the major divergence region is over the Asian region.

I am sorry this previous one was not Krishnamurthy's but this is also from Trenberth analysis and it shows both for JJA and DJF the major region of divergence is the Asian region.

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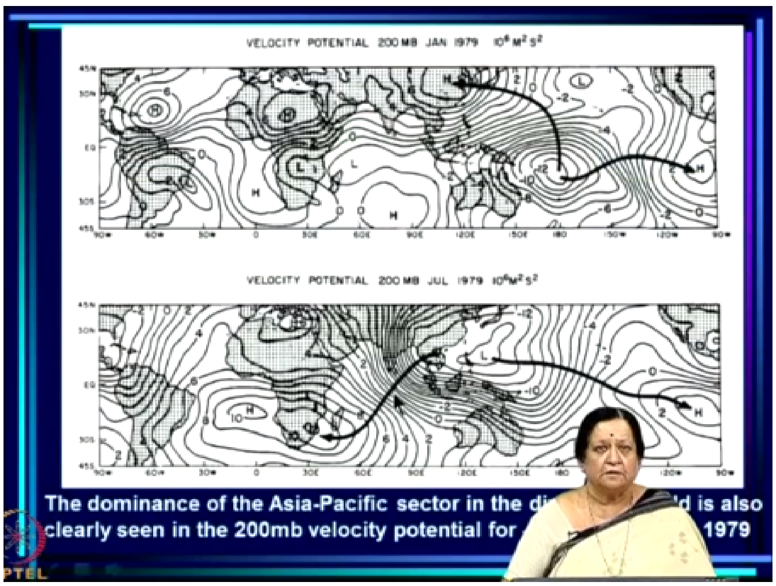

This is also seen in Krishnamurthy's velocity potential maps which is another way to represent divergence and this is only for January 1979 when it has come slightly to the south. You can see Australia here and this is July when it has come slightly to the north but it is very much over the Asian-Australian region where it is dominant.

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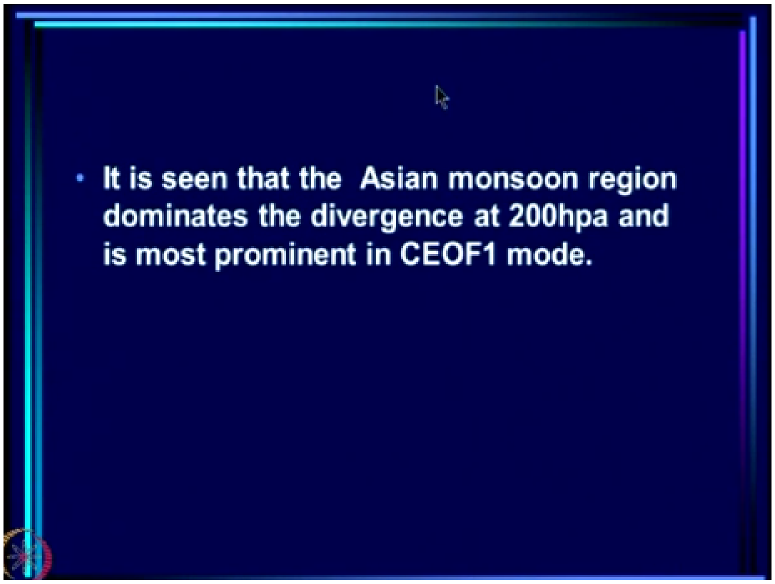

So, the Asian monsoon region dominates the divergence at 200 millibar and is the most prominent in the CEOF mode, okay.

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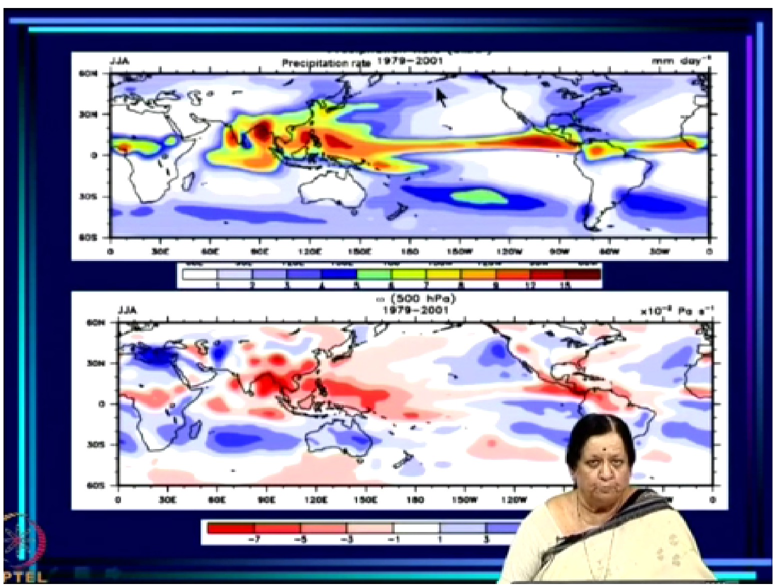

Now, we see the following. You know, we are interested in the rainfall and this is the rainfall for JJA. This is the average rainfall and this is from Trenberth and everything above this green colour is above 5 mm per day that is the unit used. So, 5 mm per day for 90 days, we have 90 days in June, July, August, actually 92 days and so that comes close to 50 cm of rainfall in that season, so that is substantive and the other shades in that have even higher rainfall.

So, you have June, July, August this Asian zone here and in addition there is also rainfall over

Africa and there is also rainfall over East Pacific, okay. These are the major regions and you see also a band here over Atlantic which is joining with the African region rainfall. Now, below is derived quantity. It is the vertical velocity at 500 millibar. 500 millibar remember is halfway through the troposphere right because at the surface the pressure is roughly 1000 HPA.

So, 500 HPA is halfway through the troposphere and pink and red means the velocity is upward, okay. Now, if the velocity is upward in the mid-troposphere that means the cell is very, very deep like the TCZ that we have seen, okay and you see that there is a close correspondence between these rainy regions which are green shade and above and the pink regions here you see, that is to say most of the large-scale rainfall that we see is associated with dynamic assistance with ascent at 500 millibar or halfway through the troposphere which means deep convection.

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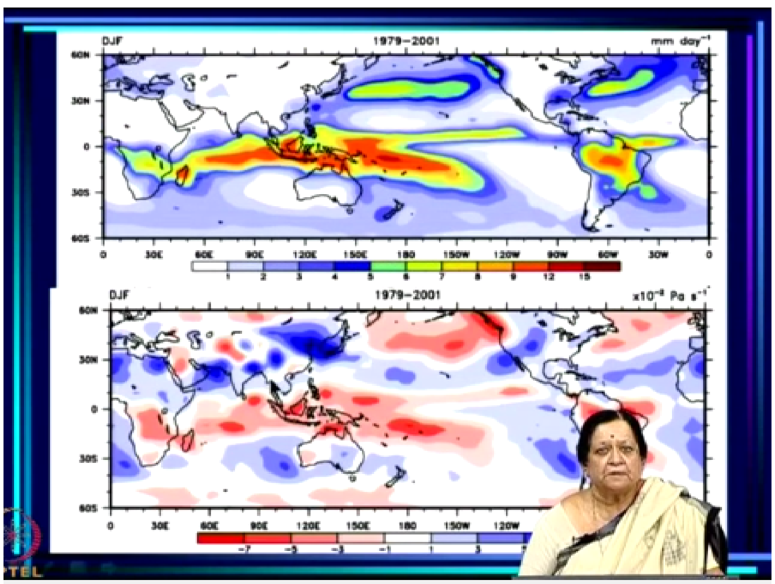

Now, this is also true of DJF, what you saw earlier was JJA and DJF also you see the same band, very beautiful correspondence between the actual rainfall which is observed in the tropics and this is the vertical velocity of the wind.

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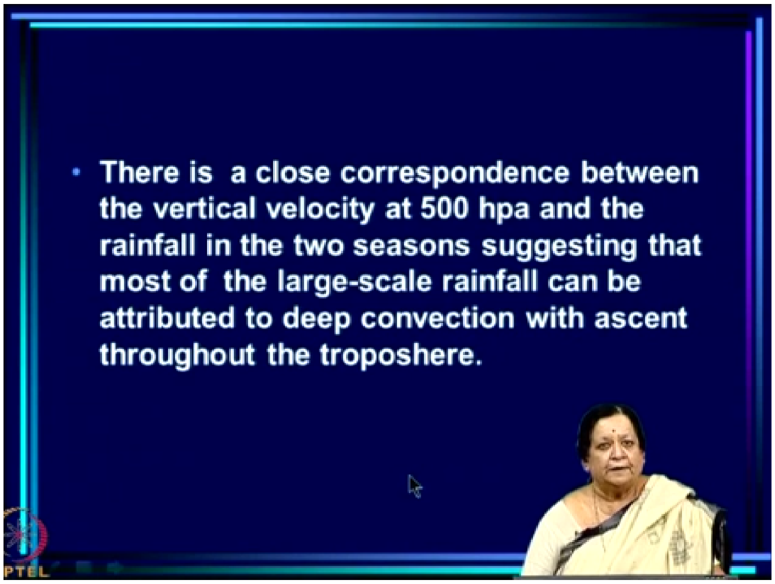

So, there is a close correspondence between the vertical velocity at 500 HPA and the rainfall in the 2 seasons suggesting that most of the large-scale rainfall can be attributed to deep convection with ascent throughout the troposphere, i.e., we are coming back now to the TCZ system. So, most of the large-scale rainfall in the tropics can be attributed to this tropical convergence zone kind of a system which involves ascent throughout the troposphere and descent in the surrounding region, okay.

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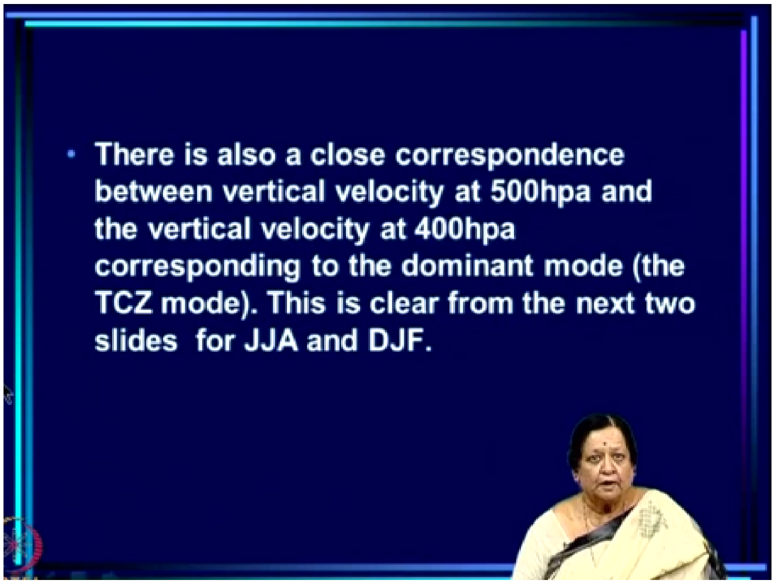

Now, we have looked at vertical velocity at 500 HPA. Now let us look at what is the signature of this dominant mode of the divergent circulation CEOF1, okay.

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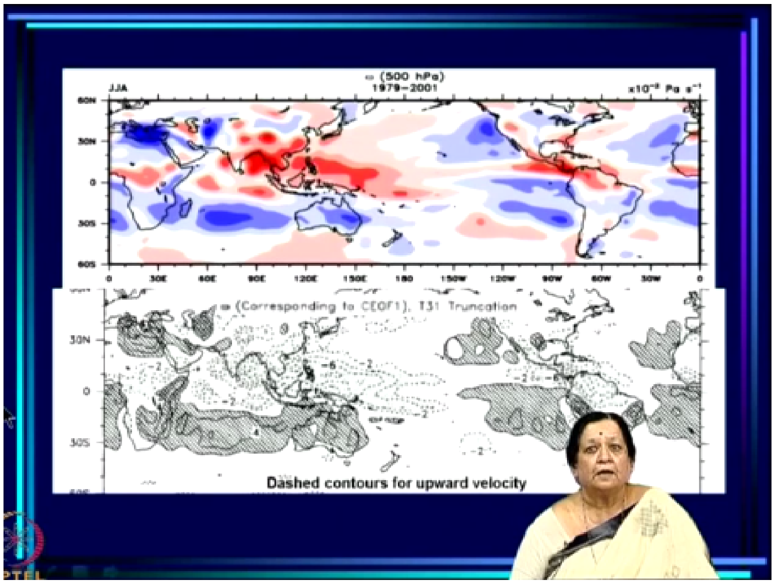

This below, now this is the same picture that you saw earlier. This is the vertical velocity and remember pinks are regions where you have ascent and this is the CEOF1 amplitude and this dash region is where it is ascending where you have convergence in the lower troposphere divergence aloft and this is the region where the air is descending and you can see how close the correspondence is between CEOF1 and the vertical velocity.

See even here in East Pacific for example. You know, you have a huge region with very little rain and that huge region corresponds to non-occurrence of the ascending zone. This ascending zone is only here. So, there is a very close correspondence then between these 2, which means like I said before this mode is the one which really is associated with rainfall in the tropics.

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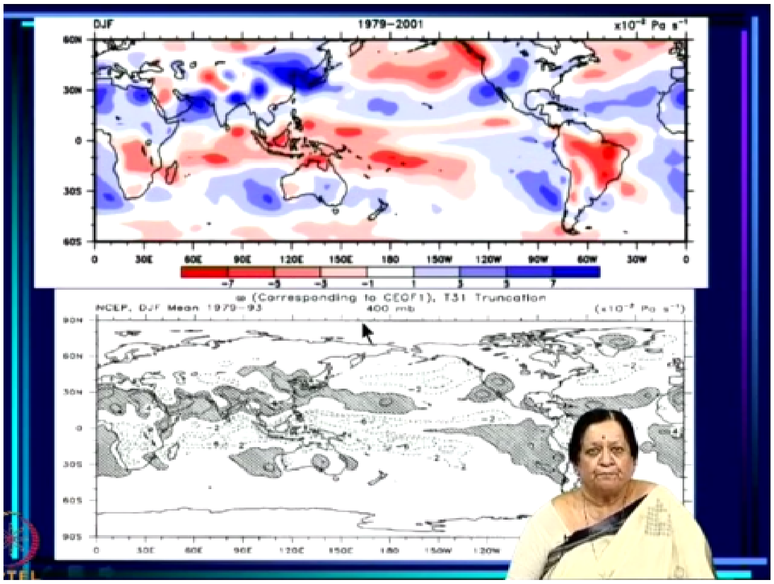

Now, this is the same thing for DJF. Again, you see this band of rain here associated with this band here, right from South Africa all the way here, totally coherent band exactly like you saw in omega. So, this CEOF1 which has been determined from the divergent field is very close to omega and therefore very close to rainfall.

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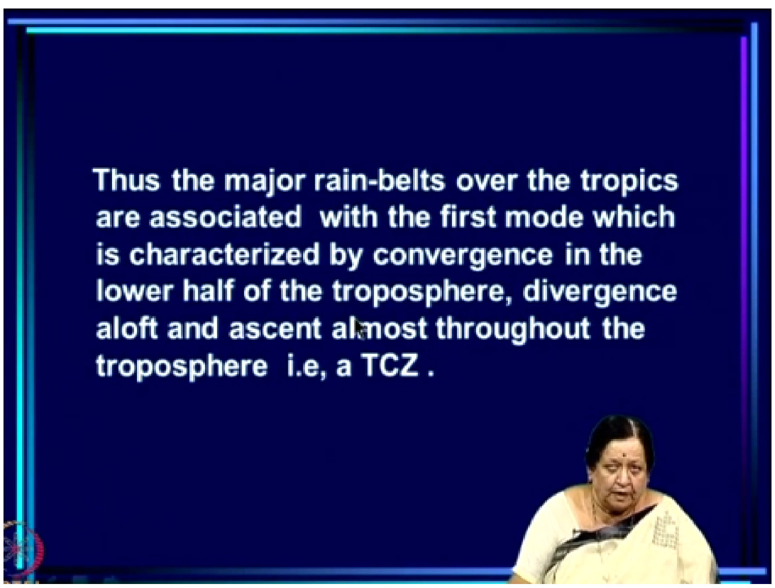

So, we can say that the major rain-belts over the tropics are associated with this first mode which is characterised by convergence in the lower half of the troposphere, divergence aloft and ascent throughout the troposphere namely a TCZ, okay.

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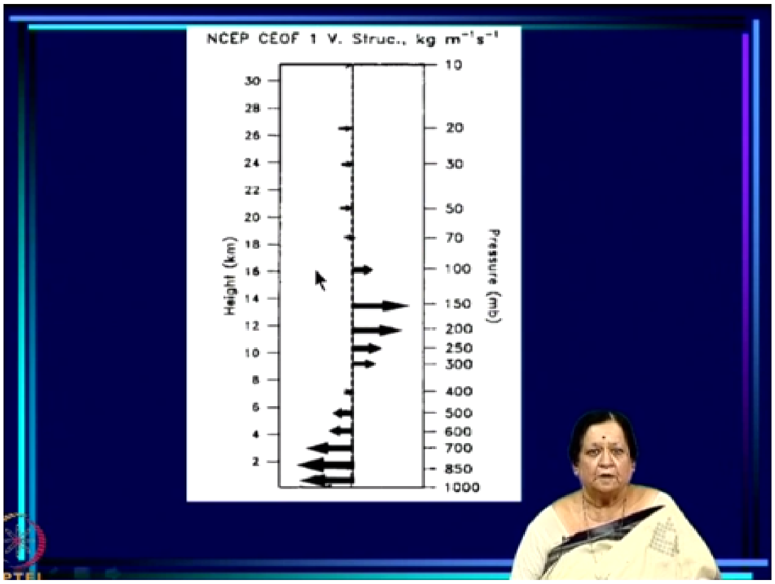

This is the first mode, convergence lower half of the troposphere, divergence aloft and ascent throughout the troposphere. This is the first mode and what we have just said is that major rain-belts over the tropics are associated with the first mode which is characterised by convergence in the lower half and divergence aloft, okay, i.e., to say it is associated with a TCZ.

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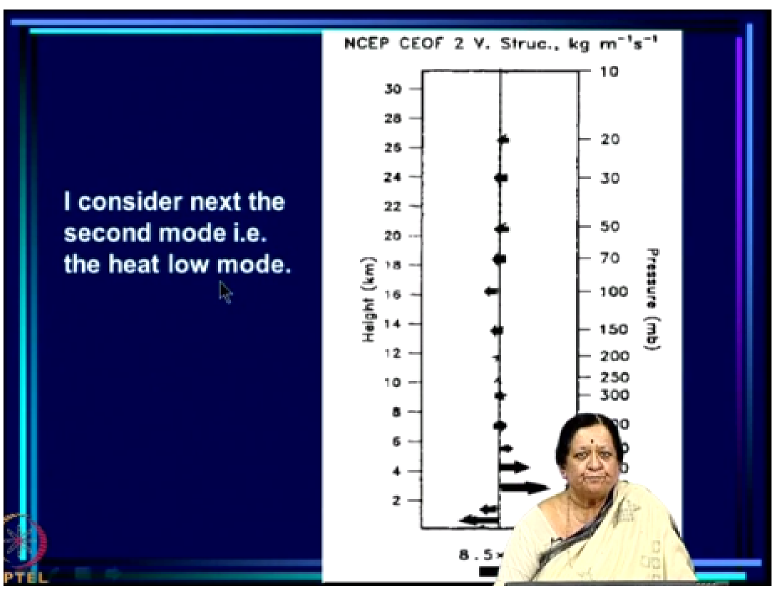

Now, let us consider the second mode because Trenberth not only derived the first mode but also the second mode which you remember explain about 20% of the variants, the first mode explained 60% of the variants and the second mode is the shallow cell, okay here. This corresponds to a heat low kind of mode and let us see where it is maximum.

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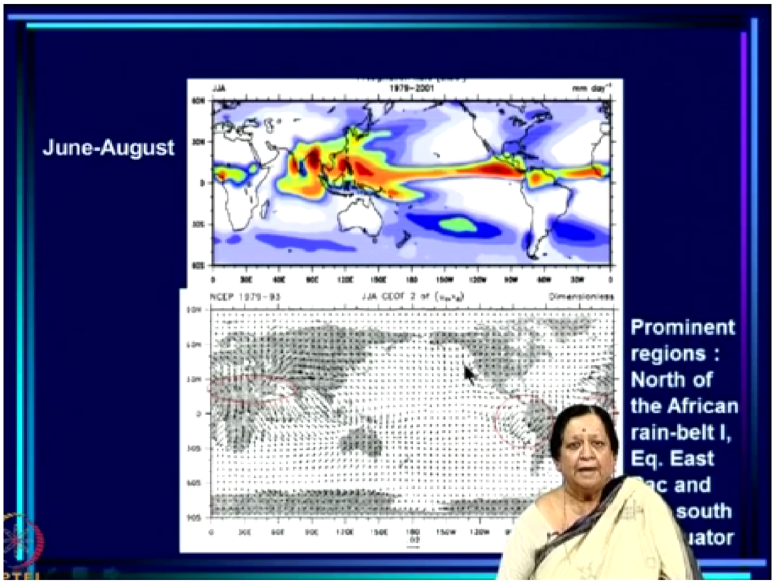

Again, Trenberth's figures are not very easy to delineate, so therefore to read and understand what he has shown is by amplitude of these arrows which come off. But what you can see is that largest amplitude is here and over this region here and over the eastern Atlantic here, okay. This is where CEOF2 has largest amplitude and notice where this is. If you compare with rainfall, this belt is to the north of this and in fact it extends all the way to our Rajasthan desert.

This is India here. I am sorry this is not the best possible slide but this is the only one available. So, CEOF2 has a large amplitude over Sahara Desert and our Thar Desert here, okay. It also has a large amplitude over East Pacific and over East Atlantic. This is for June, July, August.

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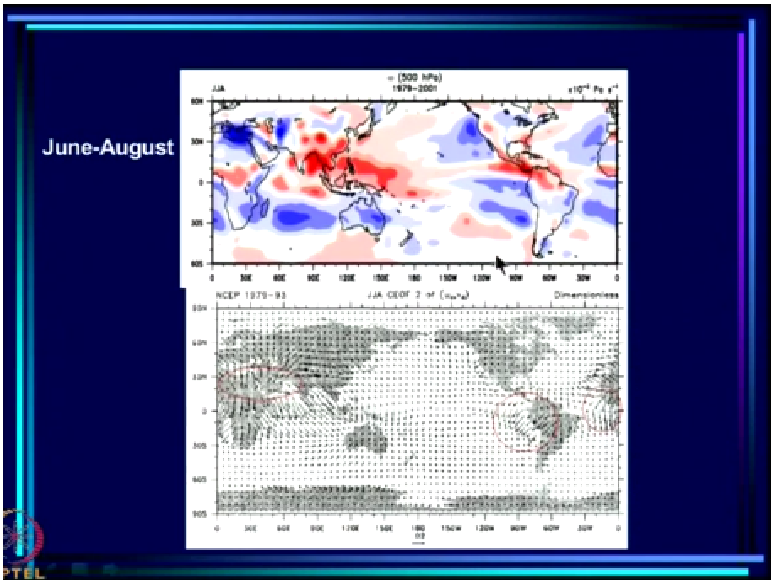

Now, let us look at Omega and what the CEOF2 is doing, second mode, corresponding to heat low. You see that where the heat low is prominent which is this area is exactly where the blues are occurring here. It is north of the pink belt, okay that is where for JJA it is occurring. In other words, you have the second mode dominant to the north of the rain-belt, okay and same thing here.

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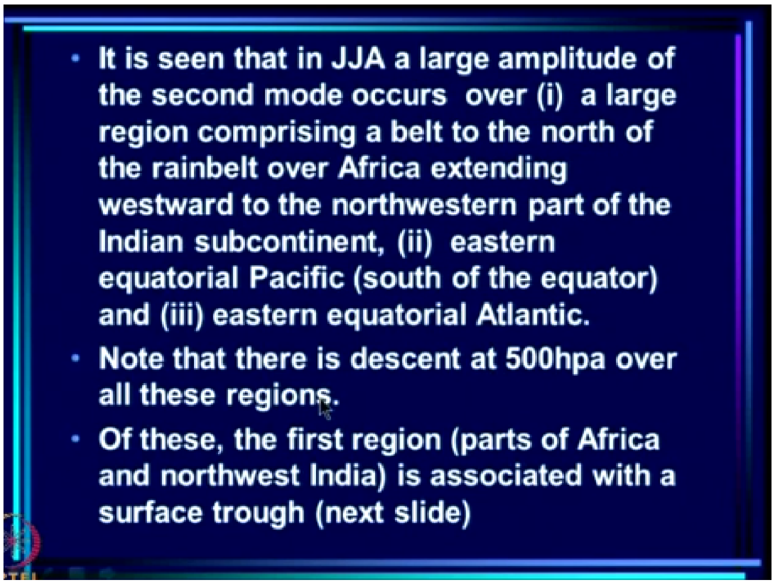

Now, if you go to the next one it is seen that in JJA, a large amplitude of the second mode occurs over a large region comprising a belt to the north of the rain-belt over Africa extending westward to the north-western part of the Indian subcontinent, eastern equatorial Pacific and eastern equatorial Atlantic, okay and that there is descent at 500 HPA over all these regions.

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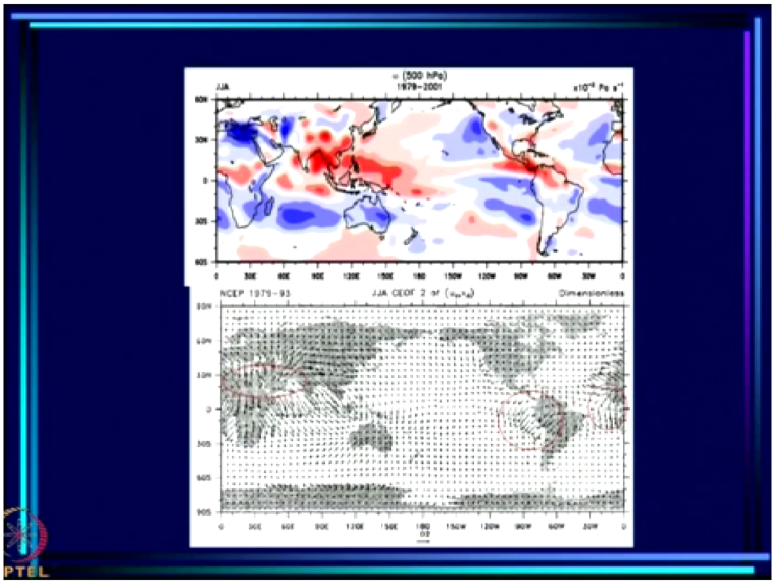

So, let us see. See, these are the 3 regions over which second mode is dominant and you can see clearly. See this whole thing is blue here, this corresponds to descent over this region. This is blue. This corresponds to dissent over this region and you see the blue part here corresponds to descent over this region. So, there is descent at 500 HPA over all these regions. So, as we expect in fact the ascent is very shallow and at 500 HPA, there is descent over these regions.

In fact, of these, the first region which are parts of Africa and Northwest India is associated with the trough.

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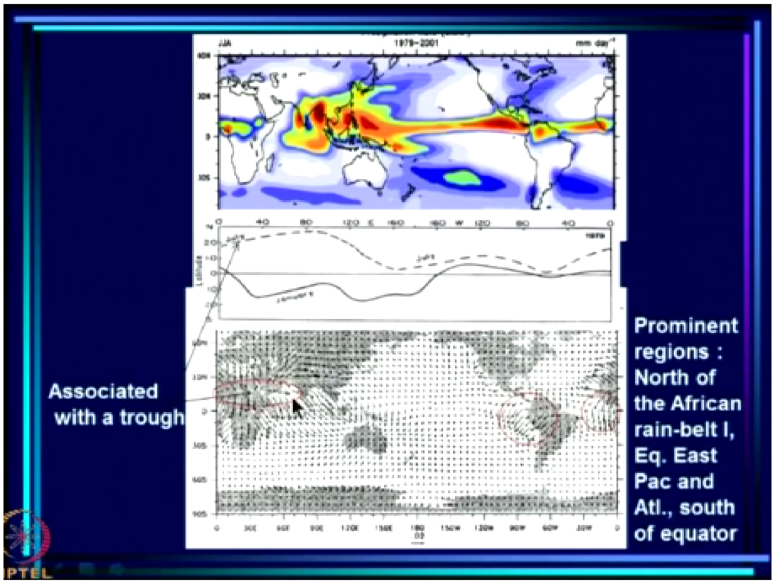

Now, you see the same figure, okay for JJA. This is the rainfall for JJA, okay that you have seen before. This is the CEOF2 where the amplitude is large of the second mode, okay. This is the heat low mode and what you see in between is a picture we have seen before. This is the location of the surface trough at July. This is the location of the surface trough in January, okay and over the same longitudinally regions this is drawn.

So, what you can see is that this region here is associated with a surface trough. See, there is a surface trough around 20 degrees north or so which is where this region is. So, this is in fact associated. This region is associated with the surface rough, so we can call it a heat trough, okay. So, this is a heat trough to the north of the rain-belt.

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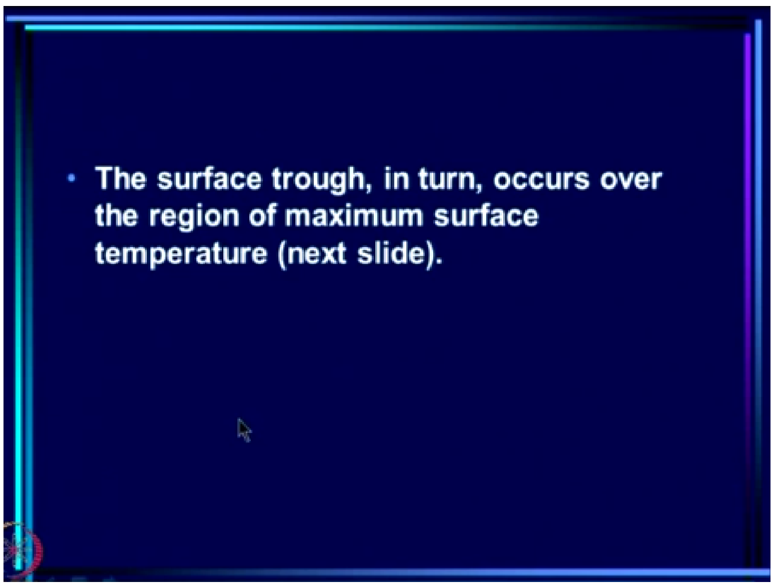

Now, the surface trough in turn occurs over the region of maximum surface temperature as we expect a heat trough to do.

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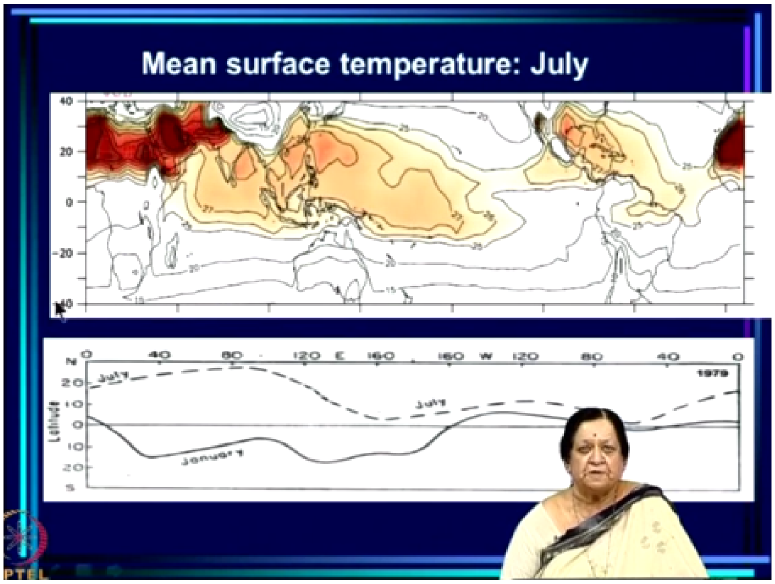

So, this is a mean surface temperature for July, you can see how high it is around 20 north, it is very, very high and that is where the surface trough is and that is where the second mode has a very large amplitude. So, we are saying that this in fact marks the presence of a heat tough over this region, okay.

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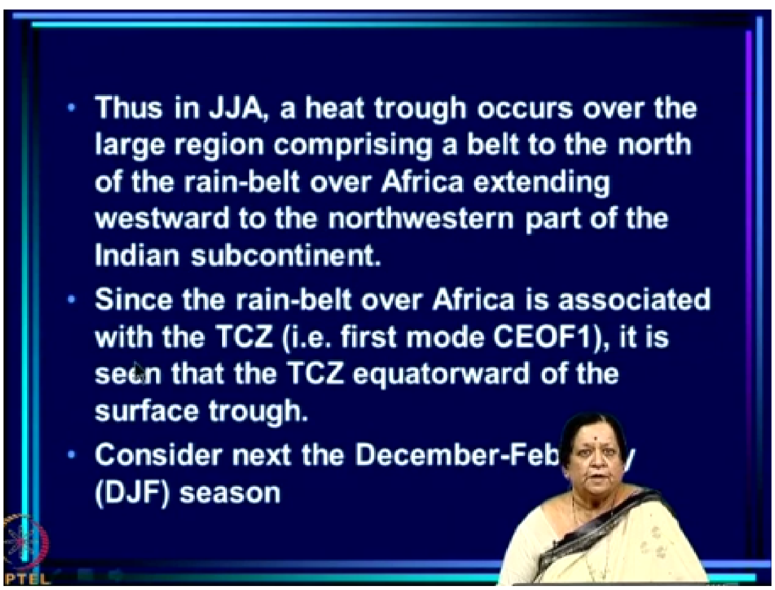

In JJA, a heat trough occurs over a large region comprising a belt to the north of the rain-belt over Africa extending westward to the north-western part of the Indian subcontinent. So, there is a heat trough over Sahara and Thar, the whole big region there, okay. Now, since the rain-belt over Africa is associated with the TCZ which is the first mode of CEOF1 which we showed, it is seen that the TCZ is equator word of the surface trough. This is to be noted. So, over the surface trough, we have a heat trough and to equatorward of the surface trough, we have a topical convergence zone.

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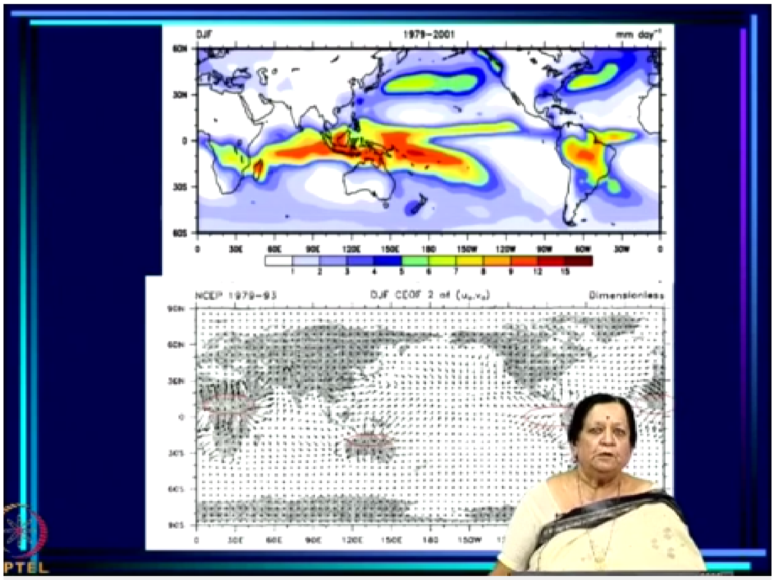

Now, let us see what happens in December, January, February. December, January, February this is what happens. The second mode is dominant over this part here and over Australian region here and of course over the East Pacific and the East Atlantic here, okay. Again, if we compare it with the vertical velocity as we expect, it is sinking everywhere, okay. There is descent of air over all these zones where you have dominant heat low kind of things, okay.

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So, a large amplitude of the second mode occurs over a zonal belt to the north of the rain-belt over Africa, zonal belt over the northern parts of Australia southward of the rain-belt over the maritime continent in northern Australia.

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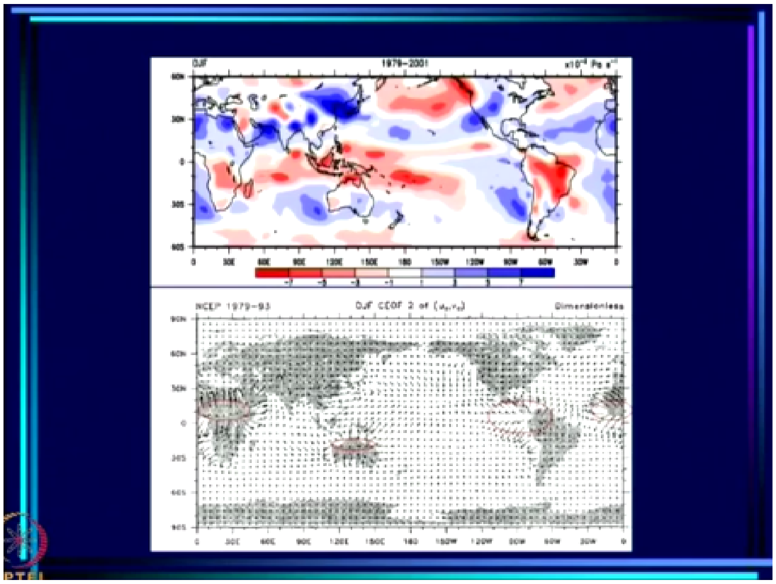

So, let us go back and confirm this. What we are saying is that you see here. This mean rainfall in just touching the northern tip of Australia, okay and just to the south is this prominent region here of the CEOF2. So, here also this is sort of all south of the equator and this is slightly to the north of the equator. So, towards the equator from the rain-belt, we are getting these heat low regions both in Australia and Africa, okay.

Then, of course we have the eastern equatorial Pacific and eastern equatorial Atlantic and again we have noted already that there is descent at 500 HPA over all these regions.

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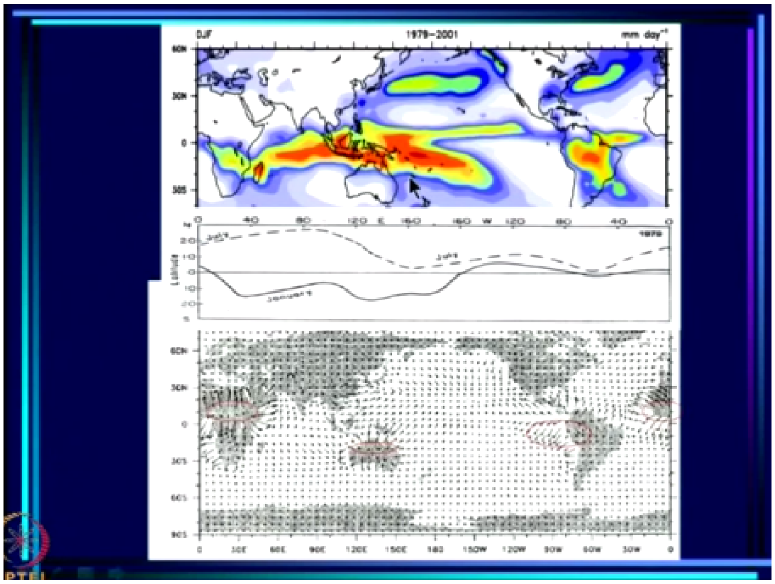

Now, the Australian region is associated with the surface trough and that we can see from this slide here that actually you see here the surface trough has come to about 20 degrees south and this is 20 degrees south where the CEOF2 has very large amplitude.

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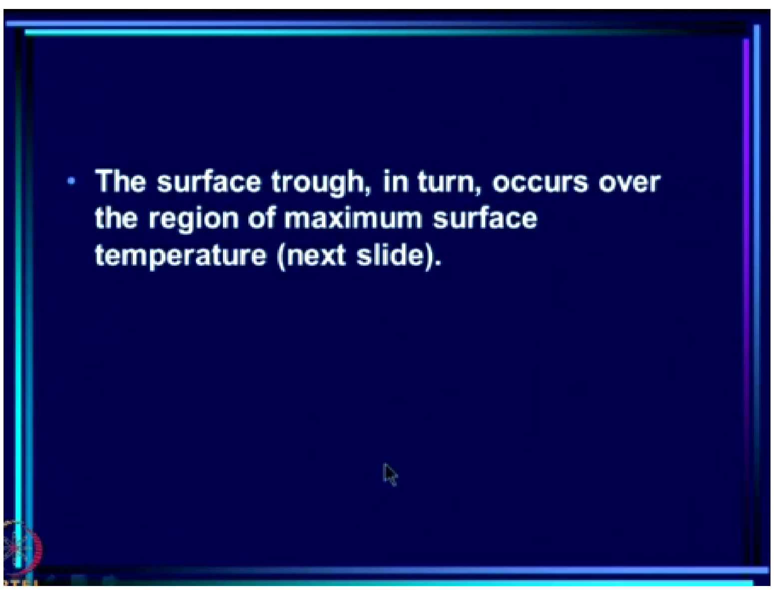

So, the surface trough in turn occurs with the maximum or you can say how high the temperature over Australia is and the surface trough is actually associated, now you can see, this is 20 south or so and the surface trough has come to about 20 south in that region. So, what do we find, that the large amplitude of the second mode CEOF2 is associated with the surface trough which in turn is associated with highest surface temperatures, okay.

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So, in DJF, heat trough occurs over the northern part of Australia, south of the rain-belt over the maritime continent in northern Australia. Since, this rain-belt is associated with the topical convergence zone which is the first mode CEOF1, it is seen that the TCZ is equatorward of the surface trough. Thus over Africa in JJA and Australia in DJF the surface trough associated with a heat tough. So, surface trough is associated with a heat tough and the TCZ is equatorward of these.

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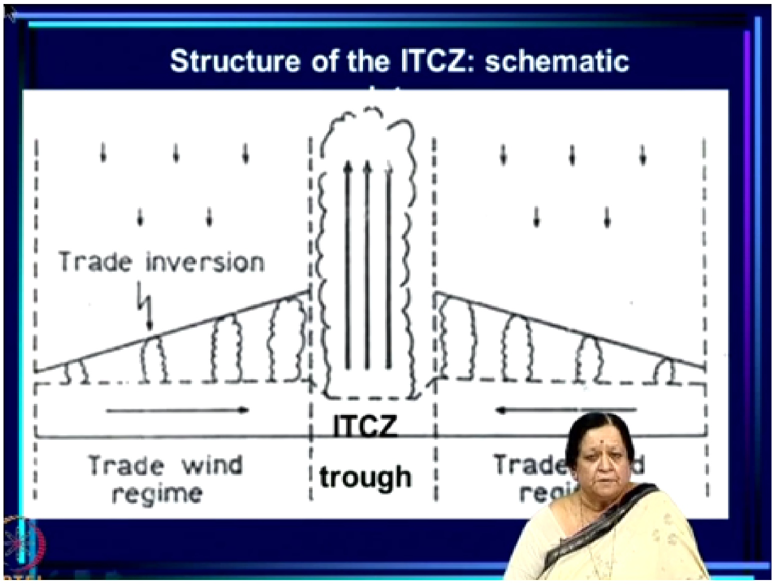

So, this is what prompted a very emphatic remark from Hastenrath. Let me just remind you that this is the basic structure assumed for ITCZ. It is of course schematic. The idea that ITCZ lies over the trough, okay and you have ascent over the entire region. This corresponds to the inter-topical convergence zone, okay.

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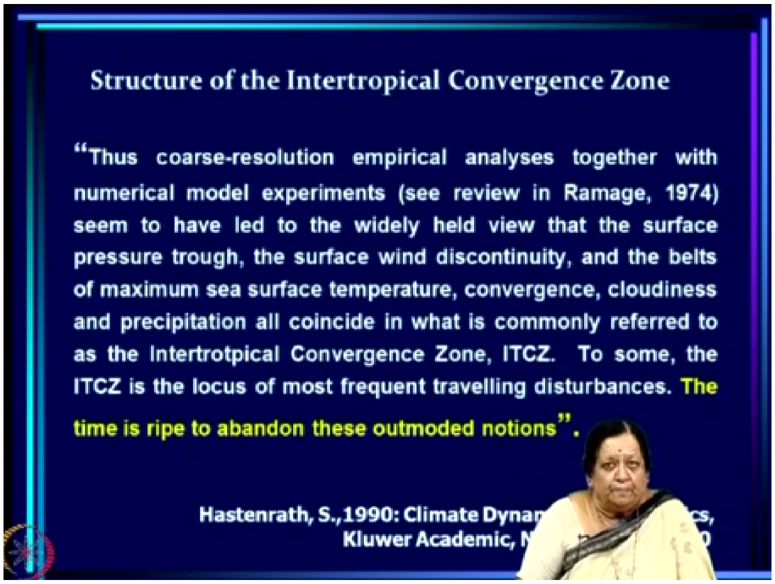

So, one of the assumptions of the dynamical part of ITCZ is that the system is vertical, okay and it is over the surface trough but what Hastenrath says is that coarse resolution empirical analysis together with numerical model experiments seem to have let to the widely held view that the surface pressure trough, the surface wind discontinuity and the belts of maximum sea surface temperature, convergence, cloudiness and precipitation all coincide in what is commonly referred to as the inter-topical convergence zone or ITCZ.

This is Chinese picture of the ITCZ if you wish. To some, the ITCZ is also the locus of most frequent travelling disturbances, we have seen that. We have seen that lowest born of ITCZ become cyclones and so on and so forth. Now, then Hastenrath makes a comment. This is in 1990 that the time is right to abandon these outmoded notions, okay.

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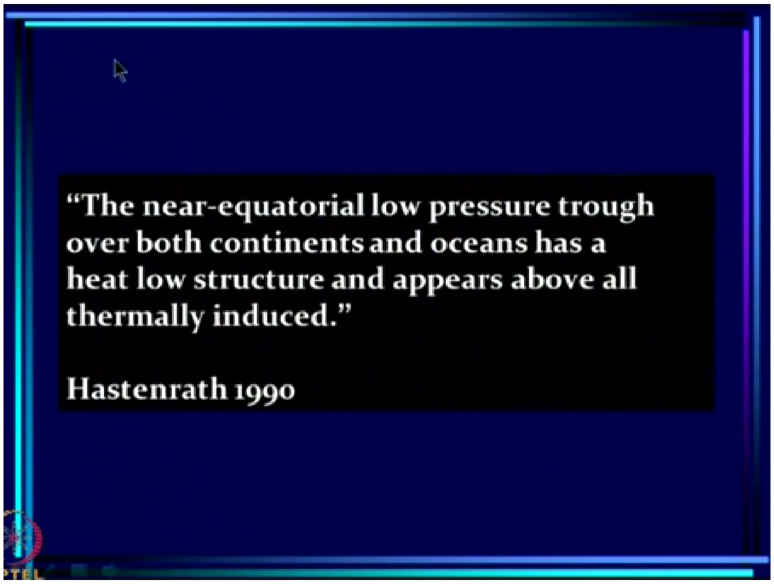

He further says that the near equatorial low-pressure trough over both continents and oceans has a heat low structure and appears above all to be thermally induced, okay. So, this is a very serious criticism of the ITCZ thing.

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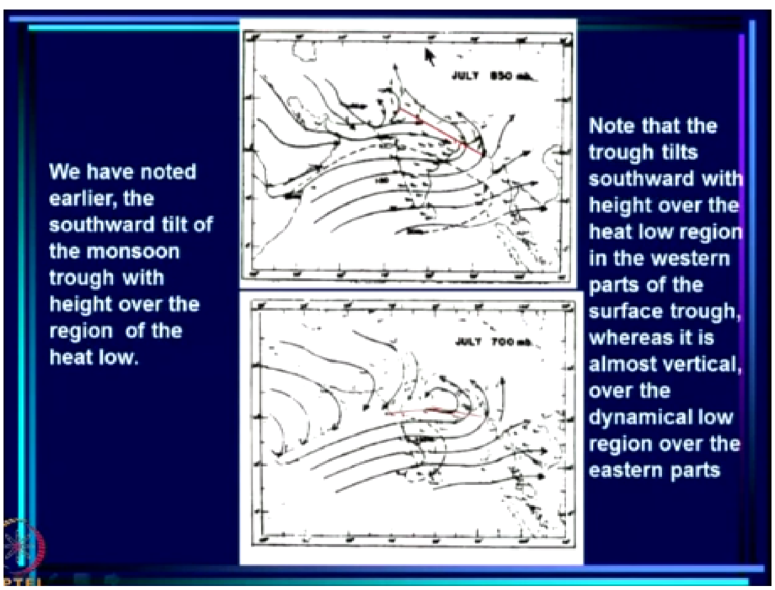

Remember we have seen that over the Indian region also you know, over part of the surface trough, part of the surface trough is a heat low and the other part is a dynamic low and we talked about the tilt, you know particularly over the western part where there is a tilt of the trough from the heat low to wear the dynamic low is. So, if you go above with increasing height, there is a southward tilt of this trough particularly over the north-western parts here or western parts of the monsoon zone.

So, we have notice that there is this kind of a tilt which also means, you remember 700 millibar is the axis of non-orographic precipitation. So, it also means that the TCZ is here, whereas the surface trough is here. This is again the discrepancy that Hastenrath is trying to point out and eventually we have to address his concerns and try and understand how this comes about, we will do so.

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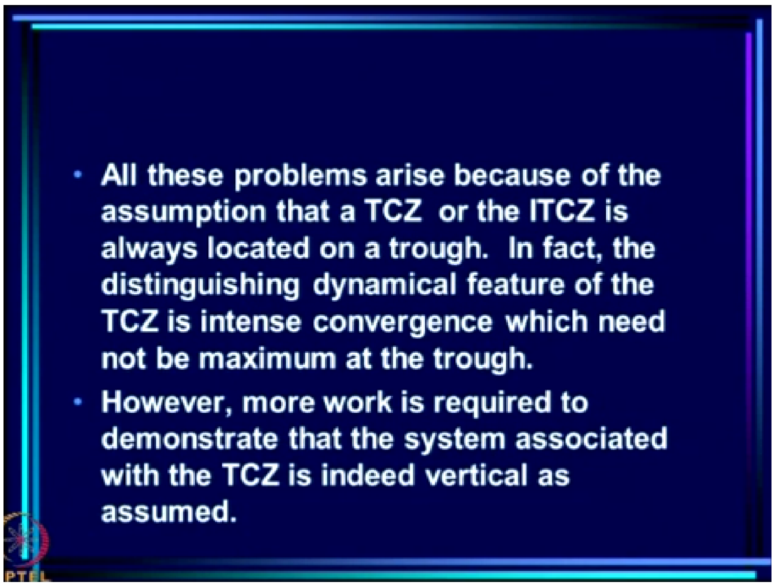

But at this point it is a good idea to mention that all these problems arise because of the assumption that a topical convergence zone TCZ or an ITCZ is always located on a trough. In fact, the distinguishing dynamical feature of the TCZ is intense convergence which need not be maximum at the trough.

See maximum cyclonic vorticity or maximum ascent need not always be associated with the trough; however, more work is required to demonstrate that the system associated with the TCZ is indeed vertical as assumed and at a later stage in these lectures, I will come back to this.

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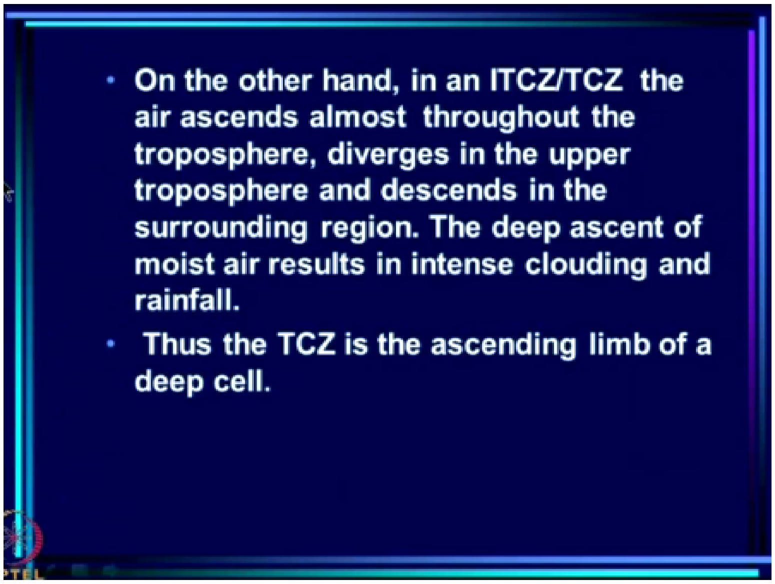

On the other hand, in an ITCZ or TCZ, air ascends almost throughout the troposphere, diverges in the upper troposphere and descends in the surrounding region. The deep ascent of moist air results in intense clouding. Thus, the TCZ is the ascending limb of the Hadley cell. So, what we have learned today is that there is a major problem between in the kind of theory we had of the ITCZ which was developed by Chinese and supported by others and which we showed for the Indian region actually is consistent.

In other words, we could say that the rain giving system corresponding to the monsoon is indeed a system something like this and we also showed that on days on which there is a very clear cloud band like an ITCZ, actually the system is vertical. So, the problem here is that we are looking at mean monthly and mean seasonal patterns but ITCZ itself or the topical convergence zone comprises clouds.

Now, as you know clouds are products of instability and actually even the lows on the synoptic scale systems are products of instability. So, the ITCZ by its very nature is not constant day after day. This is very clear from the cloud patterns that satellites provide. So, the ITCZ fluctuates and very often disappears and we have ourselves seen how, we have active spells and breaks during breaks of the monsoon, there is no topical convergence zone over the Indian region.

So, by its very nature, the ITCZ fluctuates from time to time and when we look at the mean picture what we see is the average of the number of days on which the TCZ is present and the number of days in which it is absent. Therein, I believe lies the problem because if as has been shown by several studies beginning with the Sikka, Gadgil ones, if during intense episodes of the topical convergence zone, the system is vertical, okay.

But during our breaks for example what happens is that the TCZ disappears and the surface trough is the only trough remaining and we get a heat low kind of circulation there. So, when you take an average over the entire month, the location of the trough is the location it would have had when it was active and average of that over the break spells as well and this is what creates the problem and creates a tilt in the dynamical thing.

Now, there is no problem at all that as far as heat low is concerned, it remains a perpetual heat low but the region which is a dynamic low which gets converted to a heat low and thereby the surface trough moves towards the Himalayas will generate a tilt in the mean picture, even though the actual system that gives us rain, the TCZ is vertical as (()) (43:38).

So, we will now do in the next lecture is look at the monsoonal regions of the world, look at where we have the TCZ appearing and we have seen that in the first mode that we had rain over African region, rain over South American region, rain over Asian region of course, all in association with the TCZ and that there was some variation in the location of the TCZ which we have particularly seen over the Indian monsoon zone.

So, in the next lecture, we will ask a question about how does the monthly average differ from the actual one. What are the kind of fluctuations that are observed in the tropical convergence zone because there was another explanation that we had namely when the objection was raised that the mean monthly OLR pattern over India had a much larger latitudinal extent than over other parts of the globe.

We pointed out that this had to do with the intra-seasonal variation or the sub-seasonal variation in which the TCZ gets burn over the equatorial Indian Ocean and moves northward and this is what creates a low OLR region over the entire zone occupied by the primary zone, the CTCZ and the secondary zone. So, same way we will have to also look at fluctuations of the TCZ over land as well as ocean and see the extent to which the serious objections of Hastenrath be answered.

We need to understand is indeed the system on a shorter scale vertical or does it have a tilt of any kind and if so do we have to go back and modify Chinese hypothesis in anyway. So, these are open questions to which we will try and give answers. Now, what we will do is to actually try and derive the monsoonal regions of the world and try and see what is the kind of variability over different monsoonal regions.

Because you know if all the monsoonal regions are associated with tropical convergence zone, we have already shown that the Indian monsoon region is associated with arrival of a tropical convergence zone over a region during the summer monsoon. So, if that is also true for other monsoonal regions of the world which we will objectively identify, then in that case we will be able to further our understanding of what is happening to the system?

Whether it is vertical or not by looking at different realisations over different continents; Africa, Australia, Indonesia, and so on and so forth. So, as I said the heat low is a very, very important entity which is not referred too much in the modern literature and in fact even Trenberth did not mention it but this heat low and what we may call a TCZ or a dynamic low has to be understood in greater depth before we can actually be able to say over which region will the tropical convergence zone occur.

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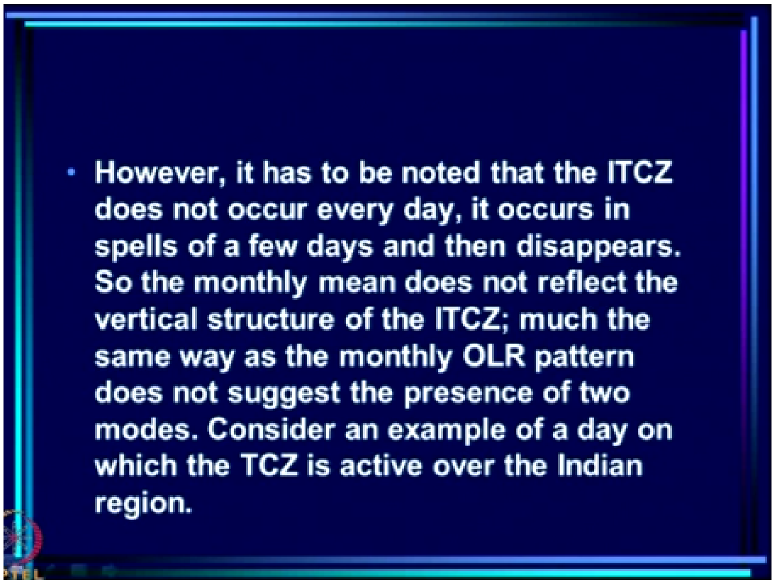

So, Hastenrath has objected because he feels that the ITCZ is not located over the trough; however, it has to be noted that the ITCZ does not occur every day. It occurs in spells of a few days and then disappears. So, it is not a system that hangs on forever and ever. So, the monthly mean does not actually reflect the vertical structure of the ITCZ but monthly mean over any region, say the trough region in the monthly chart would reflect some days of the ITCZ and some days without the ITCZ or clear days.

So, much the same way the monthly OLR pattern does not suggest the presence of 2 modes over the Indian region. You know, monthly OLR pattern just shows a smeared low OLR region extending all the way from tens out to monsoon zone same way and we do not get an idea of what we see on the daily scale at all that there are 2 ITCZs and so on and so forth. So, same way the monthly mean does not reflect the vertical structure of the ITCZ. So, this is a point to be noted, okay.

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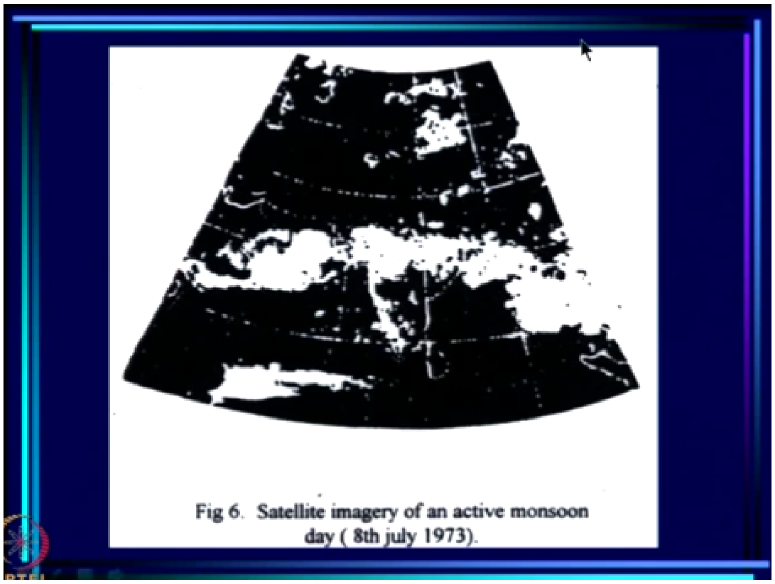

Fig 6. Satellite imagery of an active monsoon day (8th july 1973).

So, for example suppose we took an active monsoon day over India and we have seen this picture before for 8th of July, 1973, then what we find.

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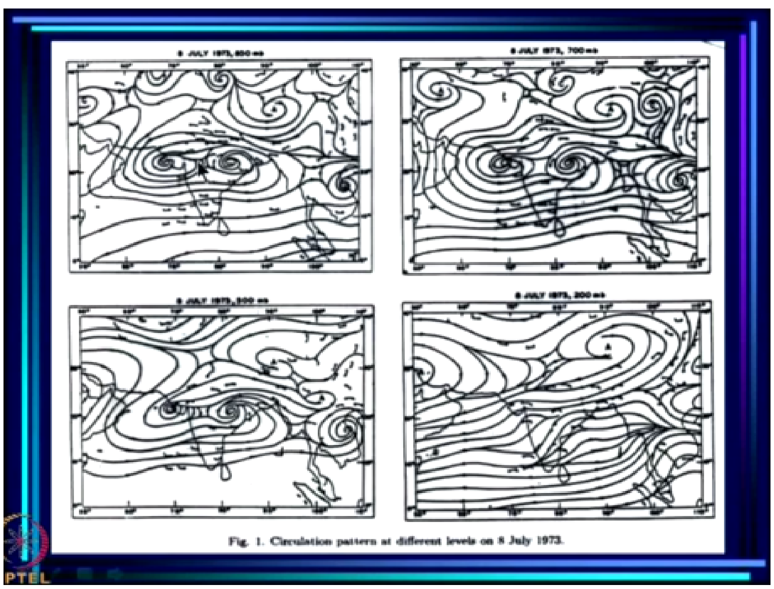

Fig. 1. Circulation pattern at different levels on 8 July 1973.

These are the streamline patterns that you see for 850, for 700, for 500 and this is in the upper atmosphere and what is striking about this picture is that there is no heat low signal seen here. In fact, the vorticity associated with the TCZ or the topical convergence zone has totally overwhelmed the heat low vorticity. So, what you see is actually a vertical system with cyclonic vorticity at 850 millibar, so the trough at 850 is here, the trough at 700 is here right above that, and trough at 500 is also right above it.

So, on a single day on which the ITCZ is active what you see is actually what Chinese (()) (49:12) a vertical system.

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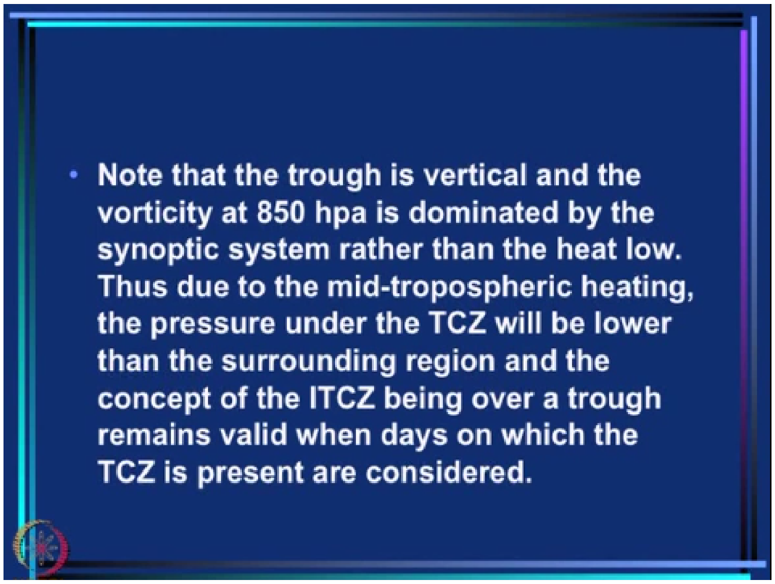

Note, that on an active day, the trough is vertical and the vorticity at 850 HPA is dominated by the synoptic system rather than the heat low. Thus, due to mid-tropospheric heating, the pressure under the ITCZ will be lower than the surrounding region and the concept of the ITCZ being over a trough remains valid when days on which the TCZ is present are considered. So, one should not take averages over days on which TCZ is present and on which it is absent that is what creates a problem of displacement of the TCZ from the trough on the monthly scale.

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So, it is necessary of course to establish the vertical nature of the system by looking at more cases and so on, but it appears that the problems that Hastenrath has pointed out are more because he concentrated on the monthly scale rather than looking at an active ITCZ system. Now, since Hastenrath has also commented on the oceanic ITCZ, I will consider now the seasonal variation of the precipitation over the global tropics focusing on the oceanic regions.

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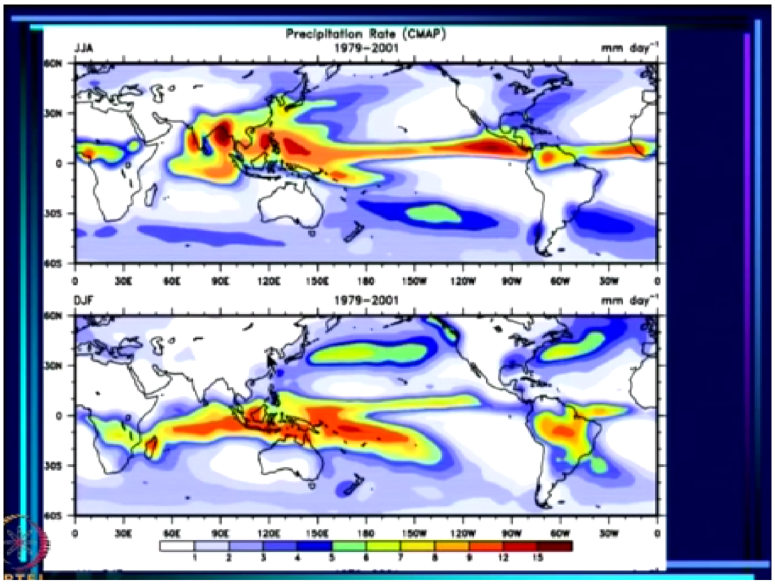

Now, this is the precipitation. This is JJA. This is in millimeters per day and basically regions over this green and the colors within the green have reasonable amount of precipitation. This is what we pointed out yesterday also. This means that the precipitation is more than 5 mm per day which is significant because for 5 mm it comes to about 45 cm for the season.

So, this is a reasonable amount of rain occurring here in June, July, August and reasonable amount of rain occurring here in January, February, March. Also something in South America, something in South Africa here and here of course the Indian monsoon and the Africa region as well.

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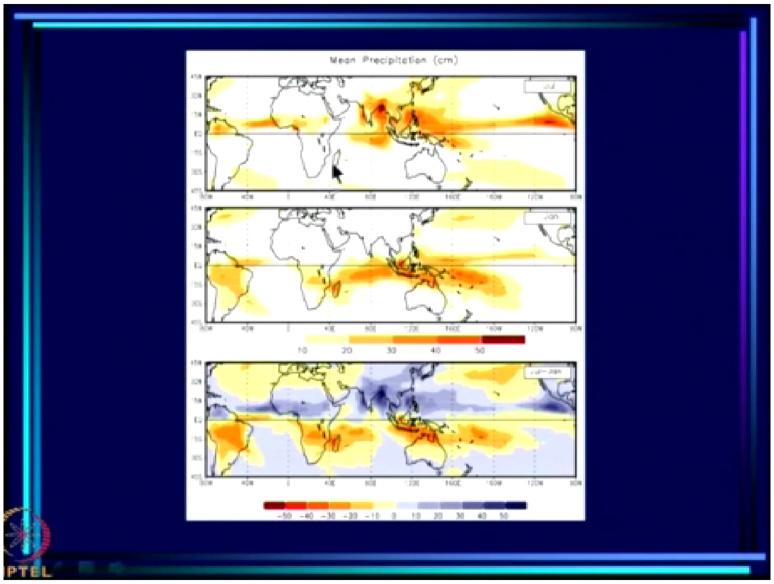

So, this is what shows the picture of the rain and this is the same thing for July and January just to give you an idea and most of the regions in yellow here are those that have more than 10 cm of rain in that month. So, this is July and this is January, again pretty much similar picture that we saw earlier.

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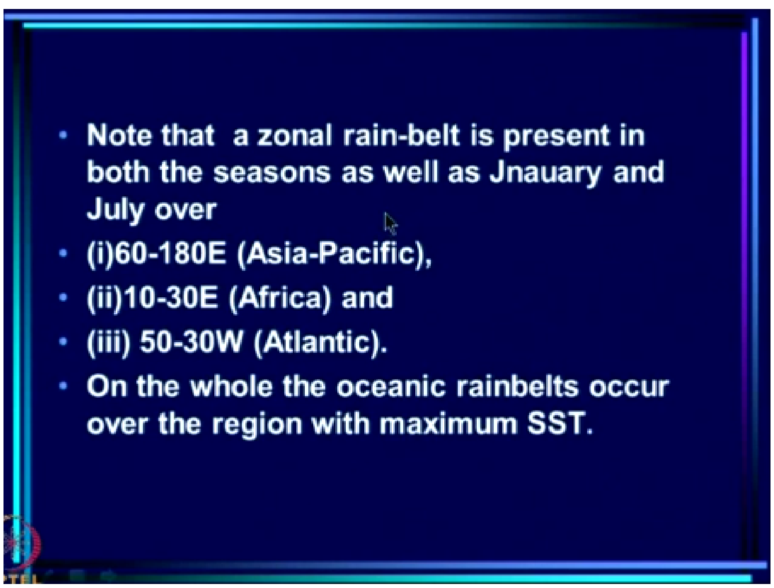

So, we have a zonal rain-belt present in both the seasons as well as January and July over the following region. That is here, over this region. From over 60 degrees East to 180, there is a very clear zonal belt seen in both the seasons. In addition to that, there is also zonal belt seen over Africa in both the seasons. So, we see zonal belt over the Asia-Pacific, over Africa and also over the Atlantic. So, let us see in the Atlantic also, we see a zonal belt seen but only a part of it here, not extending up to here but this part you see in both the cases. So, in both the seasons, we see zonal belt over these 3 regions.

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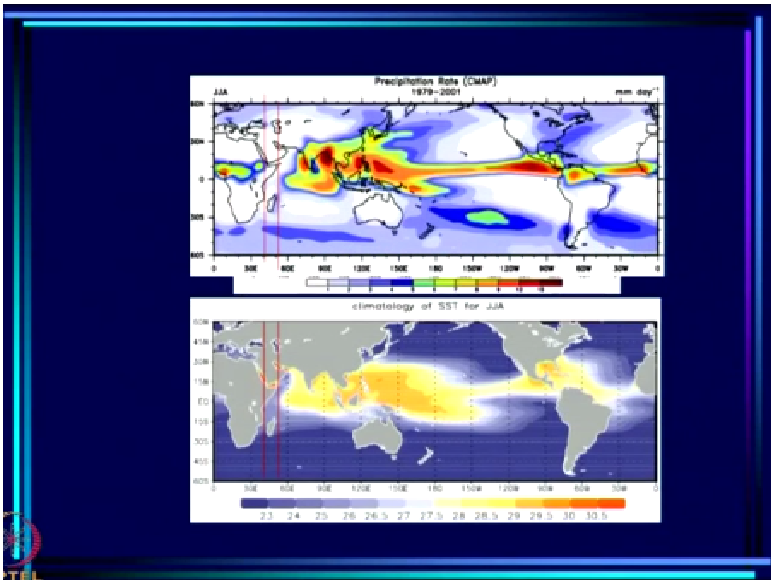

On the whole, the oceanic systems seem to coincide with the SST. Now, what you see here is for again JJA and this is the sea surface temperature mean for JJA and what we have done is marked in light yellow onwards all the regions with SST above 27.5 which as you know is a threshold of SST for convection. So, all these regions are warm and you can see actually this is JJA, you can see this is where the warmest regions are and that is where it is raining, okay.

Similarly, here this is where the warm region is and that is where it is raining here. Of course, here also you see over the warm parts, there is rain. What is interesting is that there is this blank here. You know, there is no rain at all in this region over the Western part of the Indian Ocean or off the coast of Africa over Western Arabian Sea and this part is totally cloud free, has no rain at all and in fact, is the part where SST is below the threshold.

So, it is very interesting that SST has to be above the threshold for us to get a rain-belt of this kind.

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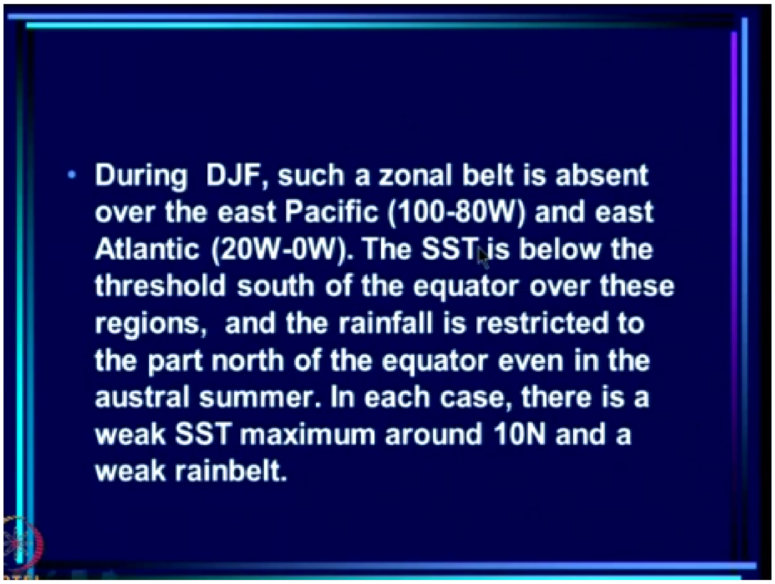

Now, during (DJF) December, January, February, again we see a rain-belt here 60 to 180. Again, there is a rain-belt over Africa and there is some over here and here. So, where do we see the rain-belt. During DJ F, such a zonal belt is absent over 100 to 80 West and East Atlantic.

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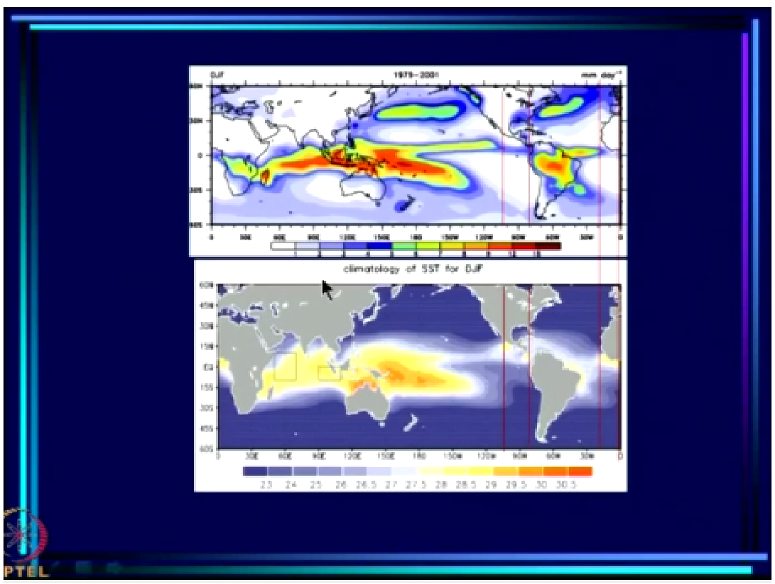

So, let us see. See, it is absent over these 2 regions I have marked in red; this is the East Pacific and this is the East Atlantic. You see the rain-belt is absent and you see that is the region where south of the equator, the sea surface temperature is below the threshold here, okay and here also, the sea surface temperatures south of the equator is below the threshold.

North of the equator, you do get a weak small region in which it is above the threshold, not very large region and that is where you get some rain here, okay but in this part there is not much rain at all and that corresponds to these cold seas to the south of the equator. So, the SST is below the threshold south of the equator over both these regions, East Pacific and East Atlantic and the rainfall is restricted to the part north of the equator even in the Austral summer. Austral summer is DJ F, okay. In each case, there is a weak SST maximum around 10 knot and a weak rain-belt, that is all there is to it, okay.

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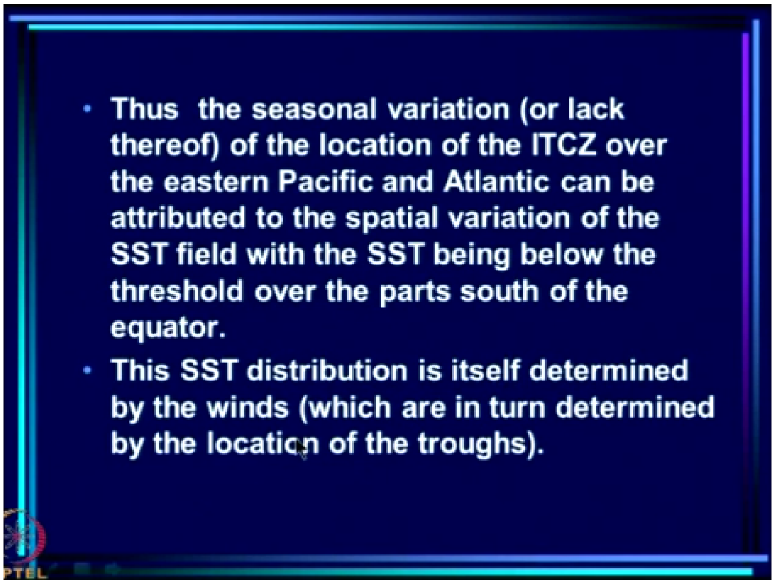

This is the case for DJF. Thus, the seasonal variation or lack thereof because what we are saying is over East Pacific and East Atlantic, there is hardly any seasonal variation. The rain-belt remains around 10 knot throughout the year it becomes very, very weak in part of the year. So, the seasonal variation or lack thereof of the location of the ITCZ over the Eastern Pacific and Atlantic can be attributed to the special variation of the SST field with the SST being below the threshold over the parts of the south of the equator.

So, south of the equator SST is below the threshold and that is why, we are getting this kind of a situation. This SST distribution itself, how does that arise. Now, this is where it is very clear that it is a bit of a chicken and egg problem, because SST distribution is itself determined by the winds and what determines the winds. Winds are determined by the pressure gradients, okay and the pressure gradients in turn depend on where the rain-belt is, where the ITCZ is and so on.

So, this is a situation where you have consistency between SST and the winds. While you can say that because SST is called the ITCZ did not occur there, but it is also a fact that the winds are the way they are because of the ITCZ occurring at a special place.

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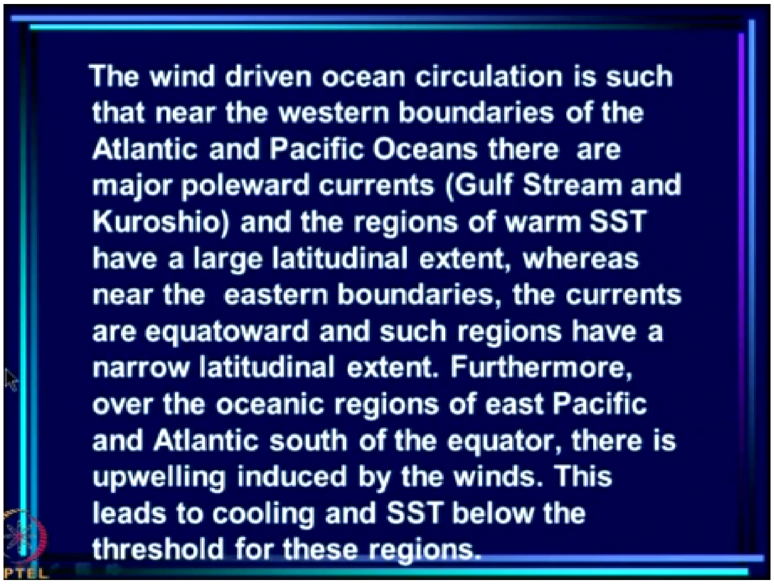

Now, the wind driven ocean circulation is such near the western boundaries of Atlantic and Pacific, there are major poleward currents and regions of warm SST have a large latitudinal extent, whereas near the Eastern boundaries, the currents are equatoward and such regions have a small latitudinal extent. Let us just see this. Now, you see these are the warm regions for DJF and you can see near the Western boundary of Pacific, this region is very, very large. Latitudinal extent is very large. Near the Eastern boundary, it is very, very small.

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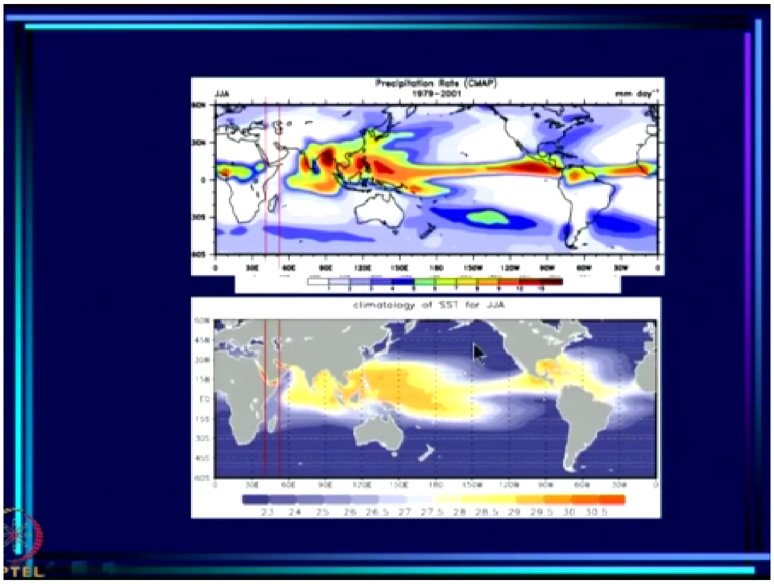

That is the same thing we saw for JJA as well, that near the Western boundary it is much larger and is larger also over the Atlantic near the Western boundary and near the Eastern boundary, the latitudinal extent of the warm region is relatively small.

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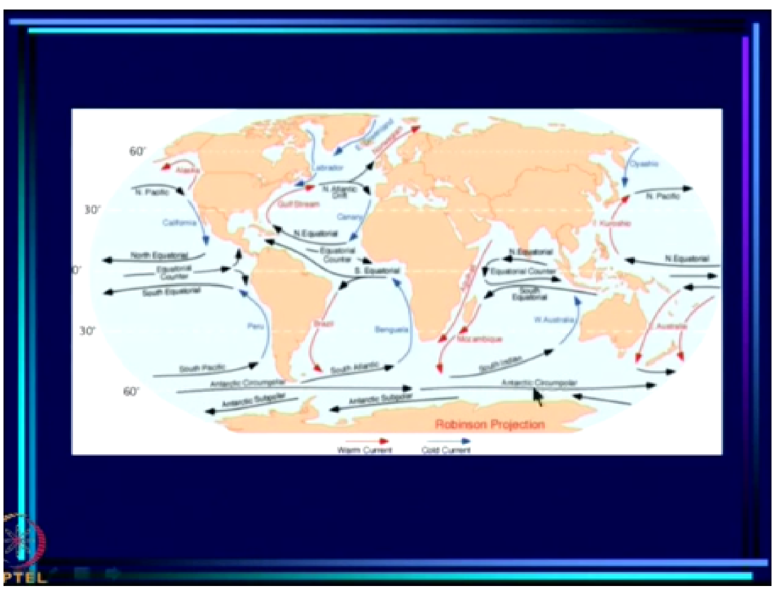

Now, how does this come about. So, let us look at what the circulation is like and this shows you the circulation drawn in red are the warm currents, okay and drawn in black are the cool currents. So, now you see here, this is the Atlantic Ocean and you have a very warm current gulfstream going from the equatorial regions to poleward region. So, this is a warm current. So, this is what makes the sea surface temperature warmer over the larger latitudinal extent here.

Whereas, see here this is blue, blue means cold current. So, on the Eastern side of the Atlantic, the currents are cold currents. So, naturally with cold currents coming from both sides, the SST is going to be restrained. The warm SST region is going to be restricted to a smaller latitudinal extent. The same story over the Pacific.

Over the Pacific also, we have the Kuroshio current which is the Western boundary current here, very strong current which is a warm current which makes large part of West Pacific very warm. A large latitudinal extent characterizes the region of warm SST, whereas if you go to East Pacific, you see these are cold currents coming from higher latitudes. So, the warm SST is restricted to a relatively narrow region. So, this is what happens.

So, the currents, you have warm currents flowing polewards in the Western boundaries which make the latitudinal extent of the warm SST region in the Western parts of Pacific and Atlantic very large, whereas you have cold currents coming from the poles towards the equator near the Eastern boundaries which makes the latitudinal extent of warm SST regions near the Eastern boundaries very, very small, okay.

Now, in addition what we saw was definite suppression of convection to the south of the equator and very, very cold SST south of the equator. So, what happens there is that the winds are such that there is also upwelling induced by the winds. Upwelling means you know you always have colder water in the ocean below the surface. The temperature decreases as you go away from the surface deeper and deeper.

Whenever wind force upwelling, i.e., water from below the surface to come up that also causes cooling. So, this leads to cooling and the SST below the threshold for these regions. So, we see why the SST is below the threshold and given that SST is below the threshold, the seasonal migration of the ITCZ is very much restricted in these regions. That is what happens here. So, I think we can understand because of this.

You know why the seasonal migration is much larger over these oceanic regions than it is over these oceanic regions. In fact, here there is no seasonal migration at all over the East Pacific and the East Atlantic, okay. So, this we can now understand.

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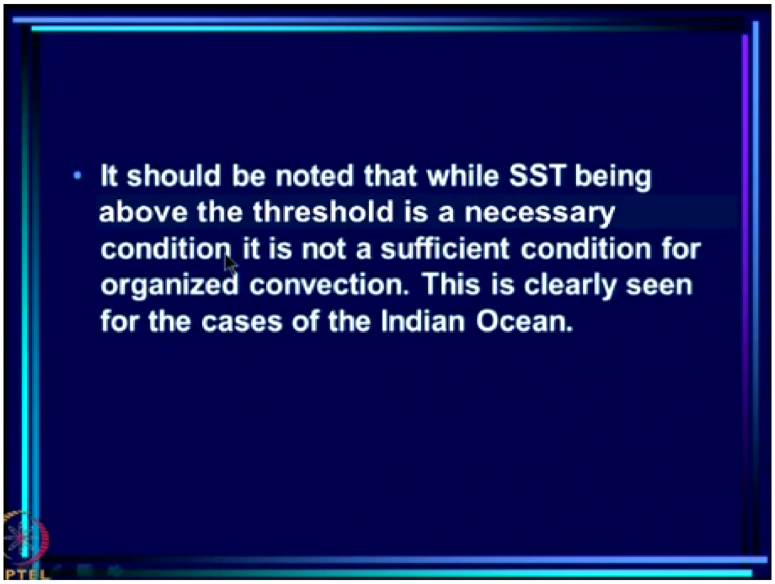

Now, it should be noted that while SST being above the threshold is a necessary condition, it is not a sufficient condition for organised convection and I want to show that a further cases of the Indian Ocean.

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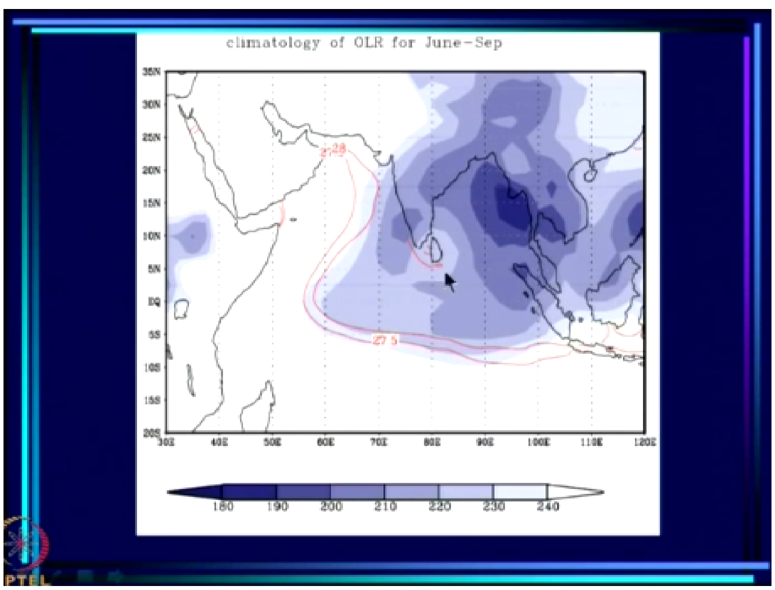

Now, this is the June to September case. This is the OLR for June to September and we have actually shaded all OLR below 240 or so because this is seasonal mean, okay and in this seasonal mean you can see these 2 red things. This is the SST 27.5 and this SST 28. So, you can say that almost the entire region oceanic region which is above the threshold has OLR below 240 that is to say there is convection filling almost the entire region where SST is warm, but this is not generally the case.

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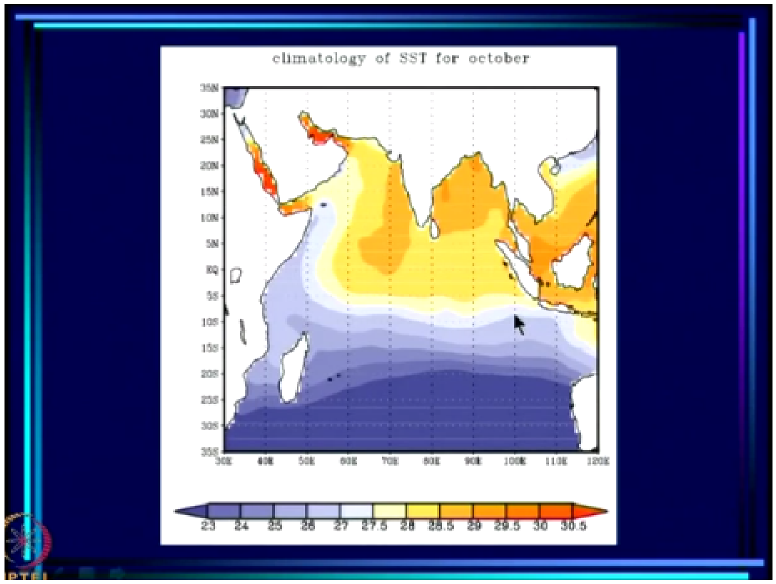

You see that for the case of October. Now, this is the climatology of SST for October again above 27.5 is yellow and you can see a large part of the basin is very warm in October but where is the rain. The rain is restricted to this part. You know, this is a part of Indonesia's Sumatra. So, the rain or the TCZ is restricted to this part and it by no means fills all these warm regions. So, Arabian sea is quite warm but there is no rain there. There are no deep clouds there in October.

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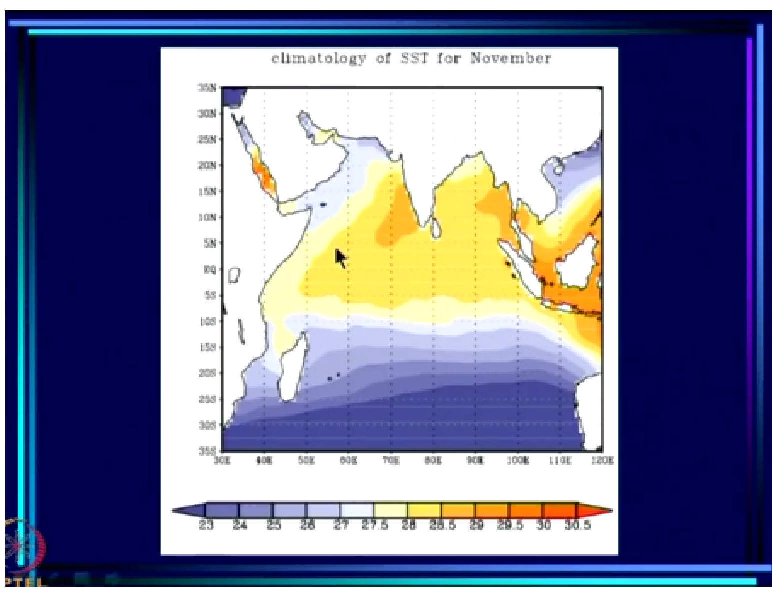

Same thing you see in November, again this region is very very warm and yet you see that the deep clouds are restricted more or less to this region and now northern part of the Bay has begun to cool a little bit but a large part of the Bay and a large part of the Arabian Sea although the SST is above the threshold, we do not get any deep convection.

This brings us to a point that Graham and Barnett meant which we talked about in the threshold lecture that in fact what is constraining the rain in this kind of a situation is not SST at all because SST is above the threshold and it is dynamics where low-level convergence will occur that determines where you are going to get a deep convection or low OLR. So, this is a point to be born.

So, I think we have now sorted out how the heat lows differ from TCZs and we have understood to some extent how the distribution of these over the thing.