The Monsoon and Its Variability
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Lecture – 31
Indian Ocean and the monsoon - Part 2

We will continue our discussion on the Indian Ocean and the Monsoon today.

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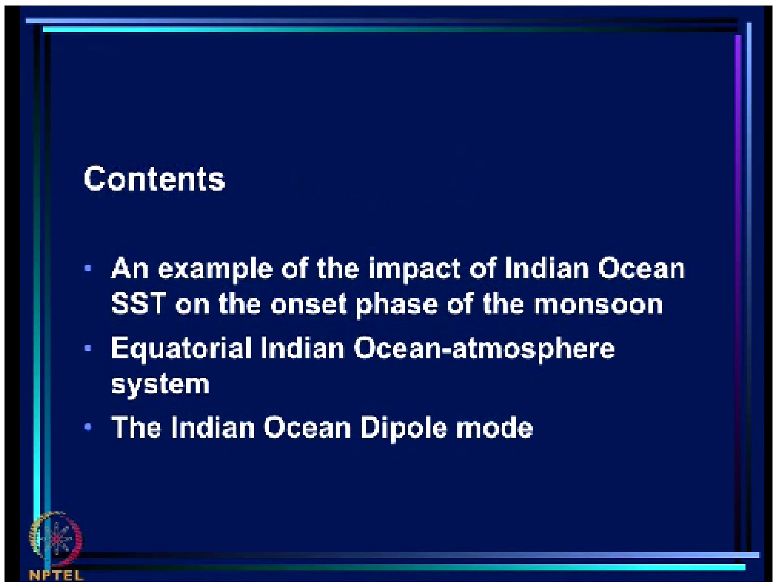

And I said that it is important to understand how the variability of convection in the monsoon region depends on the variability of SST of the north Indian and equatorial Indian Ocean.

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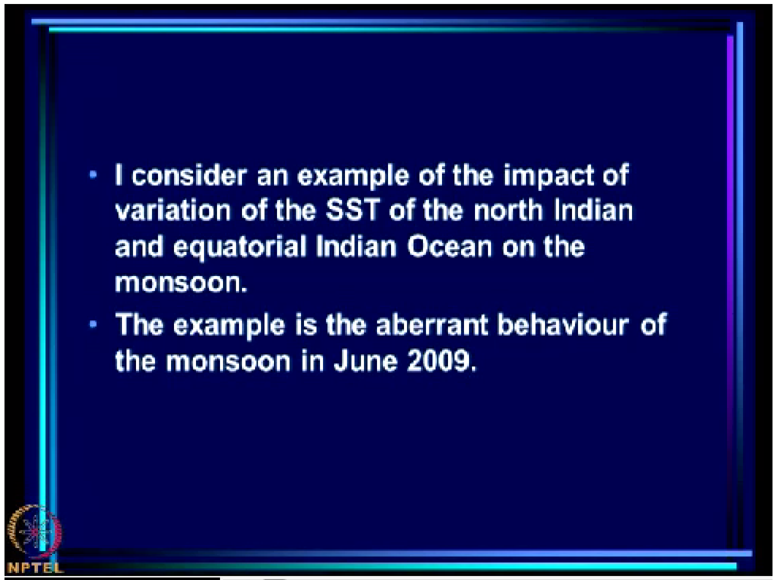

So I am going to first talk about an example which is the aberrant behaviour of the monsoon in June 2009.

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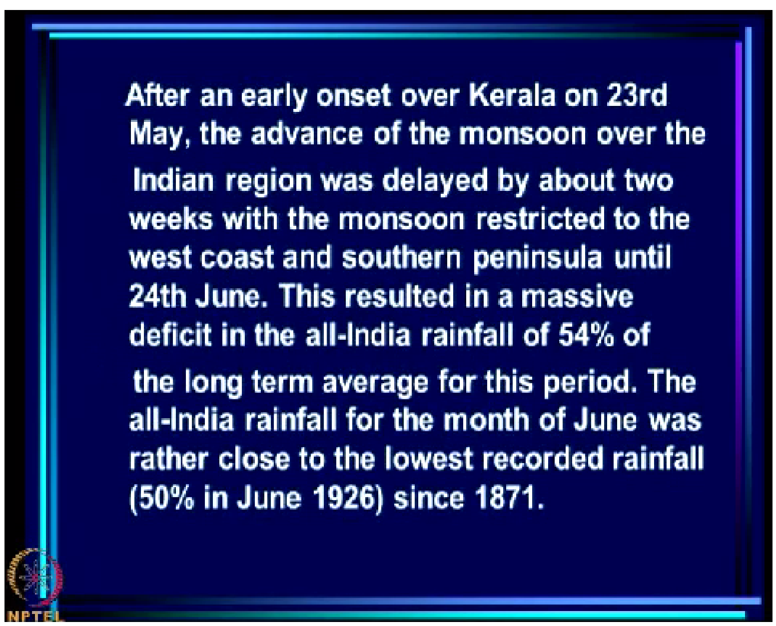

So what happened in June 2009 was intriguing. After an early onset over Kerala on 23rd May, the advance of the monsoon over the Indian region was delayed by about 2 weeks with the monsoon restricted to the west coast and southern peninsula until 24th of June.

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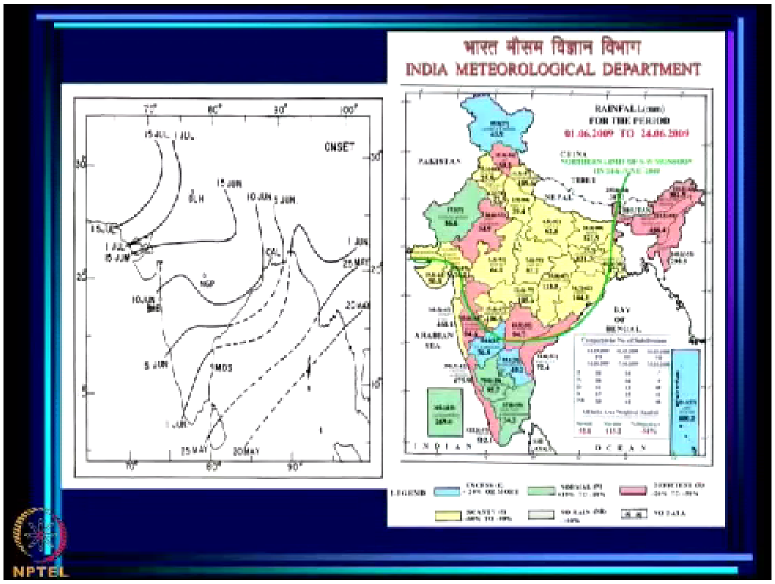

So you can see what happened here see, actually these are the dates of onset when the monsoon is supposed to come, the mean dates. By 15th June, it should have come here and by 24th, it should have come somewhere here. Instead of that, by 24th June, the northern limit of the monsoon was still this one and because of that, see all these regions had very very high deficits in rainfall, all these subdivision, because monsoon had not come there at all.

Only in the south, we got some rain. So what happened was that this resulted in a massive deficit in the all-India rainfall of 54% of the long-term average for this period. The all-India rainfall for the month of June was rather close to the lowest recorded rainfall which is 50% in June 1926 since 1871. So it was close to a record in terms of deficit in June.

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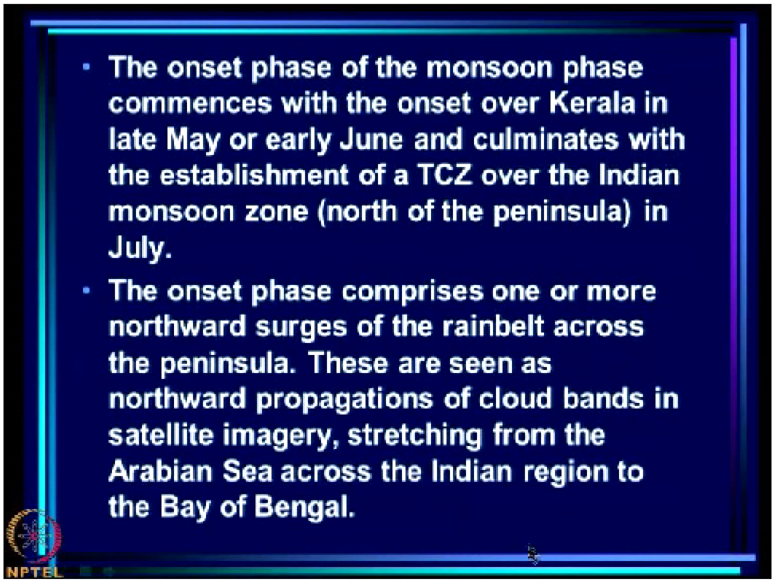

And of course this was not predicted by anybody. Now let us remind ourselves that the onset phase of the monsoon commences with the onset over Canada in late May or early June and culminates with the establishment of a TCZ over the Indian monsoon zone north of the peninsula in July. We have already seen this. The onset phase comprises one or more northward surges of the rain belt across the peninsula, this also we have seen.

These are seen as northward propagations of cloud band in satellite imagery stretching from the Arabian Sea across the Indian region to the Bay of Bengal.

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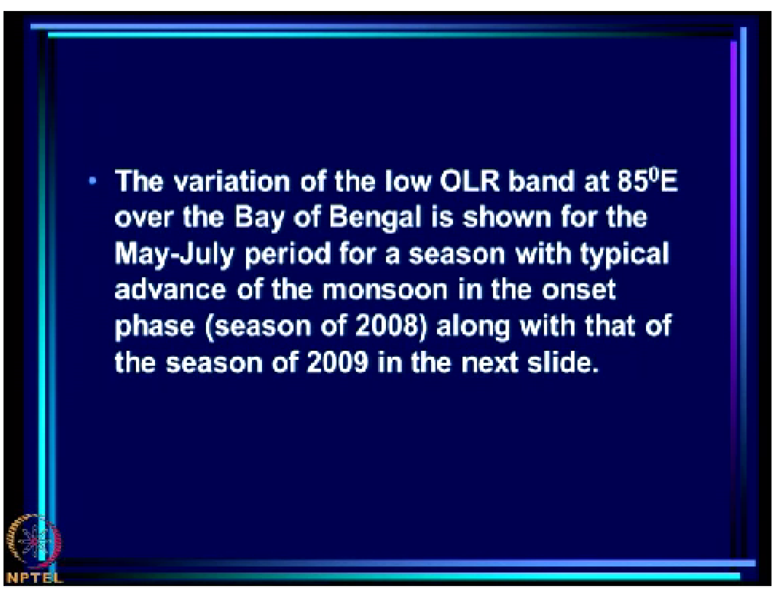

Now the variation of low OLR band at 85 degrees east over Bay of Bengal we will look at, we are going to look at it for the May to July period for a season with typical advance of the monsoon in the onset phase which is the season of 2008 along with this aberrant onset phase in 2009.

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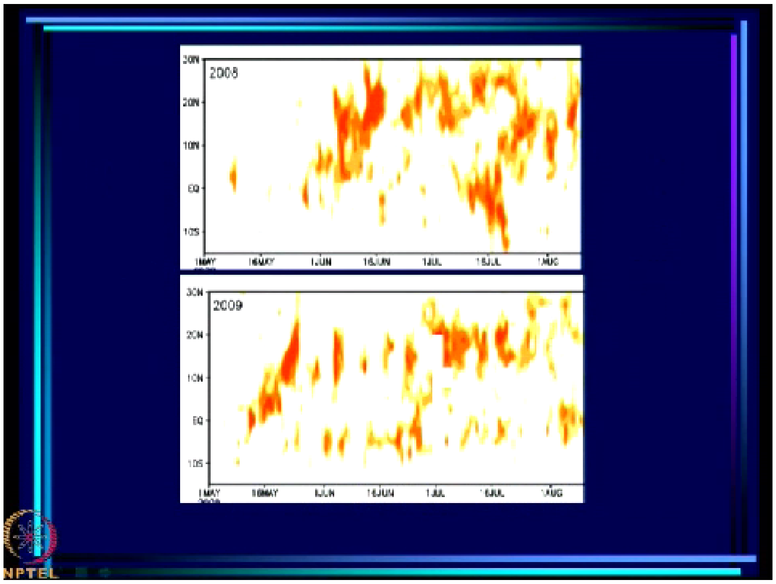

So what you see here above is 2008 and here you see 2009. We got a reasonably good onset but after that, you can see 85 degrees east, east is the longitude just across the Bay, right. It is slightly to the west of Kolkata. It is going across the Bay. So this is the first northward surge but you see what happens in a typical year is after the northward surge, then the band hangs here in the monsoon zone, that never happened.

After this, the band kept on appearing over the Bay but for very very short periods, 2 days, 3 days and so on, okay. Whereas you see typical here, this is what would happen but you also see that there was some convective activity over the equatorial Indian Ocean, you see equator to 10 south, you kept getting a seesaw between convection here and here you can see. This band had become prominent then this got born and died.

This band was here, then this got born, it died and so it continued till about 24th of June. So this is the story which is very different from a typical onset phase of the monsoon.

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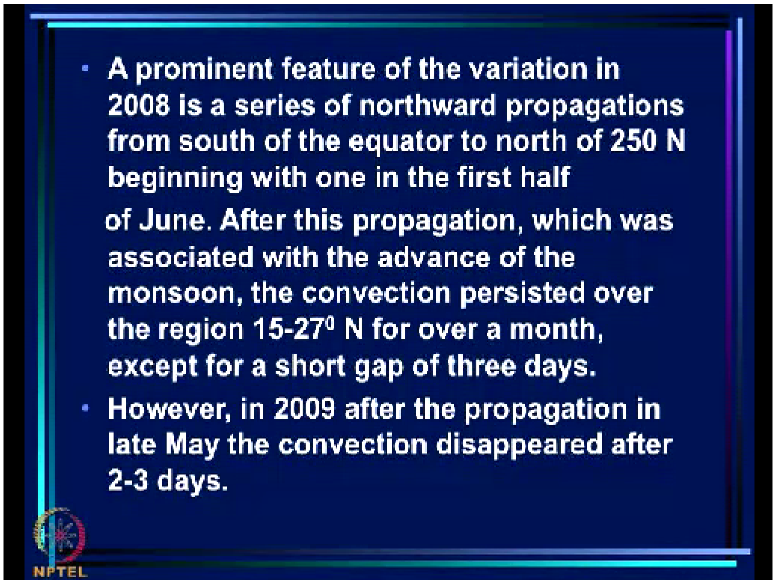

So prominent feature of the variation of 2008 is a series of northward propagations from south of the equator to north of 25 north beginning with one in the first half of June. After this propagation, which was associated with the advance for the monsoon, the convection persisted over the region 15 to 27 north for over a month except for a short gap of 3 days. We have seen that once this advanced, it persisted over this zone for several days except for a gap of very very few days.

However, in 2009 after the propagation in late May, the convection disappeared after 2-3 days, we have seen this. Once it propagated here, after 2-3 days, the convection just disappeared.

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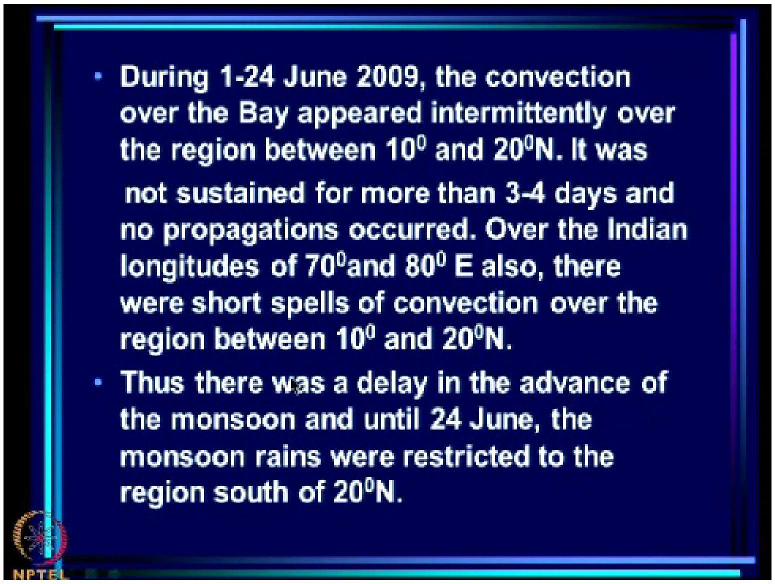

During 1 to 24 June, the convection over the Bay appeared intermittently over the region between 10 and 20 north, we have seen this also. See between 10 and 20 north is this region, so the convection went on papering and disappearing. It appeared intermittently in this region and it was not sustained for more than 3-4 days and no propagations occur. Over the Indian longitudes of 70 and 80 also the story was the same.

There were short spells of convection over the region between 10 and 20. Thus there was a delay in the advance of the monsoon and until 24th June, the monsoon rains were restricted to the region south of 20 north.

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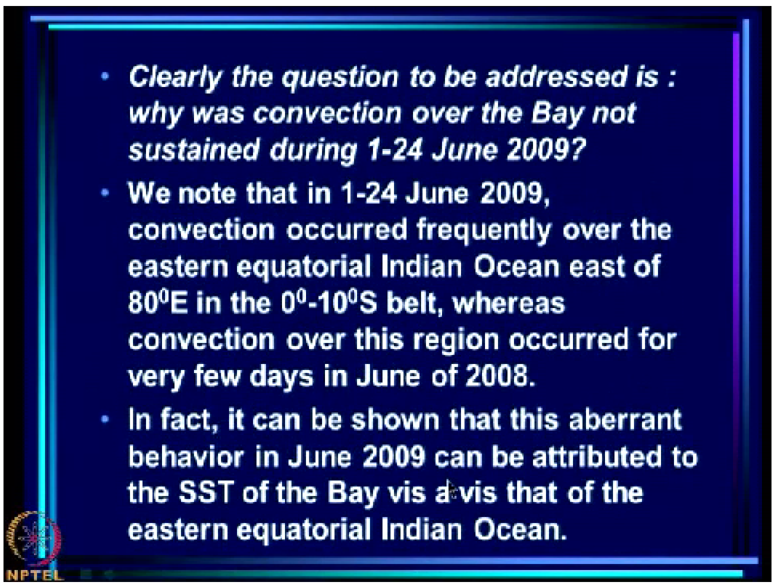

So clearly the question to be addressed is, why was convection over the Bay not sustained during 1-24 June 2009? Now we note that in 1-24 June 2009, convection occurred frequently over the eastern equatorial Indian Ocean east of 80 degrees east in the 0 to 10 degree south belt, whereas convection over this region occurred for very few days in 2008.

This is something we have noted before that here between equator and 10 south hardly any days of convection but for 2009, you see large number of days with convection here. So in fact, I will show now that this aberrant behaviour in June 2009 can be attributed to the SST of the Bay vis-a-vis that of the eastern equatorial Indian Ocean. So this is an example to show how variability of SST can have a direct impact on the monsoon.

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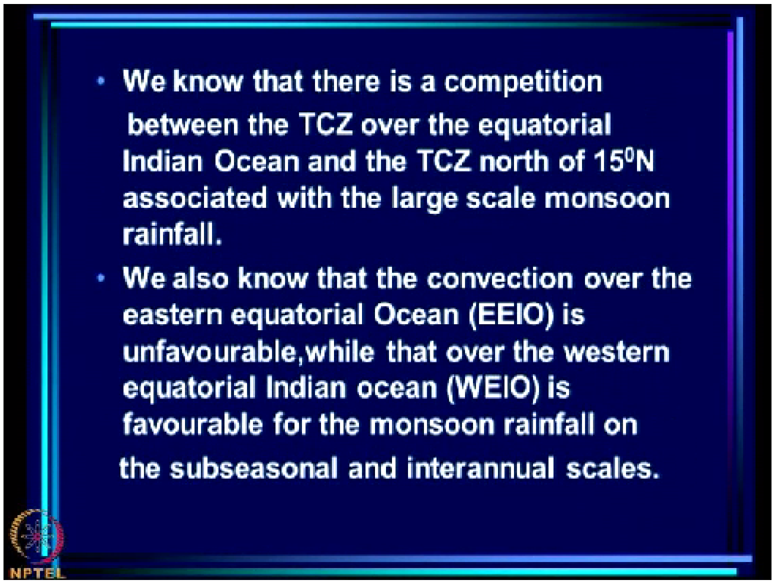

Now we know we have discussed this often that the CTCZ is actually maintained by propagations of the equatorial ITCZ or equatorial tropical convergence zone onto the land. We have also noted that the relationship between CTCZ or the tropical convergence zone in the latitude of the monsoon zone and the oceanic TCZ is very complex. On the one hand, the TCZ over the Ocean helps in maintenance of CTCZ by moving northward but on the other hand, it also competes with it and this is something we have seen.

Now we have also seen in our discussion of interannual variation as well as intra-seasonal variation, that is to say active and breaks, that convection over the eastern equatorial Indian Ocean is unfavourable for the monsoon. So that is the region over which if a TCZ appears, it competes with the monsoonal TCZ while that over the western part is favourable for the monsoon.

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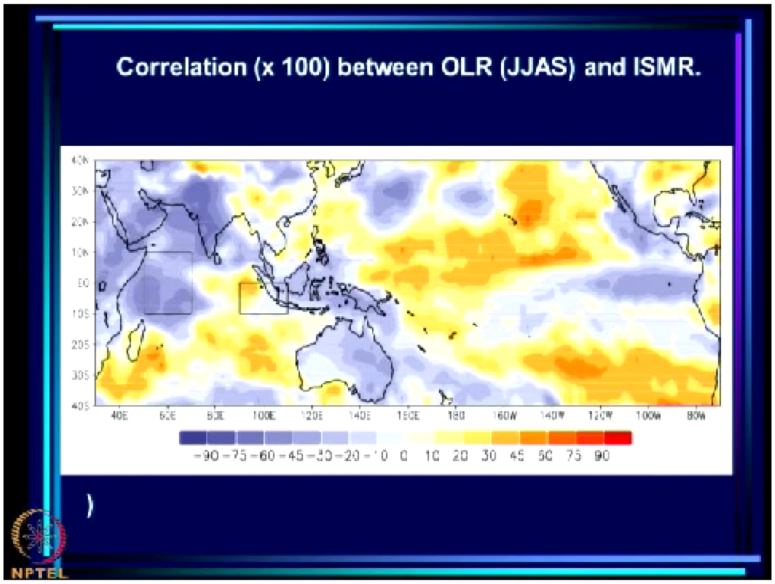

And you can see that here, this is the correlation between OLR and ISMR, all-India monsoon rainfall and you can see that there is an inverse correlation between the rainfall over India and here. Whereas rainfall over the monsoon region depends on the rain over the Bay and the rain over the Bay is negatively correlated to the rain over the eastern equatorial and central equatorial Indian Ocean, whereas it is positively correlated with the western part. This is for the seasonal scale.

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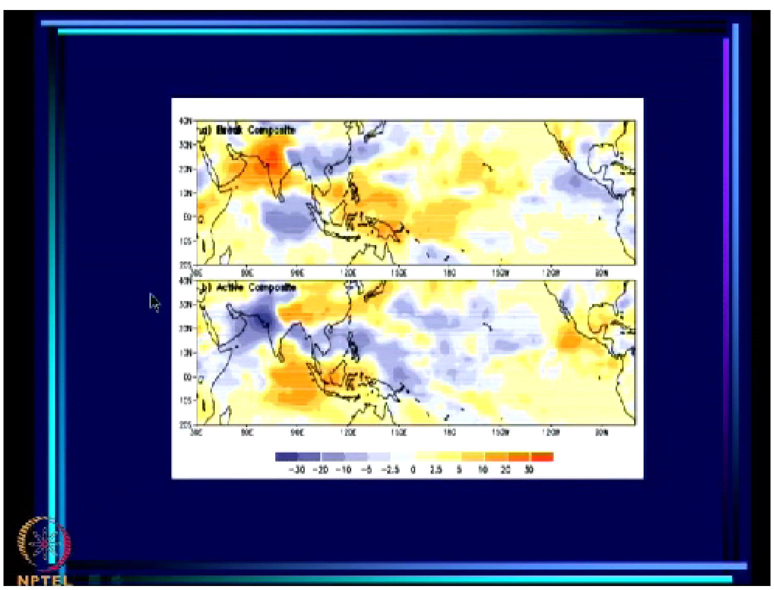

On the intra-seasonal scale also we have seen that if we look at the break composite, the biggest signal is that when there is a break, there is a flare-up of convection here over eastern and central equatorial Indian Ocean and in an active phase, convection over eastern and central equatorial

Indian Ocean is suppressed. So the competition between convection over the Bay and the monsoon zone is with the eastern part, eastern equatorial Indian Ocean and not with the western part. In fact, western part is favourable. So we know this, okay.

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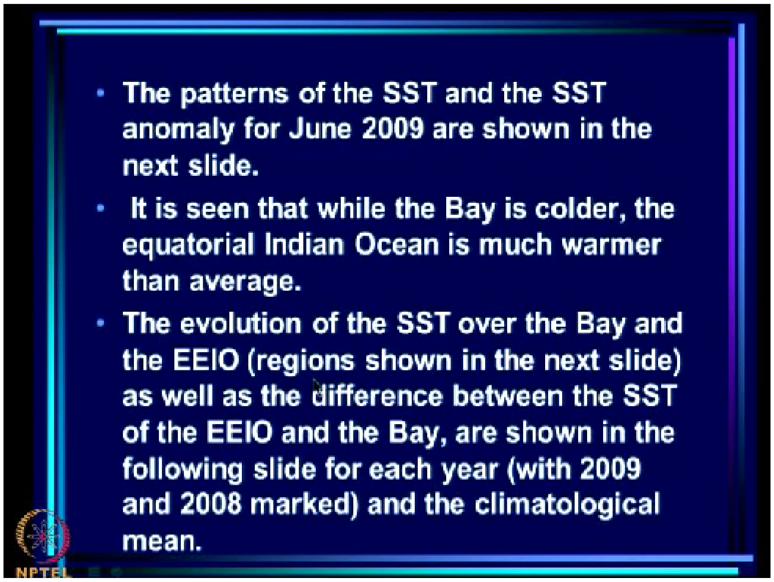

And we saw it also actually in the pictures that we saw here. Here also we could see that in 2009 as I mentioned, this died and then this was born, this flared up again after this died but again this flared up and this died and so on and so forth. So you see a seesaw in activity here, this also suggests that there is a competition between the convection over the Bay between 10 and 20 north and the convection over equator to 10 south over the same longitude.

So the question to be addressed is, okay, so we will now see why is it that the equatorial TCZ was hyperactive in June 2009 at the cost of the TCZ over the Bay of Bengal, okay and we believe the answer is in the sea surface temperature distribution.

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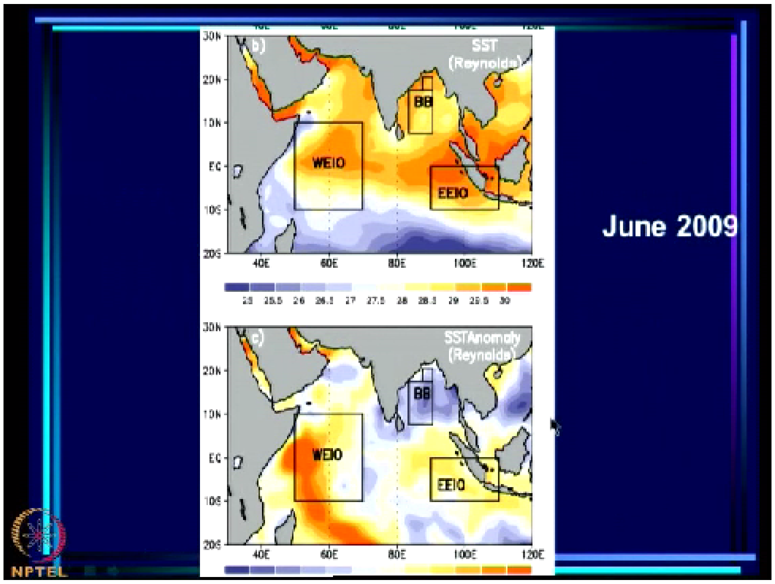

And this is the sea surface temperature SST and you see this is the eastern equatorial Indian Ocean, this is the western equatorial Indian Ocean and this is the Bay of Bengal which we are concerned with. This is the region over which disturbances form and then move onto the Indian region. Now you can see that the eastern equatorial Indian Ocean is definitely warmer than the Bay of Bengal.

And in fact, this is a manifestation of the fact that you had a lot of cooling over the bay that year. Cyclonic storm was there in May which led to a lot of cooling here. So that there is negative SST anomalies over the Bay and positive SST anomalies over EEIO. So you have a situation in which the eastern equatorial Indian Ocean is warmer than the Bay in the month in which the onset phase occurs, which is the June month.

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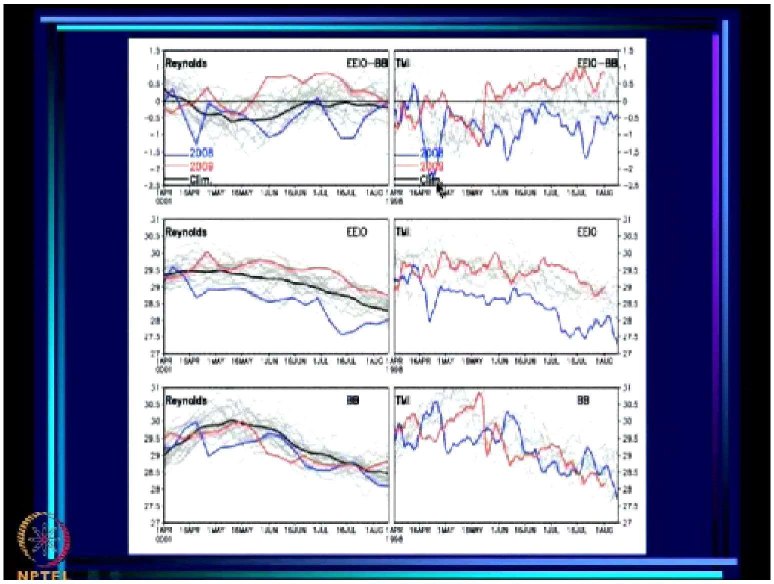

Now let us look at, we have 2 datasets, Reynolds here and TMI here. TMI is the more modern one and it is always a good idea to see whatever results you get from one, also holds for the other dataset. It should not be dependent on the dataset itself. Now what you see here, these hairs, they correspond to every year for which data are available, okay and they are, what are they? I have already shown you the regions which we are interested in. This is EEIO and this is the Bay of Bengal, okay.

And we believe at least the pictures of low OLR region have shown us that there seems to be a competition between these 2 regions. So we look at the SSTs of those 2 regions. So this is SST of EEIO, this is the SST of BB, Bay of Bengal and this is the difference in the SST of the 2, EEIO-BB. Now that we have done is, we have plotted the mean which is climatology, we have plotted 2008 which is blue and 2009 which is red. So let us see what happens.

See climatologically, you see that right from April onwards, this is plotted from April onwards, the Bay of Bengal SST builds up and it slowly starts decreasing with the onset of the monsoon. This is climatology. Now what happened in 2008, 2008 the Bay was a little bit cooler in the early part of May but then made up and then was slightly cooler than the climatology but what happened for 2009 is that you saw that after mid-May, sudden cooling occurred.

And till about 24th of June or so, it was definitely cooler than climatology. So Bay is definitely cooler than climatology in this year. On the other hand, eastern equatorial Indian Ocean had been warmer than climatology throughout June; June, July and even part of August. Whereas 2008, it was colder. So we have a case in which EEIO is warmer than usual throughout and Bay of Bengal is colder particularly in the critical time when the advance has to occur in the onset phase.

Now what does the difference show as we expect. In fact the EEIO is warmer than the Bay of Bengal throughout 2009 whereas it is colder then the Bay of Bengal throughout 2008 and climatology assess that by and large up to about third week of June, EEIO tends to be colder than the Bay, afterwards they are very comparable, okay. So during the advance phase, the mean SST gradient is such that the Bay is warmer than the eastern equatorial Indian Ocean.

But what we see here is in fact, opposite occurred in 2009 whereas in 2008 when we got very nice propagations and a very nice advance, actually the eastern equatorial Indian Ocean was colder than SST. Notice that what I have talked about is so far for Reynolds, also holds very much for the TMI. Again the same story and you see that eastern equatorial Indian Ocean is warmer than the Bay in the critical period throughout, that is to say from beginning of June throughout and this is what we believe has done the damage.

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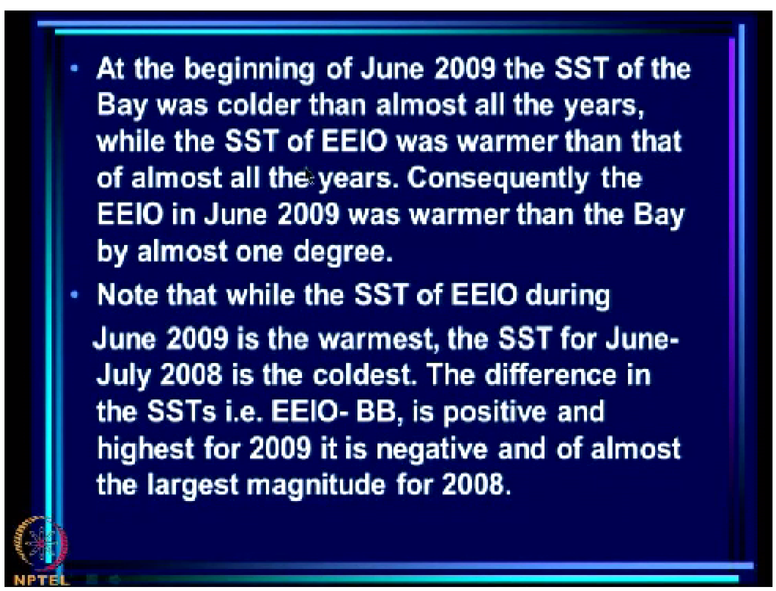

So at the beginning of June, the SST of the Bay was colder than almost all the years while the

SST of EEIO was warmer than that of almost all the years. Consequently EEIO in June 2009 was warmer than the Bay by almost 1 degree. You see this. If you look at June than this is almost 1 degree, EEIO was colder than Bay of Bengal by almost 1 degree in June. Note that while the SST of EEIO during June 2009 is the warmest, SST for June, July 2008 is the coldest.

This also we have seen that while the SST is the warmest here for EEIO, it is the coldest of all the years. So it was an exceptional year in terms of equatorial warming, okay. The difference in the SST is positive and highest for 2009 and negative and almost the largest magnitude for 2008, okay.

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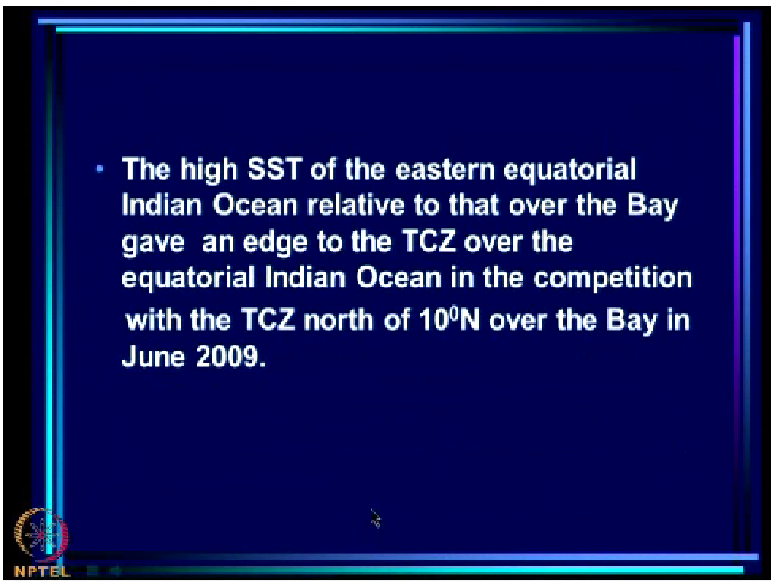

Now so what has happened is, we have 2 tropical convergence zones competing with one another, one is in the Bay between 10 and 20 north and the other is over the equatorial Indian Ocean between 0 and 10 south over the eastern part of the equatorial Indian Ocean. While normally the Bay is warmer and so the Bay TCZ has an edge over EEIO TCZ.

What has happened in 2009 is that EEIO is warmer than the bay in that critical time when advance of the monsoon should take place over the Bay and it is this high SST of EEIO relative to that over the Bay which gave an edge to the TCZ over the equatorial Indian Ocean in the competition with the TCZ north of 10 degrees over the Bay in June 2009.

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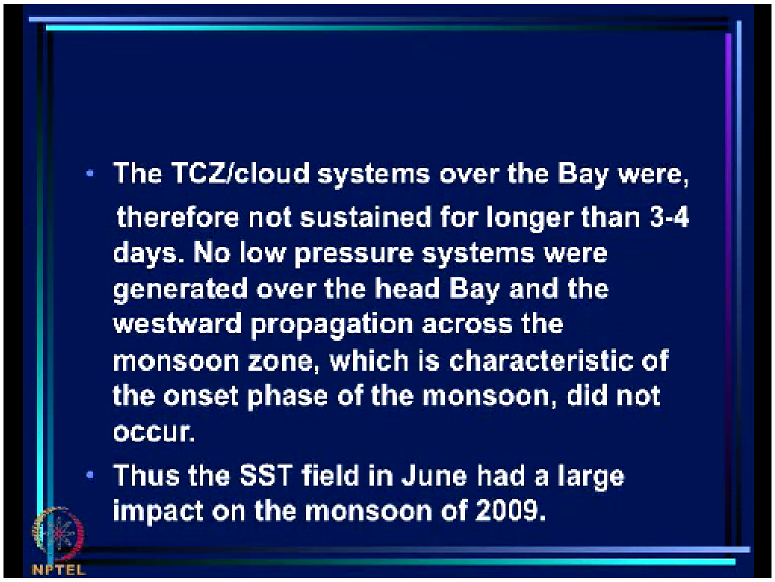

So this is a case in which we see a case of impact of SST variability, gradients of SST reversing from east equatorial Indian Ocean to the Bay which have had a major impact on the TCZ or cloud systems over the Bay and because of this, the TCZ or cloud systems over the Bay were therefore not sustained for longer than 3-4 days. No low pressure systems had been generated over the head Bay and westward propagation across the monsoon zone which is a characteristic of the onset phase of the monsoon did not occur.

So this is an example, an interesting one, in which the SST field in June had a very large impact on the advance of the monsoon and hence on the monsoon itself because actually the deficit that was so huge in June was never made up till the end of the season because the rest of the season also turned out not to be very good for other reasons. So this is just an example to say that all the effort we put in in trying to understand how SST evolve.

and eventually we would also like to model how SST evolves, predict what will be the SST in the forthcoming season and so on. Why is it important because it can have a direct impact on the competition between the different TCZs and thereby on the monsoon itself, okay. Now I will not dwell too much more on the Bay of Bengal, Arabian Sea and their relationship to the monsoon but what I will now do is to go over to the equatorial Indian Ocean-atmosphere system.

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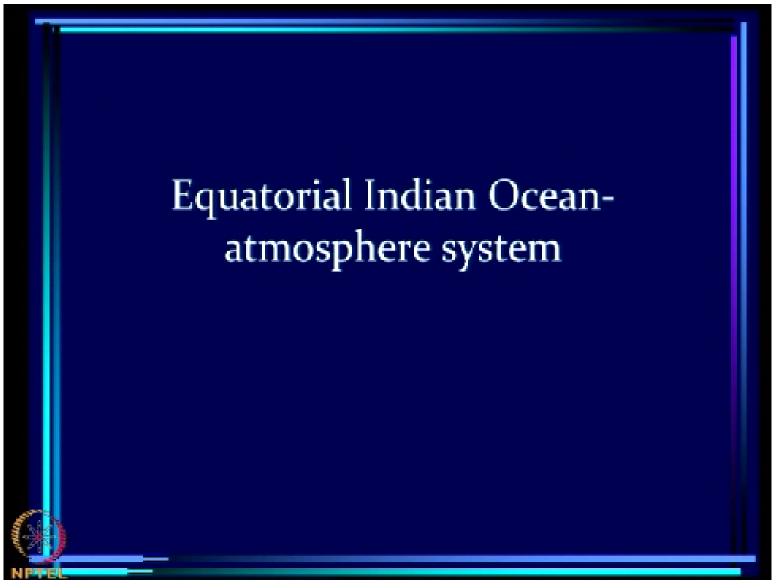

See so far we have been talking about is the north Indian Ocean comprising Arabian Sea and Bay of Bengal and we have looked at the mean patterns, how they evolve and also I tried to show you the kind of impact these temperatures can have on the monsoon but now let us go to the equatorial Indian Ocean system.

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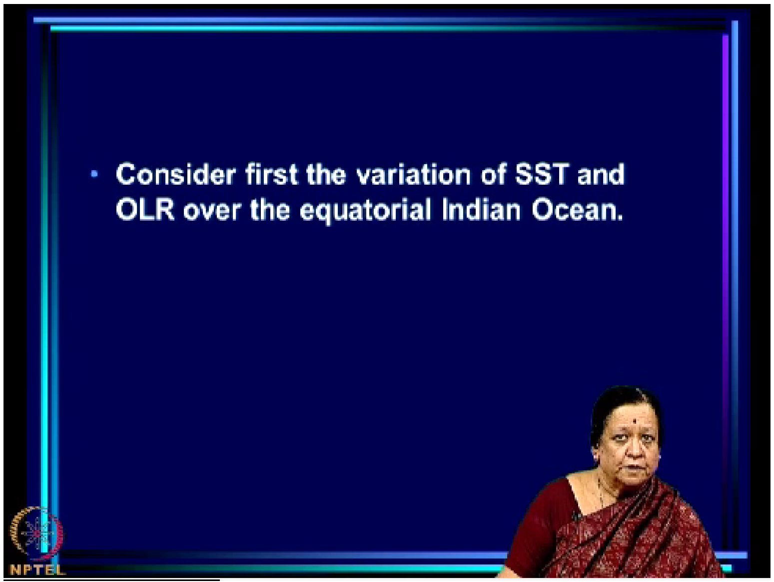

So first of all, let us consider the variation of SST and OLR over the equatorial region.

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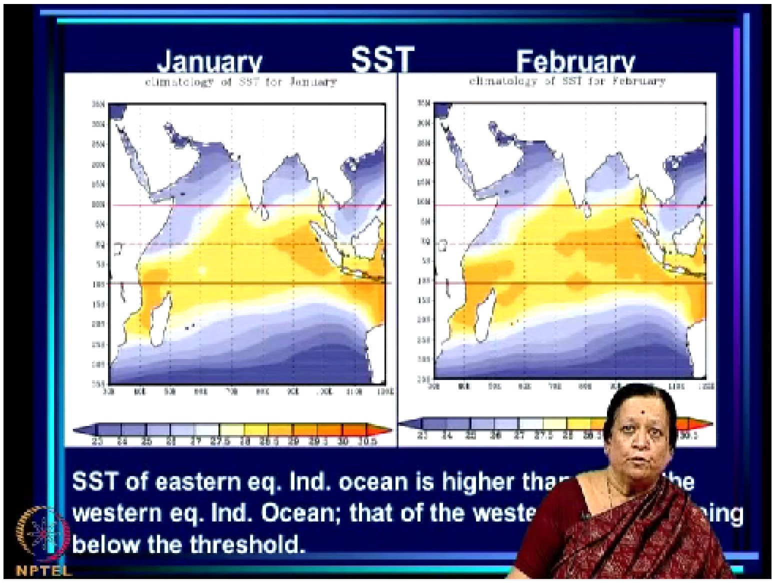

This is now January and February. Notice that the equatorial Indian Ocean is warmer in the east than in the west and west is in fact rather cold. It is below the threshold, okay. So along the equator if you look at, east is warmer than the West. Now this is opposite of what we saw in the Pacific and we will keep seeing that the picture is somewhat similar to the Pacific except we have to invert east and west. Now February again same thing, east is much warmer than the west along the equator.

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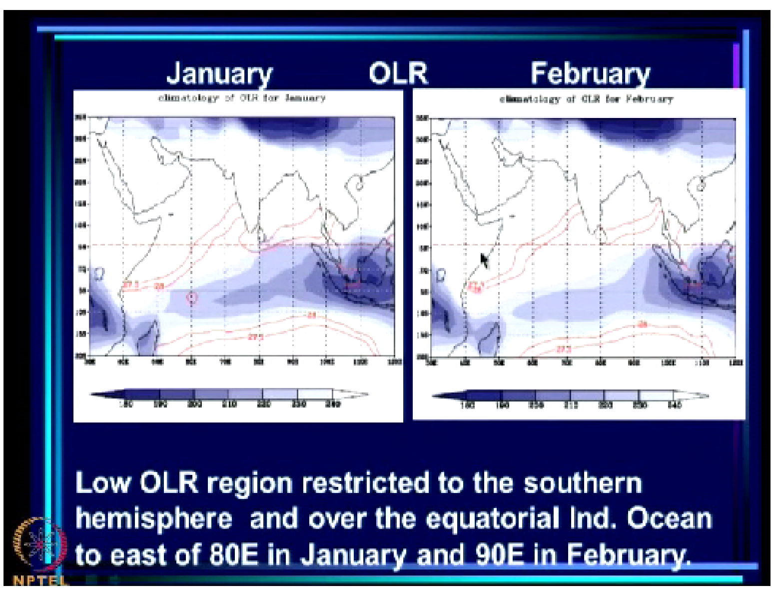

And this is the low OLR region here and you see that along the equator, January and February, the low OLR region is largely restricted to the south, southern hemisphere and in fact also restricted to the eastern part of the basin and much more restricted in February. What you see here in red are contours of 27.5 and 28, the possible thresholds in this region and what you can see is that a large part of the Ocean with SST which is warm enough to have convection, in fact does not have convection. This is true of January as well as February.

You see this part could have had convection but does not have.

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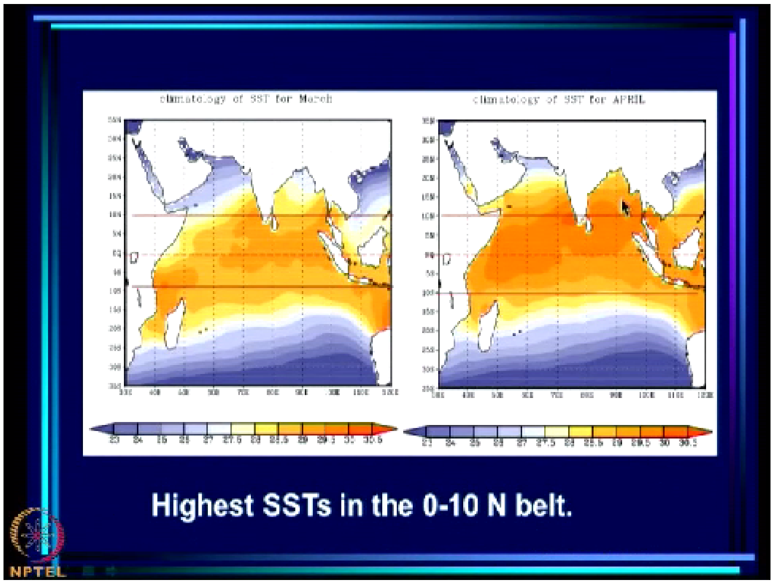

Now we come to March and April and these are lines that show 10 south to 10 north and in March and April everything has warmed up you see, these are very very high temperatures here and so the northern hemisphere because the sun has moved now over the equator and in April this is slightly in the northern hemisphere vertically above and you see this is a large body of very warm water in April and this is the warm water in March, okay.

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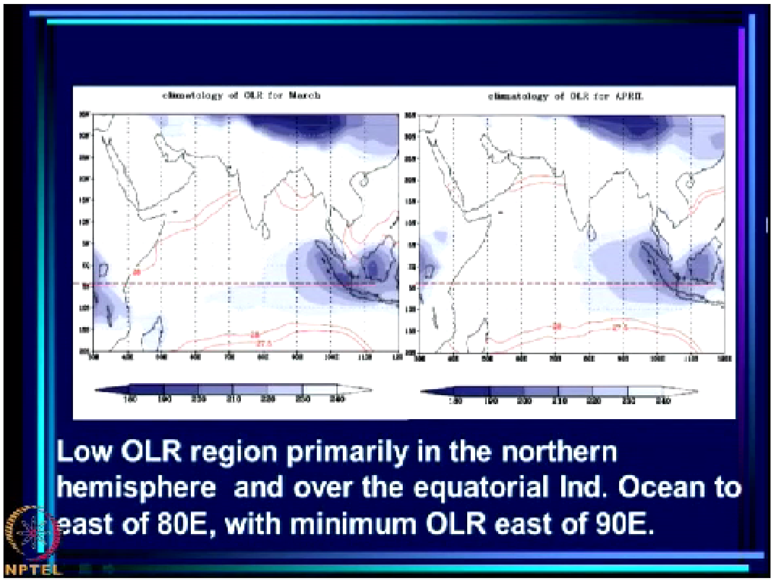

Now what happens to the low OLR region. Low OLR region in this case again occupies a very small part of the warm ocean, okay. It occupies only the eastern part, small region here but notice that now it has also come to the northern hemisphere. Earlier in January-February, it was restricted to the southern hemisphere. Now it is stretching across the equator but is very much restricted to the eastern part.

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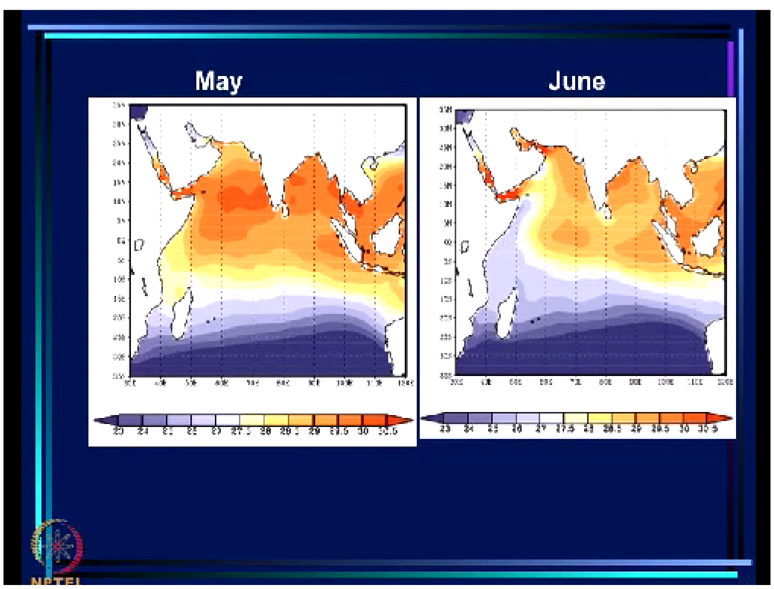

So now we come to May and June and the SSTs are getting hotter and hotter and this is June. By June, of course the onset has occurred and SST particularly of the Arabian Sea has cooled a lot and Bay also has cooled somewhat but in May, the SSTs here are very high and the maximum SST is of course in the northern hemisphere now because this is the northern hemispheric summer.

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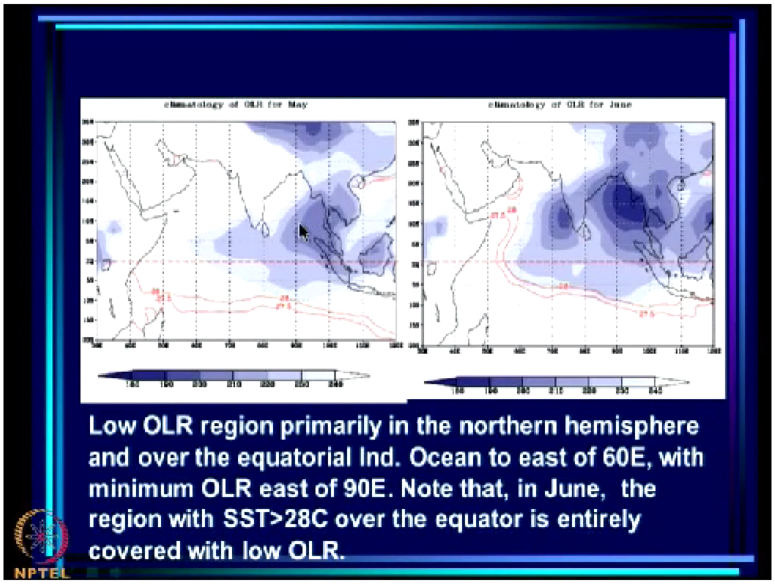

Now let us see what has happened here is, again we see that the low OLR region is restricted to the eastern part but has spread somewhat to now come also to the southern tip of eastern Arabian Sea here. So we have a low OLR region stretching all the way from 70 to 90, then the maximum intensity of convection is still along the east and this is the case for June. Again like I said for the other months, only a small part, well I will not say a small part, only a fraction of the ocean with the SST above the threshold has convection on it.

The rest of it does not have convection on it but notice that the entire ocean is rather warm in May. Now in June, this upwelling begins to develop here. So this begins to get cold and now you see a fairly large part of the warm ocean now is covered with low OLR, covered with clouds. Now you also see that in June, the convection here is as strong as the convection in the Bay.

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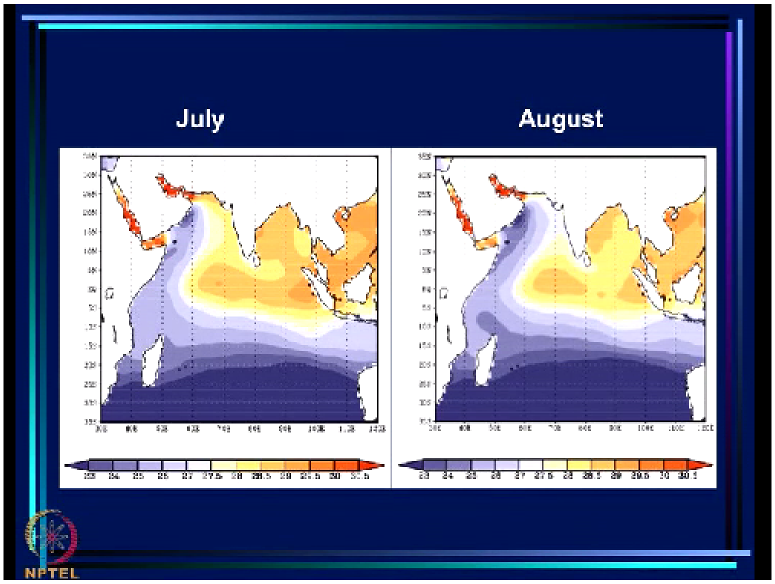

Now we come to July and August and you see this typical pattern where you see ocean, here is very warm, equatorial Indian Ocean is warm and Bay remains warm but the Arabian Sea is cooling, the warm cool region of the eastern Arabian Sea is shrinking. In July, at least you see it here but in August, you do not see it anywhere near the northern part of this coast. It is only restricted to the southern part of peninsula. So SST is cooling very fast.

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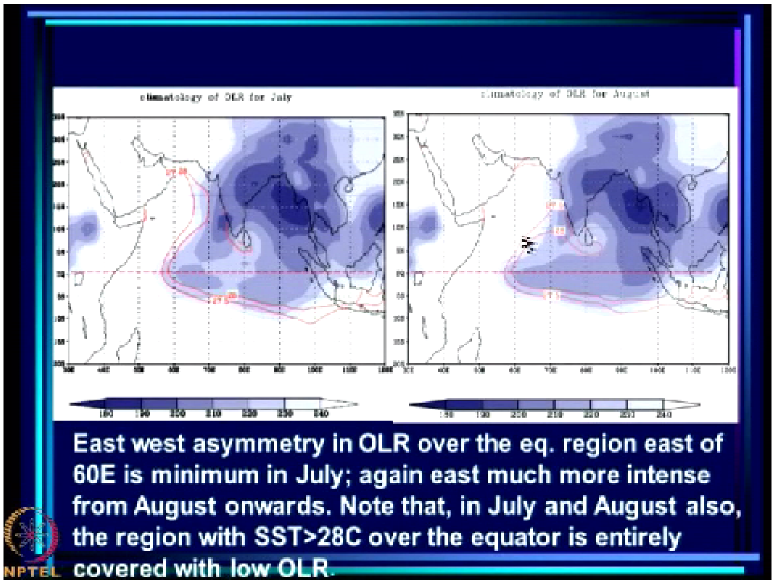

What is happening to OLR? Both for July and August, you see it looks like the dynamics is very favourable and that is why almost the entire warm pool is covered with deep convection as evidenced from the OLR maps, okay. That in July and August also almost both of these months, the warm pool is covered with low OLR.

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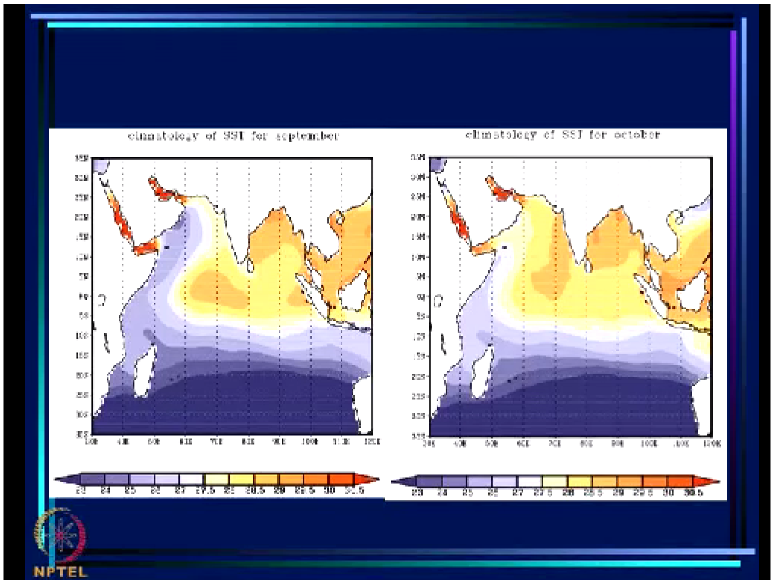

Now this is the climatology of SST along the equator for September and October. Now you see with the withdrawing of the monsoon and withdrawing of the clouds, things slowly begin to warm up again and you can see by October, quite a large pool of warm water has built up over the Arabian Sea here, okay.

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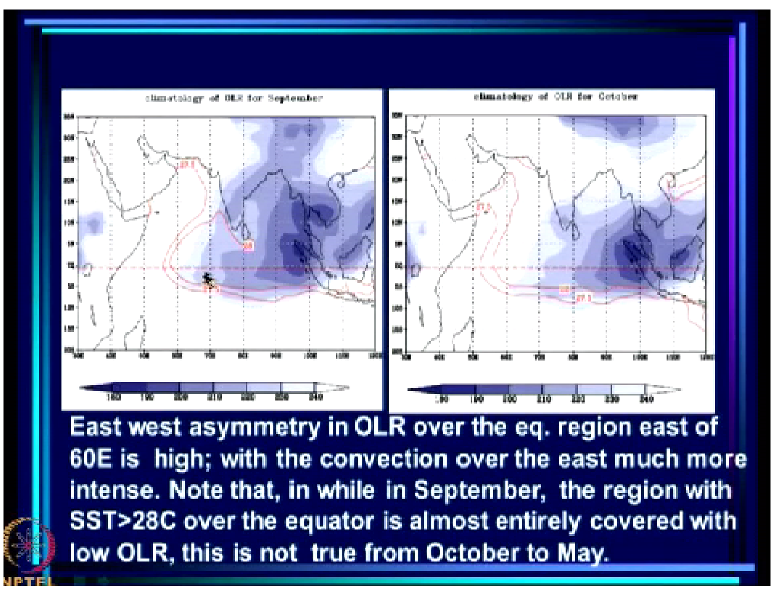

And this is the low OLR region. Now you see particularly in October, a large part of the Arabian Sea has no convection, although it is above the threshold. So although a lot of cooling of the Arabian Sea took place during July and August and we are taught in fact that north-east monsoon does not rain too much on this side because no systems form in the Arabian Sea because it has cooled.

But actually it has really not gone below the threshold .so We have to attribute the lack of rain over this part during what is called the north-east monsoon or what we call the post-monsoon to dynamics. Somehow again, the low OLR region is getting restricted to the eastern part of the basin.

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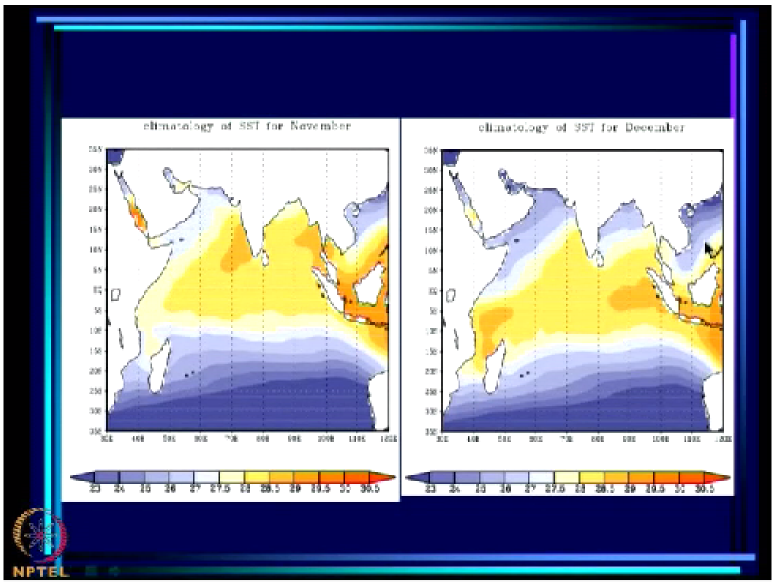

And this is November-December. Now a lot of warming has taken place but of course cooling of the northern parts because the sun has gone to the south.

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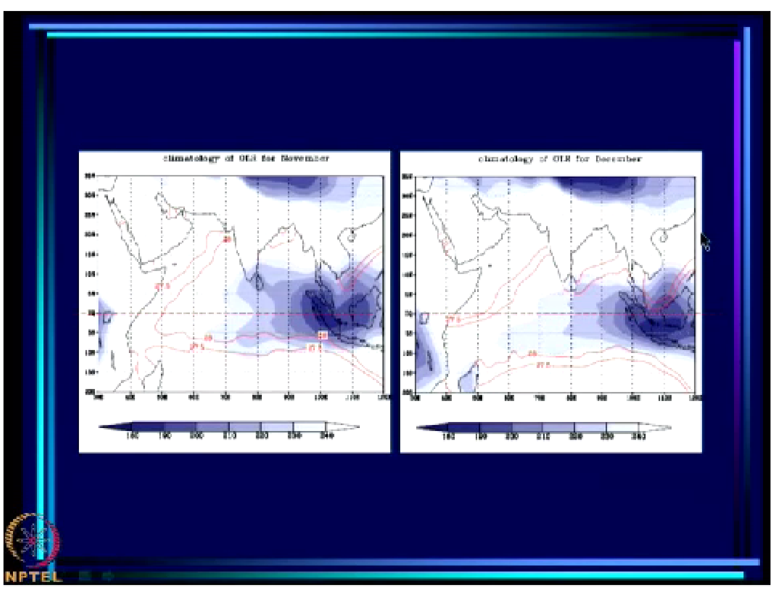

Again the low OLR region is restricted to the eastern part.

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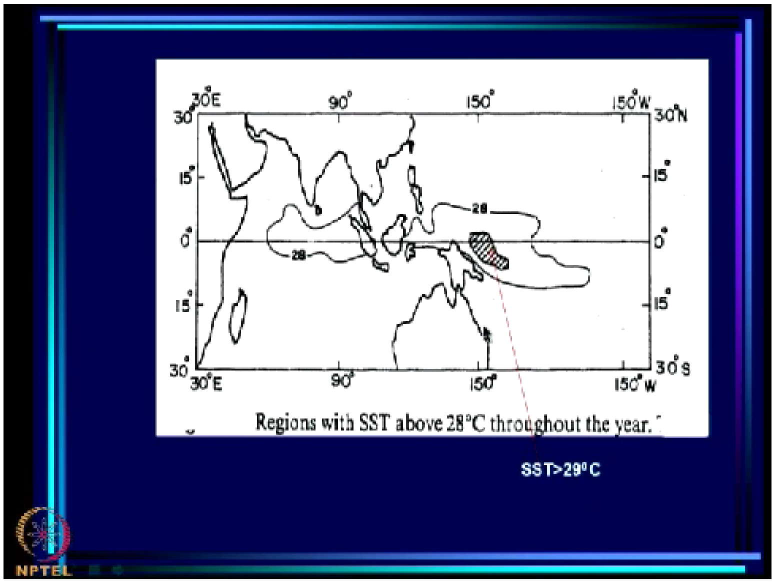

So what we have see is that there is a warm pool region, there is a region over the equatorial Indian Ocean and the west Pacific in fact which remains about 28 throughout the year and this region is about 29. So if you look at annual SST, this is the entire warm pool of the Indo Pacific region.

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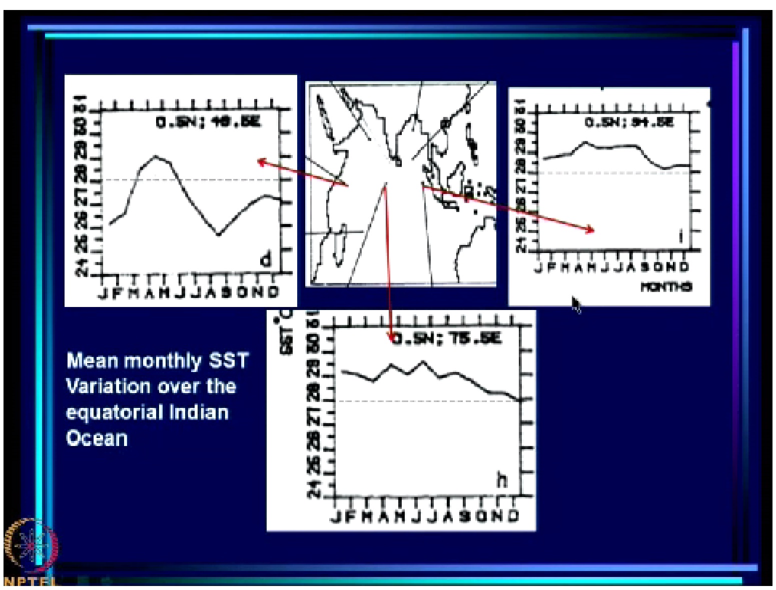

And this is the SST variation of the equatorial region. Remember we saw a similar picture for the Arabian Sea and Bay of Bengal. Now we are looking at the equatorial region. This is the region of Somalia where a lot of upwelling takes place. So what you see is initially the SST builds up till April-May, then it decreases very rapidly to become almost minimum in August and then builds up again.

So this is the SST in the western most part of the equatorial region whereas in the central equatorial region, you can see it is very very dull. SST is above the threshold and starts decreasing only after September and also in the eastern part, just of Sumatra now, again it is above 28 throughout the year bit is somewhat colder in October, November, December. So this is the variation over the equatorial region.

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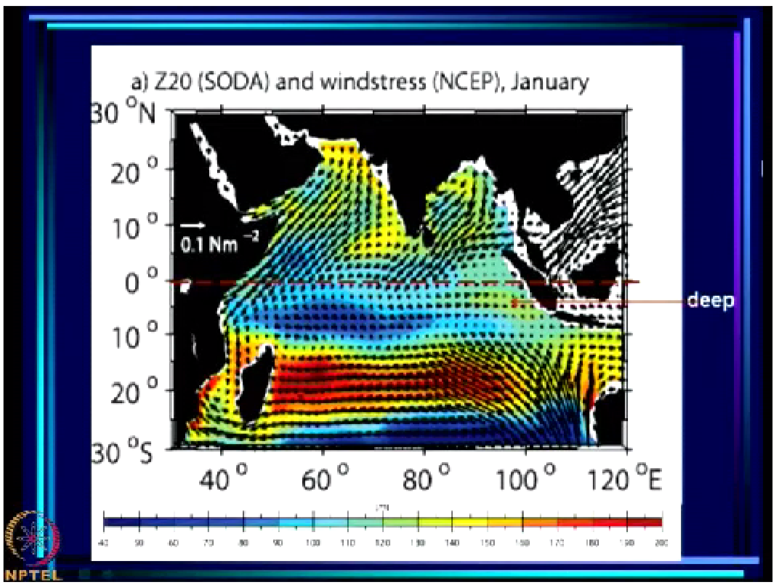

Now we have been talking about the thermocline, how deep is the thermocline and we have seen that for El Nino in the Pacific, you know that thermocline was very shallow in the East Pacific and very deep in the West Pacific. Now here, opposite situation holds. In January, you see yellow colour means deeper thermocline, what they have plotted is depth of the 20 degree Centigrade isotherm. So the deeper it is, the larger the depth, it means deep thermocline here. So if you look at the equator, then the thermocline is shallower over the west then it is over the east in January.

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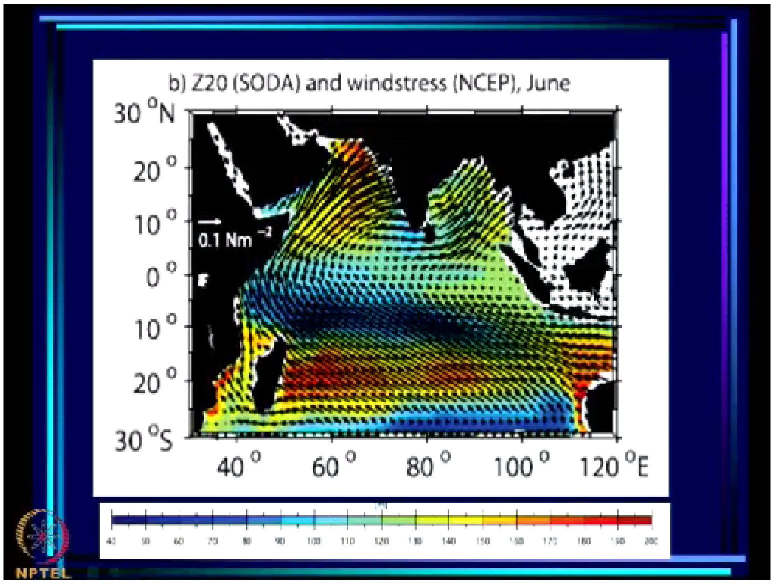

Now let us see what happens there, Also winds there which we will come too. These are the winds in June you can see. This is the south-west monsoon. This is the strong south-west flow that occurs and here also still the eastern part of the equatorial Indian Ocean is deeper than the western part.

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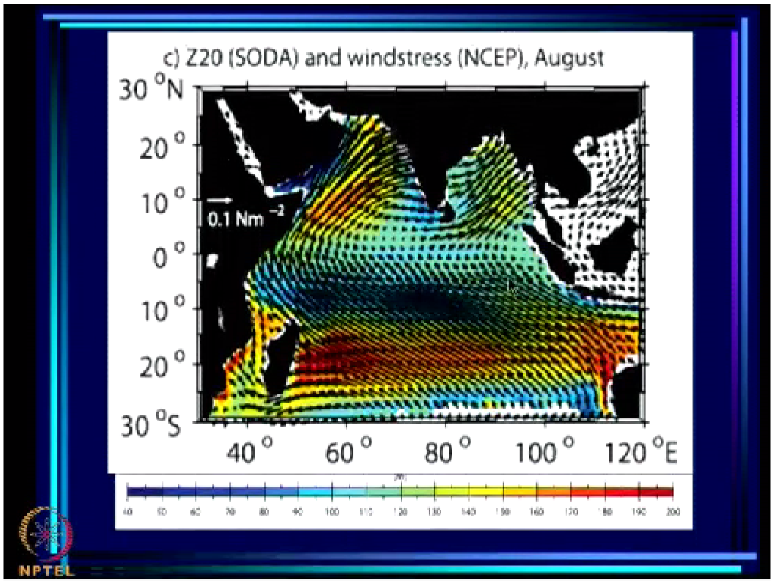

And same story continues in August but notice that in the Arabian Sea, you get a very very deep thermocline here.

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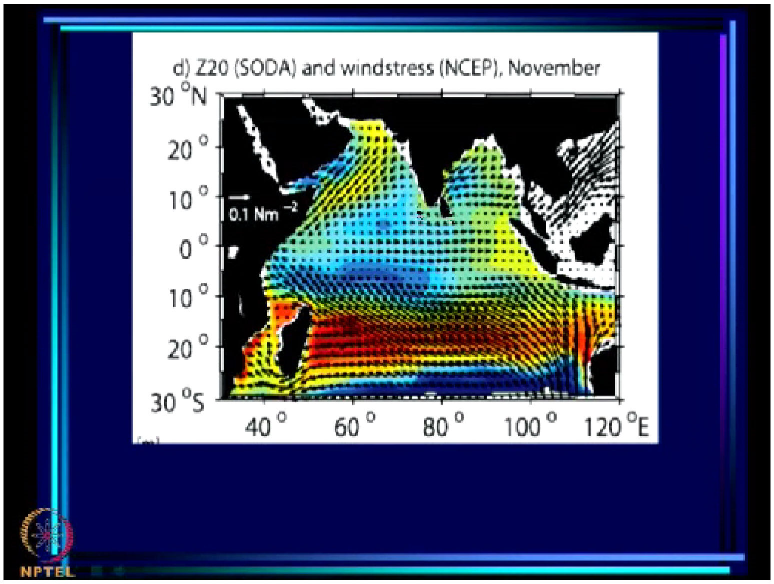

And again in November, this has become even deeper than before and this has become shallow. So we have this east-west variation in the thermocline depth. The thermocline being deeper in the east than in the west. This is almost a mirror image of what happens in the Pacific which we had looked at.

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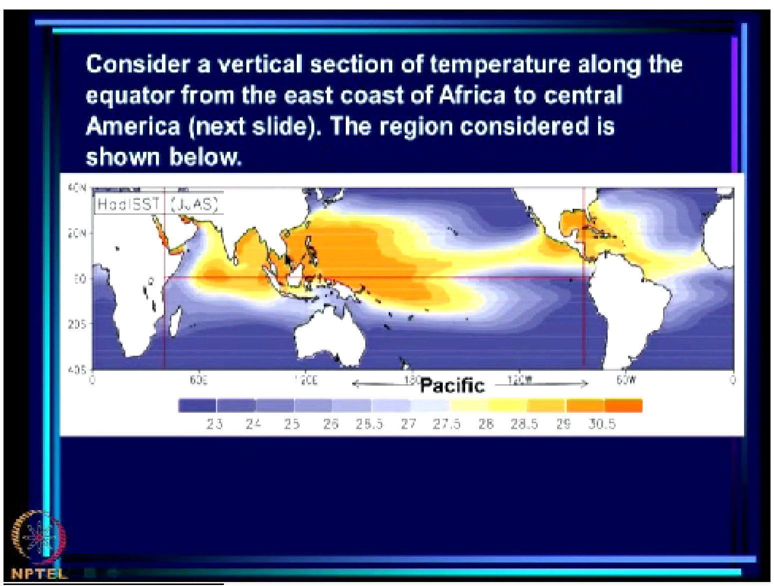

Now let us look at a vertical section of temperature along the equator from the east coast of Africa, that is from here, okay, to Central America, that is right across here. So first part is the Indian Ocean and then is the Pacific Ocean and what we are going to do is take a vertical section all along the equator and see how temperature varies.

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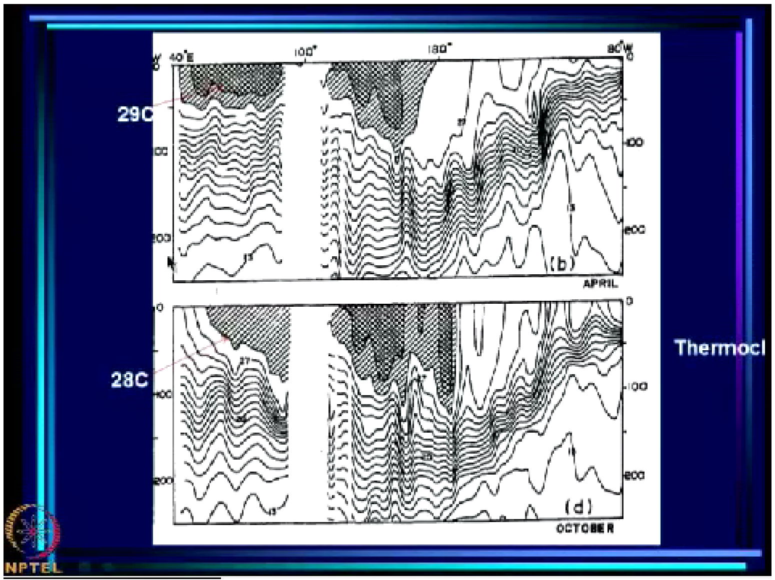

And what you see here is the picture for April and this is the picture for October. Remember this is part of the Pacific here okay and this is the classic picture of the Pacific where west Pacific has a very very deep thermocline here and east Pacific, it shoals. In April, we find that there is not too much east-west variation in the thermocline, you know. It is more or less flat but you see that by October, you see definitely that the slope of the thermocline is in opposite direction to that in the Pacific, that it becomes deeper in the east.

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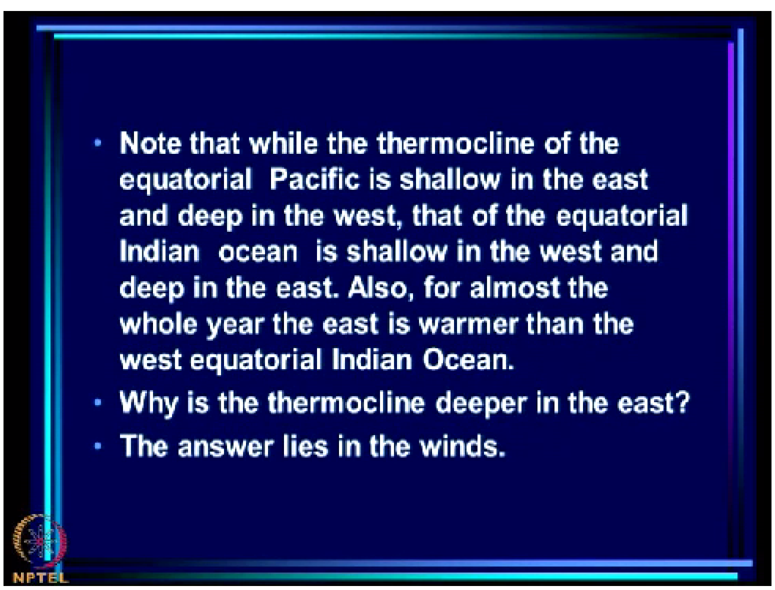

So there is a lot of east-west variation in the equatorial Indian Ocean which is of opposite sign to that in the Pacific, that while the thermocline of the equatorial Pacific is shallow in the east and deep in the west that of the equatorial Indian Ocean is shallow in the west and deep in the east.

Also for almost the whole year, we have seen that the east is warmer than the west equatorial Indian Ocean. Now the question is why is the thermocline deeper in the east.

Again, we had seen that in the Pacific also, the answer lay in the nature of the winds, it was the trade winds there. Now here also the answer lies in the nature of the winds.

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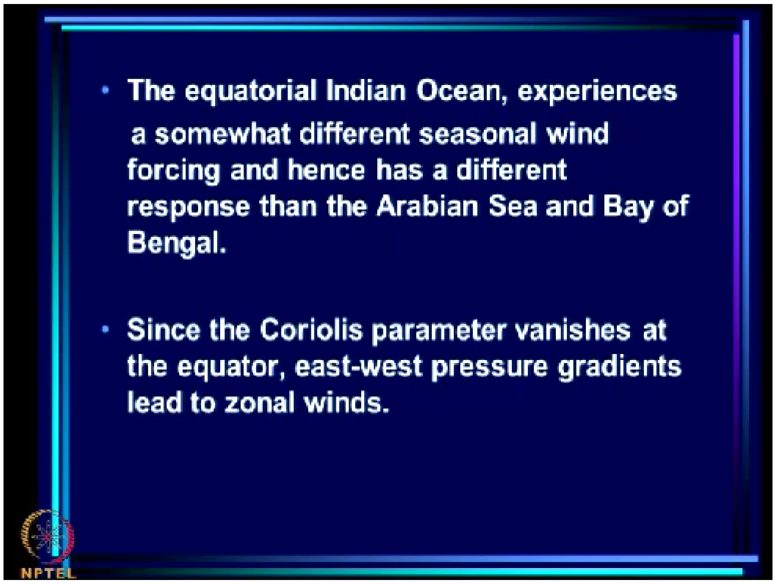

Now the equatorial Indian Ocean experience a somewhat different seasonal wind forcing and hence has a different response than this Arabian Sea and Bay of Bengal. Since the Coriolis parameter vanishes at the equator, east-west pressure gradients lead to zonal winds. This is something we have to keep in the back of our mind that we are looking at the equator. So it is like flow down a pipe, the wind will go from high pressure to low pressure.

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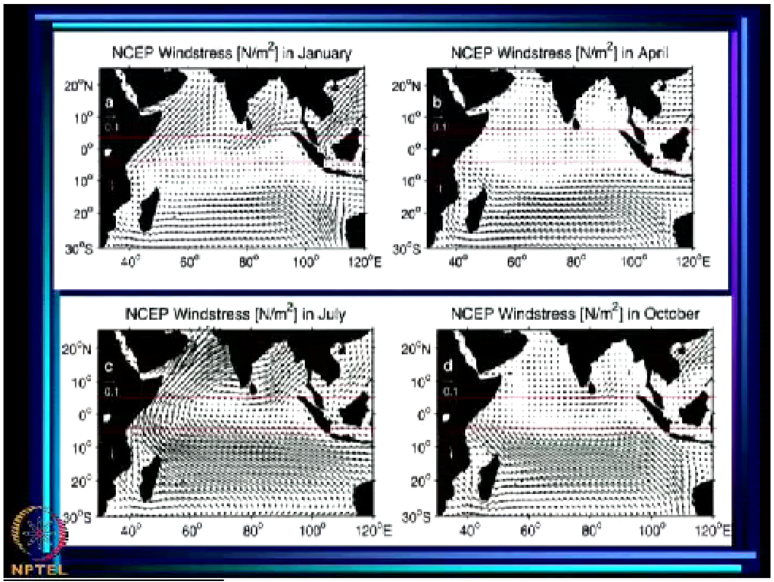

Now these are the wind stresses derived from NCEP reanalysis and what you will see by and large is that the winds are very very small and they are rather large south of 10 south and north of 10 north and they are somewhat large near the coast here in the equatorial region but otherwise they tend to be very small.

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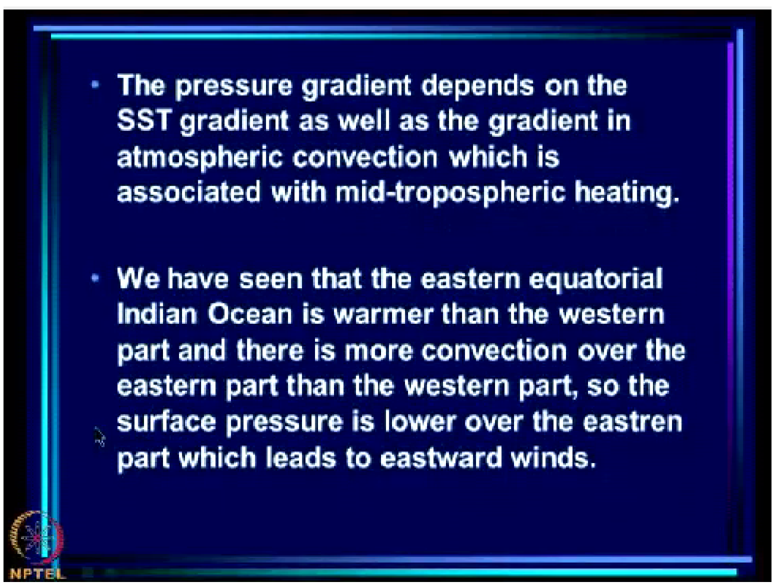

Now what does the pressure gradient depends on. See pressure gradient will depend on the sea surface temperature gradient as well as the gradient in the atmospheric convection which is associated with mid-tropospheric heating. So if you have deep clouds over a place, then because they are associated with heating at middle levels, mid-tropospheric heating, they tend to decrease the surface pressure under that column of air. So either because the sea surface temperature is high and/or because of mid-tropospheric heating, you get changes in surface pressure.

Now we have seen that the eastern equatorial Indian Ocean is warmer than the western part and there is more convection over the eastern part than the western part. So both these factors are acting to make the pressure over the east lower than the pressure over the west, okay. So the surface pressure is lower over the eastern part and that would mean that you have winds flowing, winds which blow towards the east are westerly winds.

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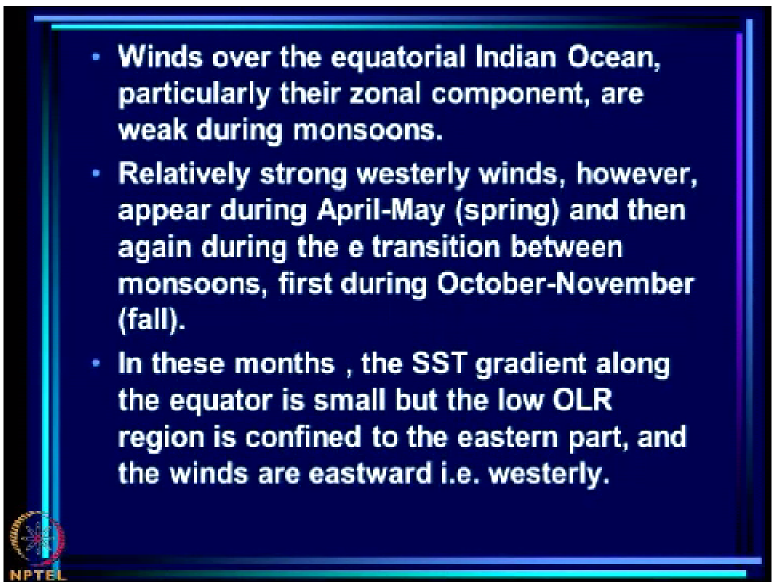

So winds over the equatorial Indian Ocean, particularly their zonal component, are weak during the monsoon because during the monsoon, most of the convection is actually over other latitudes but relatively strong westerly winds appear in April-May spring and then again during the transition between the monsoon, October-November.

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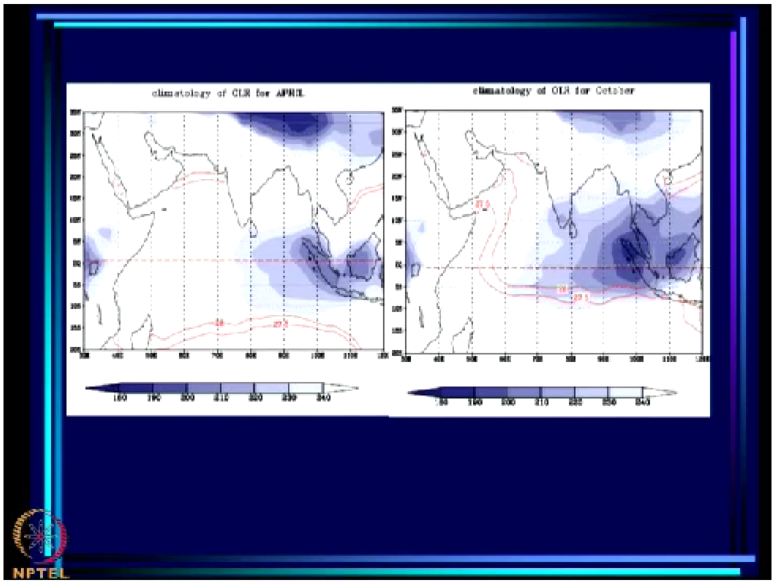

See in these months what happens. So this is the month of April and this is the month of October. No in these months, if you look at this part of the basin, then the east-west SST gradients are not that great in either of the month but what is high is the east-west gradient in convection, atmospheric convection or in mid-tropospheric heating.

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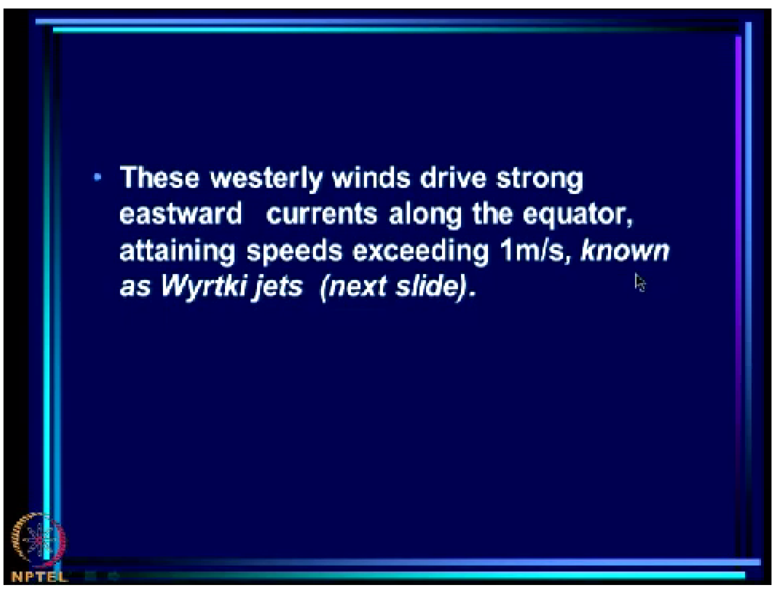

So this will lead to actually strong winds which are eastward along the equator and they can attain speeds as much exceeding 1 meter per second and these are known as the Wyrtki jets.

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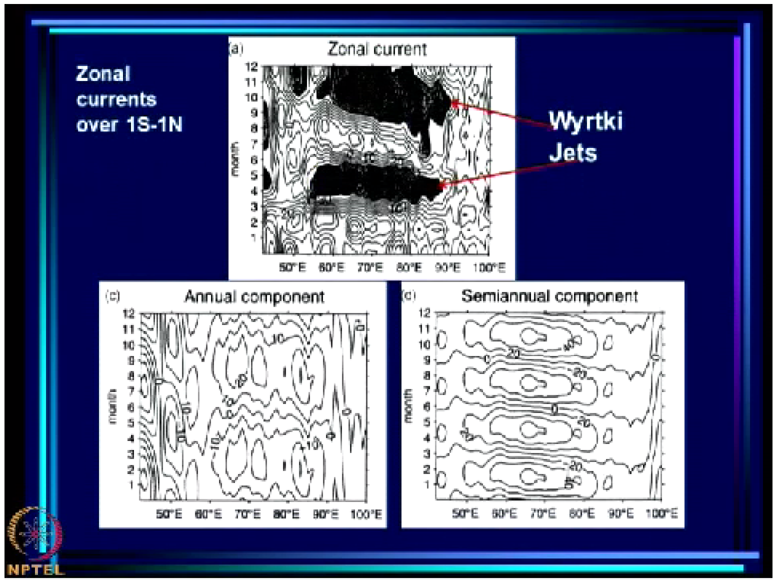

So now let us look at the zonal current. Now we are going to the ocean from the winds and the zonal current is in fact very high. This is April, this is the mean current and this is April-May when it is high and this is again October-November when it is high and it is high over the central part of the basin. See this is 60 degrees east and this is 80 degrees east. So this is very very high.

And in between, it remains eastward or westerly but the magnitude is not so high. These are known as Wyrtki jets after an oceanographer called Wyrtki who discovered and described them in great detail. Now this is in fact the annual component then the semi-annual component which shows semi-annual component is very large. So it shows that twice a year, you get very very large magnitudes of easterly flow, I am sorry, of westerly flow.

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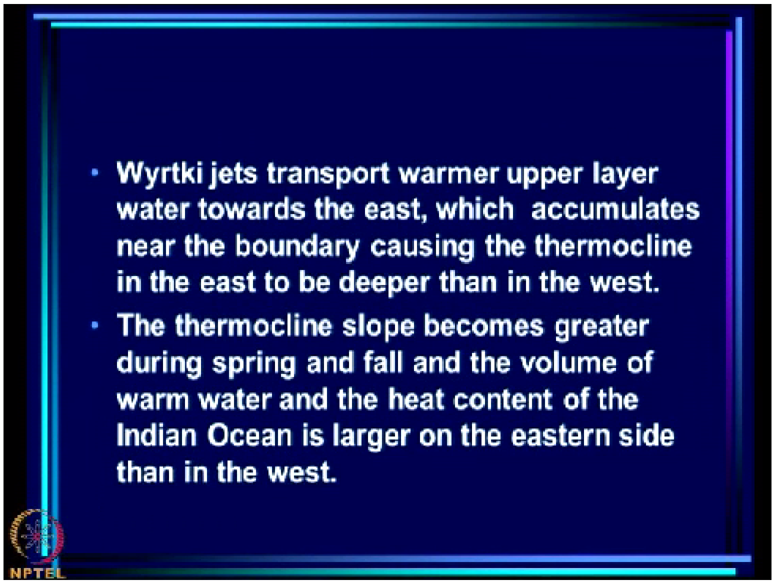

So what do these Wyrtki jets do. Again the story is somewhat similar to the Pacific but you have to replace west by east. In the Pacific, remember the warm water near the surface of east Pacific gets transported by the trades towards the west. Now here Wyrtki jets transport warmer upper layer water towards the east which accumulates near the boundary causing the thermocline in the east to be deeper than in the west.

Just like in the Pacific, the thermocline is deeper in the west where this surface warm water is pushed by the winds towards the west Pacific. Here it is carried by these Wyrtki jets to the east and so that makes the thermocline deeper. The thermocline slope becomes greater during spring and fall, and the volume of warm water and the heat content of the Indian Ocean is larger on the eastern side than the west.

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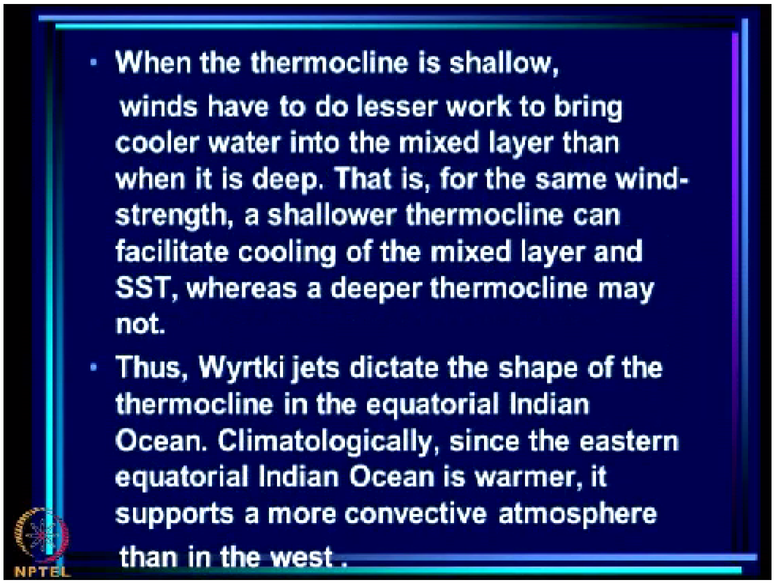

When the thermocline is shallow, winds have to do lesser work to bring cooler water into the mixed layer than when it is deep, that is for the same wind-strength, a shallower thermocline can facilitate cooling of the mixed layer and SST whereas the deeper thermocline may not. Thus Wyrtki jets dictate the shape of the thermocline in the equatorial Indian Ocean.

Climatologically, since the eastern equatorial Indian Ocean is warmer, it supports a more convective atmosphere than in the west.

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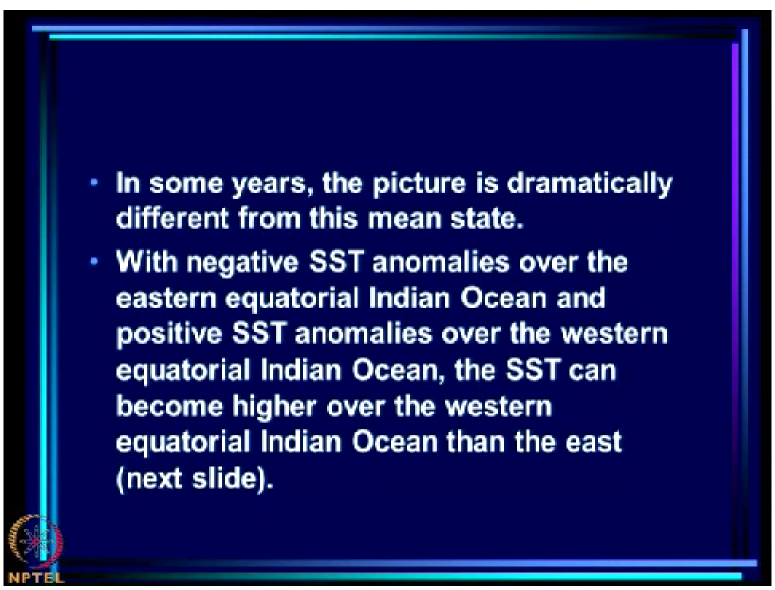

Now this is the mean picture we have been talking about, looking at mean monthly patterns but in some years, this picture changes dramatically. Of you know most, east being warmer than the west in terms of SST, east having a deeper thermocline than the west and in the atmosphere above, east having more convection in the west. This is the mean picture but this changes drastically. So how does it change, we get negative SST anomalies over the eastern equatorial Indian Ocean and positive SST anomalies over the western equatorial Indian Ocean.

So where it is warm, it becomes colder, eastern Indian Ocean and the western equatorial Indian Ocean becomes warmer.

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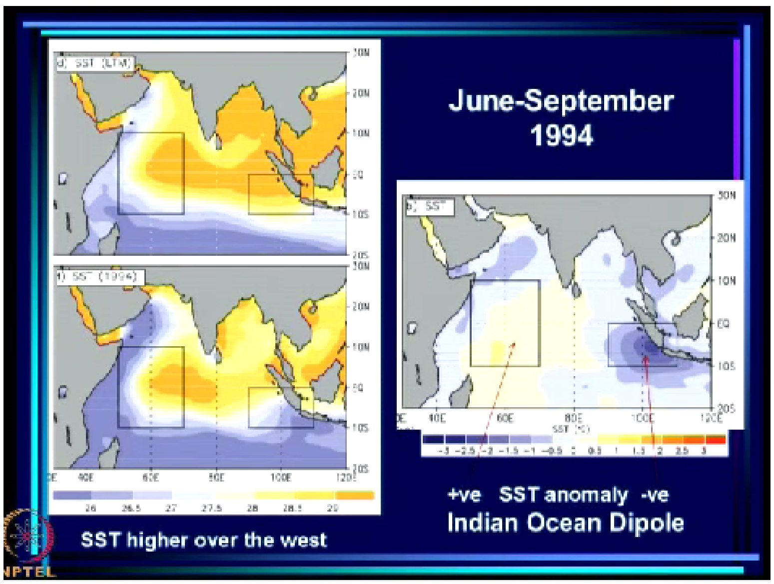

And the anomalies can be so large that the gradient itself can change, SST gradient can change sign. Now this is the case of 1994 and we generally look at June to September because that is the summer monsoon period and that is what we are concerned with most. So this is the SST anomaly and this is the climatology, I am sorry, this is the SST climatology and this is the actual SST in 1994, okay.

And what you see is, climatology says that the east is warmer than the west but actually now in 1994, west was warmer than the east and this of course is because you had huge negative SST anomalies here and positive SST anomalies here. So the gradient now has become towards the west as far as SST is concerned.

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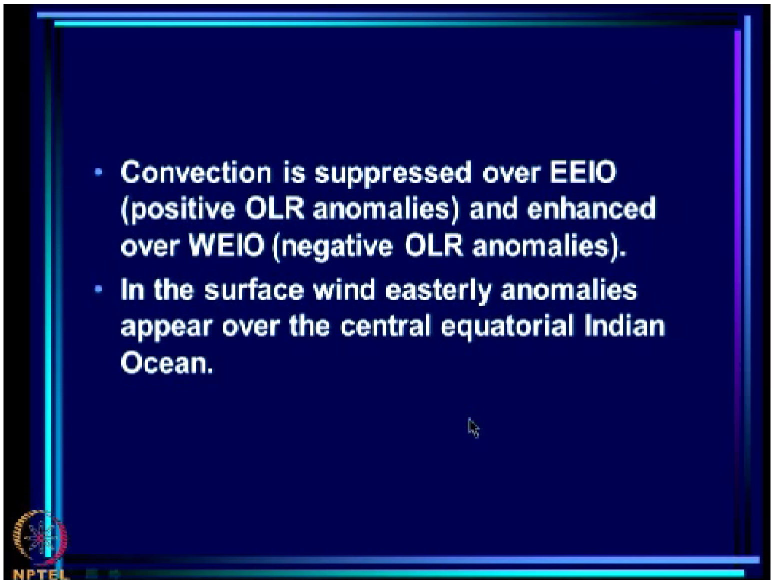

And now let us look at OLR, what happens. Now convection is suppressed over EEIO, that is to say positive OLR anomalies, and enhanced over the WEIO.

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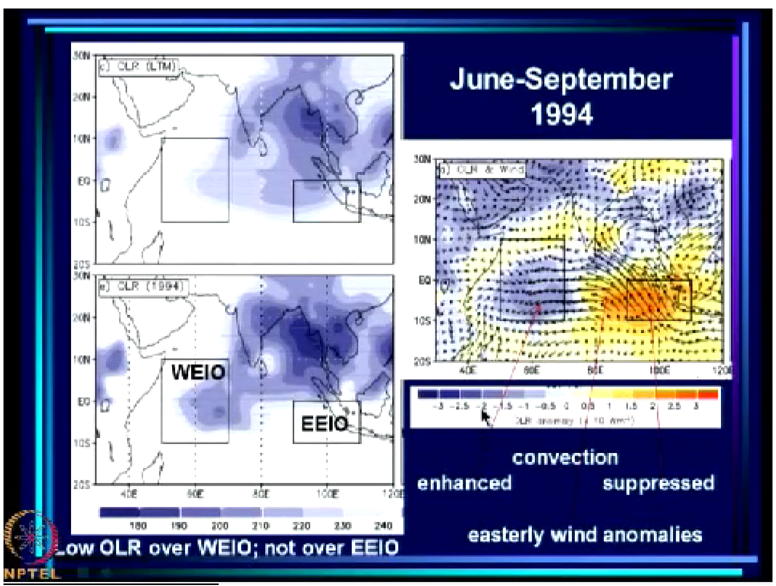

So now this is the west equatorial Indian Ocean box and this is the east equatorial Indian Ocean box. I will define the longitude and latitude later and what you see is, this is the actual OLR. So instead of convection being by and large restricted to east and central part of this region, it is now restricted to the western part. So the convection has also switched and of course, you get very large positive OLR anomalies here showing that convection is suppressed over EEIO and enhanced over WEIO.

Now what does that mean? We know that along the equator, things just go along from high pressure to low pressure, convection is suppressed here, enhanced here and actually convection is occurring here. And SST is also higher here which means pressure is lower here and you will get anomalies which are easterly winds.

So you get easterly winds here and if the gradients are strong enough, it is just not easterly anomalies but the winds themselves change direction and is instead of flowing from west to east, they start blowing from east to west. So this is the situation that occurs in some years.

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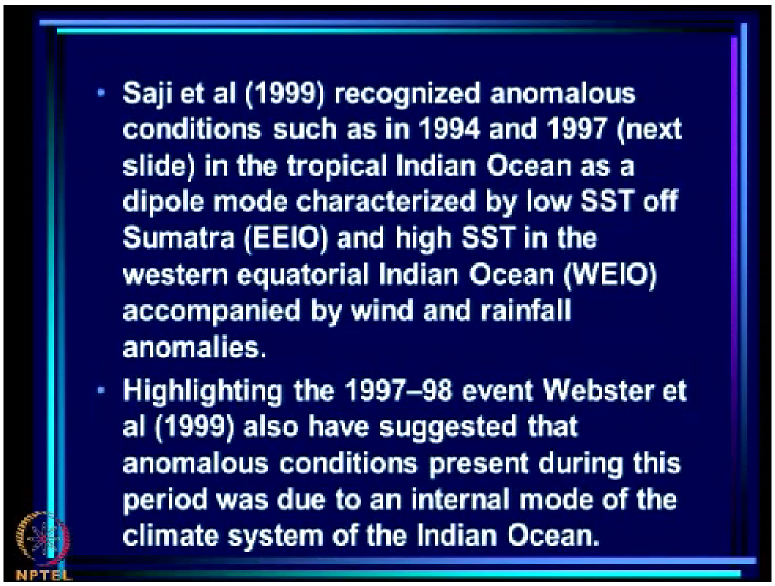

So this is opposite of what we have seen in the climatology or the mean picture. Saji et al recognised anomalous conditions such as 1994 and 1997, which I will show you.

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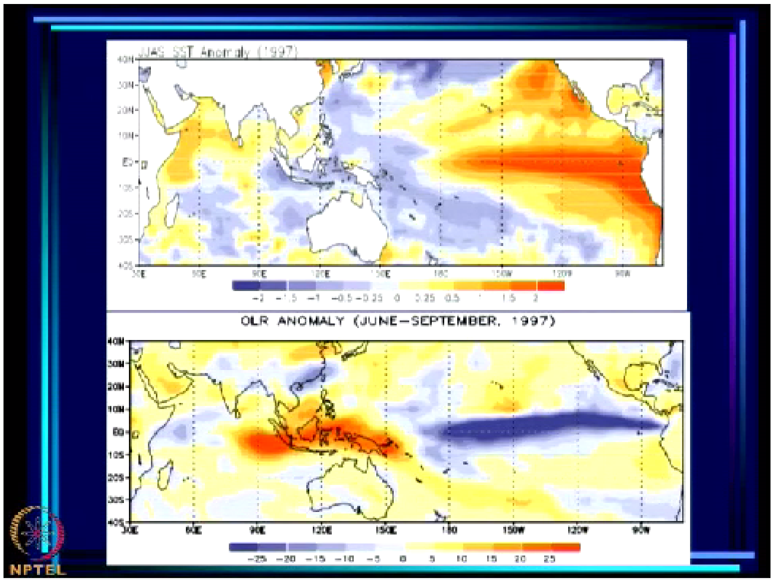

This is the case of 1997 and here again you see cold anomaly over EEIO, warm anomaly over WEIO, convection very much suppressed over EEIO, this is the OLR anomaly and enhanced over WEIO. So these are 2 major events, 1994 and 1997 and Saji et al said that these are in fact manifestations of a mode of the tropical Indian Ocean which they called the Indian Ocean dipole mode.

Why did they call it the dipole mode? Because typically, we see that this mode is associated with anomalies of the opposite sign, SST anomalies of the opposite sign, in the east and west. So this looks like a dipole, okay and in terms of OLR anomalies also, it looks like a dipole. So these people, Saji et al suggested the name Indian Ocean dipole for this mode, Indian Ocean dipole mode.

And characterised by low SST of Sumatra and high SST in the western equatorial Indian Ocean accompanied by wind and rainfall anomalies. Now highlighting 1997-1998 event, Webster et al also have suggested that anomalous conditions present during this period was due to an internal mode of the coupled system of the Indian Ocean. Coupled Indian Ocean-atmosphere system, mode of this is called the Indian Ocean mode.

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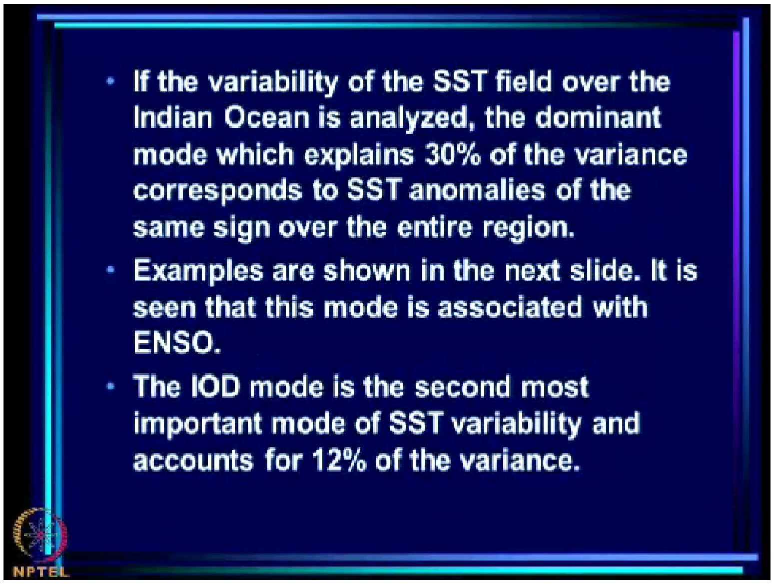

Now we have to see if this is a major mode of SST variability over the Indian Ocean, how much of variability is explained by this kind of a pattern or this kind of a mode. Now if we look at SST variability, variability of the SST field over the Indian Ocean and analyse it, then the dominant mode which explains 30% of the variance, corresponds to SST anomalies of the same sign over the entire region.

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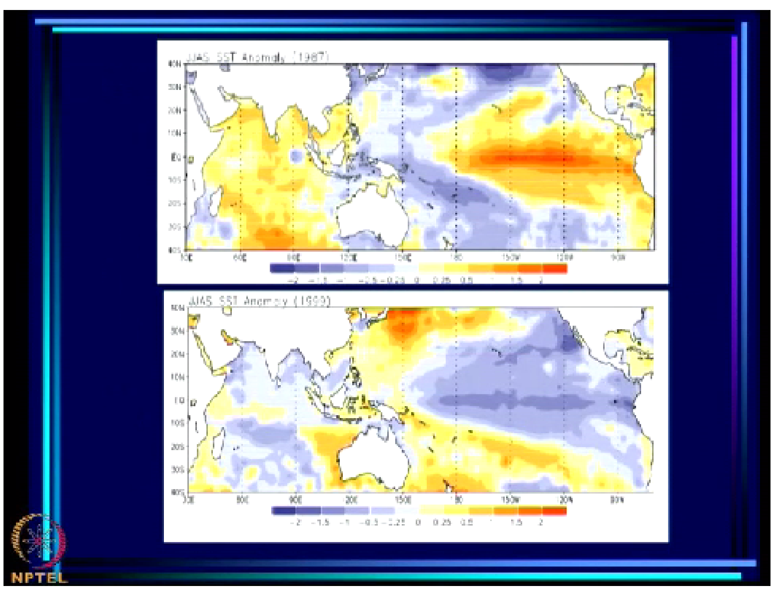

So you have pictures like this. Now this is 1997 where almost the entire region is warm and this is 1999 where almost the entire region is cold. So there is one mode in which the entire region is either warm or cold or the variation of SST is coherent across the region. So examples are in fact, this mode is associated with ENSO and you see 1987 was an El Nino year and this you see is a signal of La Nina. So during El Nino, you get warm SST anomalies and during La Nina, cold SST anomalies but uniformly so.

So this mode of the entire basin becoming warmer or colder accounts for about 30% of the variance. Now IOD mode is the second most important mode of SST variability and accounts for 12% of the variance. So overall it does not account for much of the variance but the special feature of this mode is that it has very intense events which we call positive IOD events which have a huge impact on the climate of the region.

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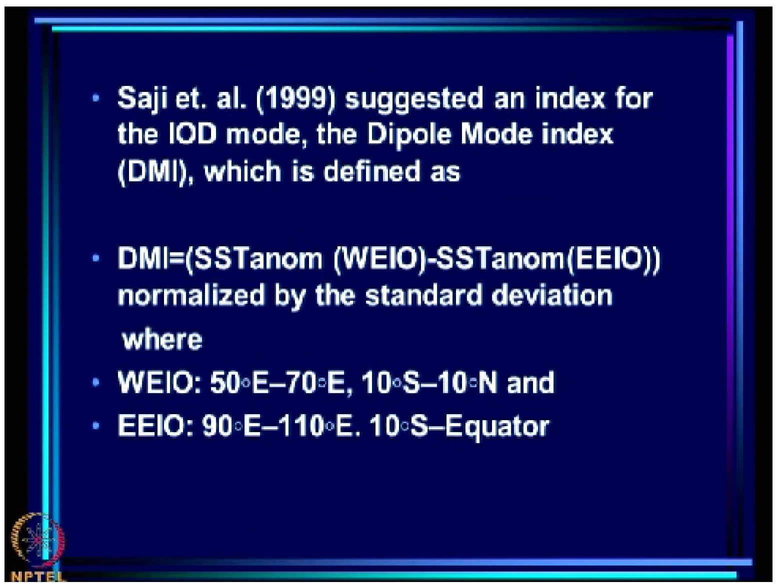

Now Saji et al actually suggested an index for the IOD mode which is called the dipole mode index and this is defined as SST anomaly of the west equatorial Indian Ocean, which I showed you, minus SST anomaly of EEIO normalized by the standard deviation, this is where we defined WEIO is 50 to 70 east 10 south to 10 north and EEIO is 90 to 110 east and 0 to 10 south.

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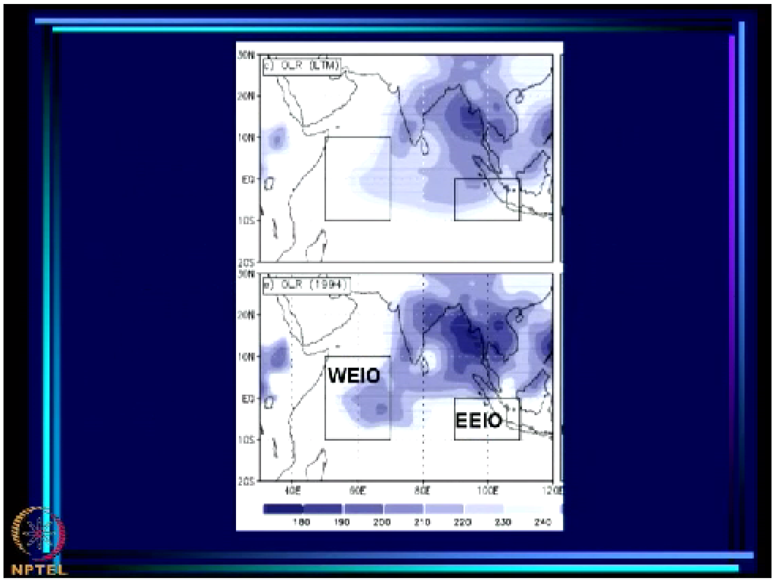

So this is EEIO, 90 to 110 east, 0 to 10 south and these boxers were actually defined by Saji et al and these are the boxes that have been continued to be used for looking at equatorial Indian Ocean dynamics and particularly for Indian Ocean dipole mode.

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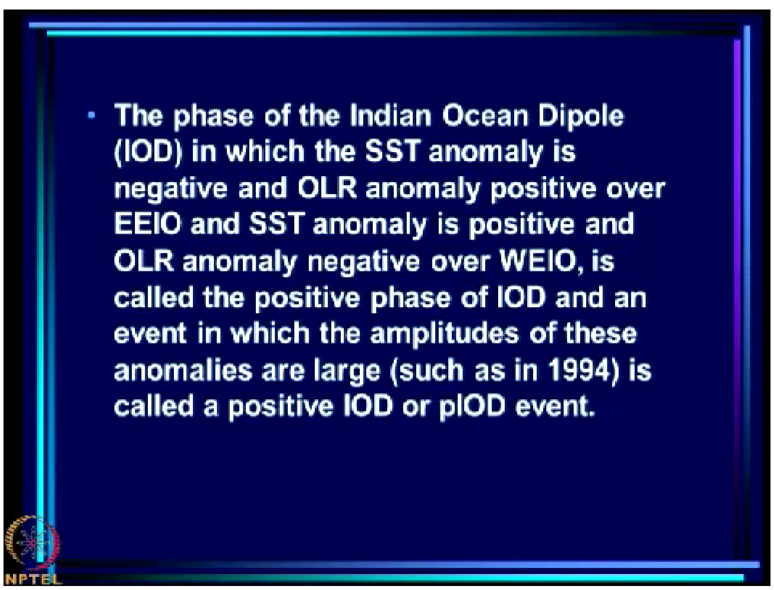

Now what are the phases. The phase of the Indian Ocean dipole mode in which the SST anomaly is negative and OLR anomaly positive over EEIO, like the 1994 case and SST anomaly is positive and OLR anomaly negative over WEIO, is called the positive phase of IOD and an event in which amplitudes of these anomalies are large, such as in 1994, is called a positive dipole event and we have seen that here.

This is a case where you have very large anomalies and convection is enhanced over the west and suppressed over the east and you also have, west is warm relative to the east, positive SST anomalies over west, negative over the east. This is the positive phase, defined as the positive phase of IOD and if the amplitude of the anomalies is large, we call it a positive IOD event, okay.

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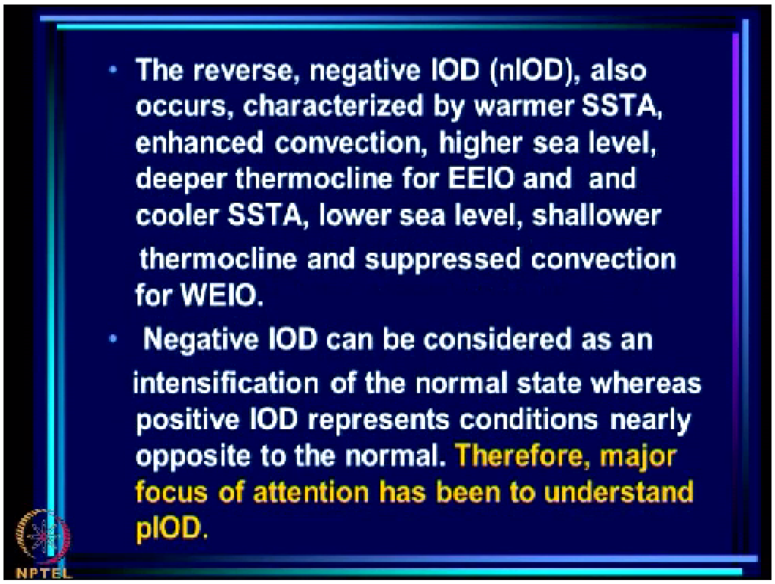

Now, the reverse, negative IOD also occurs. When would that occur? That would occur if the SST of the east is higher than average, that is to say you have a positive SST anomaly on the east and negative on the west and enhanced convection on the east and suppressed convection on the west. So this is the opposite sign of anomalies to the positive one but remember that climatology or the mean state is such that convection is generally restricted to the eastern Ocean.

What negative IOD phase means is, that is further enhanced in the east and decreased in the west. So negative IOD is an intensification of the climatological or the normal state. Whereas positive IOD represents conditions nearly opposite to the normal. Instead of convecting on the east, the atmosphere is convecting on the west, instead of being warmer in the east, the ocean is warmer in the west.

So this is a major change in the gradience, east-west gradience, pretty much the way El Nino also occurs. So this is why pIOD events are special, negative IOD is just an intensification of climatology. This is something to be borne in mind. Therefore, major focus of attention has been on positive events.

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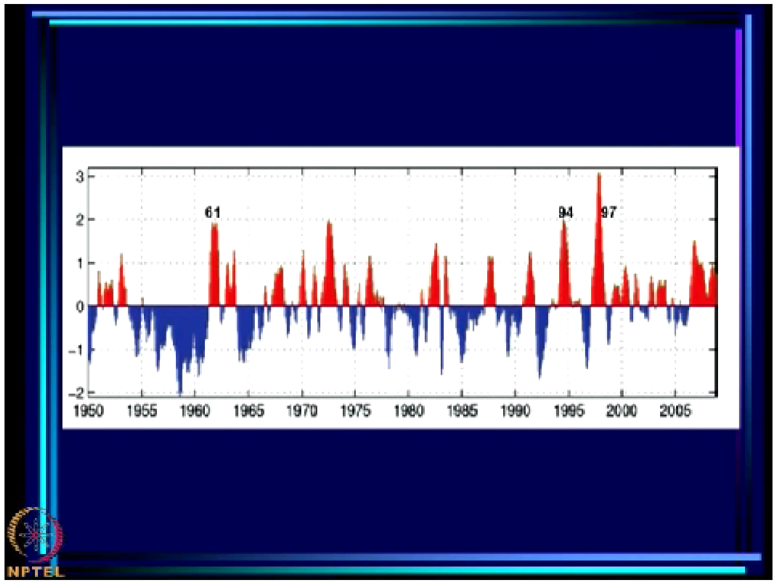

And what you see here, is a plot of DMI which I defined the dipole mode index, when it is positive, these are the events of 1994 and 1997 was a huge positive index and then afterwards recently, we have had 2006 as a positive index and earlier, 1961, was also a positive IOD event. So there have been several pIOD events in recorded history.

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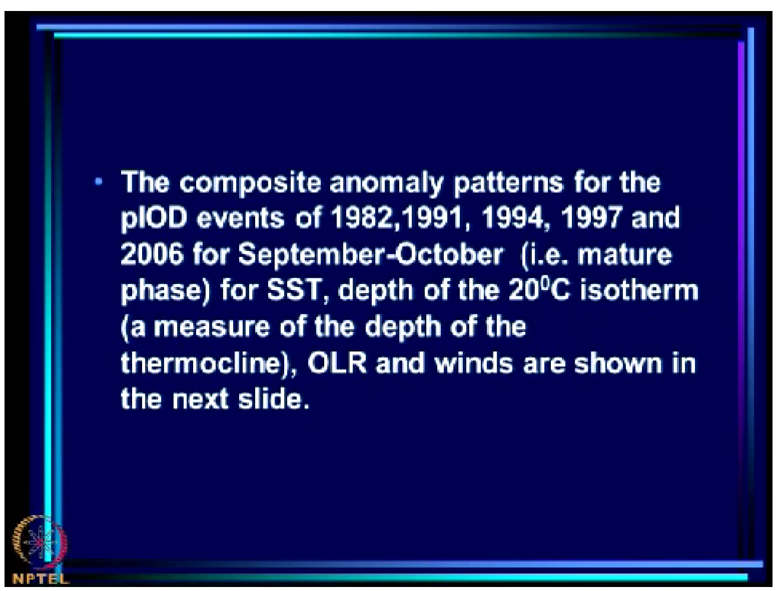

And the composite anomaly patterns of several of these events show you how they develop.

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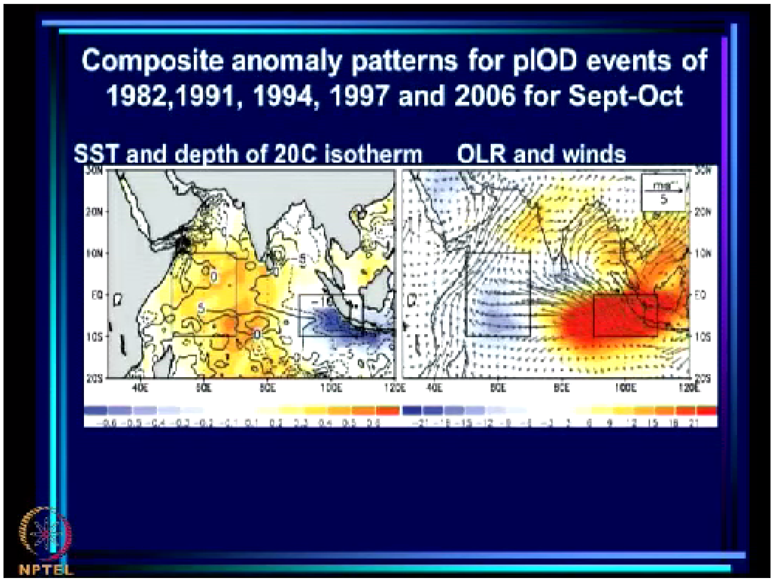

So this is actually the pattern for composite in a mature phase of the IOD and this is where SST is given in terms of shades here and the contours correspond to depth of the 20 degrees isotherm. So the contours are all negative here which shows that the depth of the thermocline is decreasing markedly over the east and is increasing over the west and west is warmer than the east, convection is suppressed over the east and is enhanced over the west.

There is one more feature to look at that associated with this is very very strong easterly anomaly of the wind which goes from east to west which we had mentioned.

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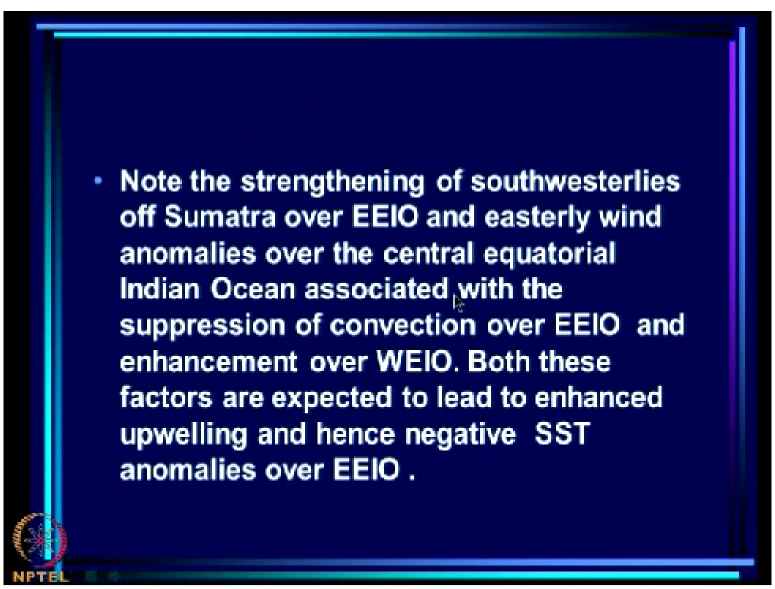

So now we will see how these things are consistent because strengthening of, if we go back here, the winds imply that all along here, you have strengthening of winds which are parallel to the Sumatra coast. Remember this is the southern hemisphere. So if you have winds like this, that will lead to Ekman drift in this direction and therefore, away from the coast, that mean there will be upwelling.

In addition to that, these winds that come from east to west, will also lead to upwelling because they are going to move water away from the coast. So both these factors are going to lead to upwelling and that means cooling of the Sea, cooling of the eastern equatorial Indian Ocean. So they are consistent with the negative SST anomalies there.

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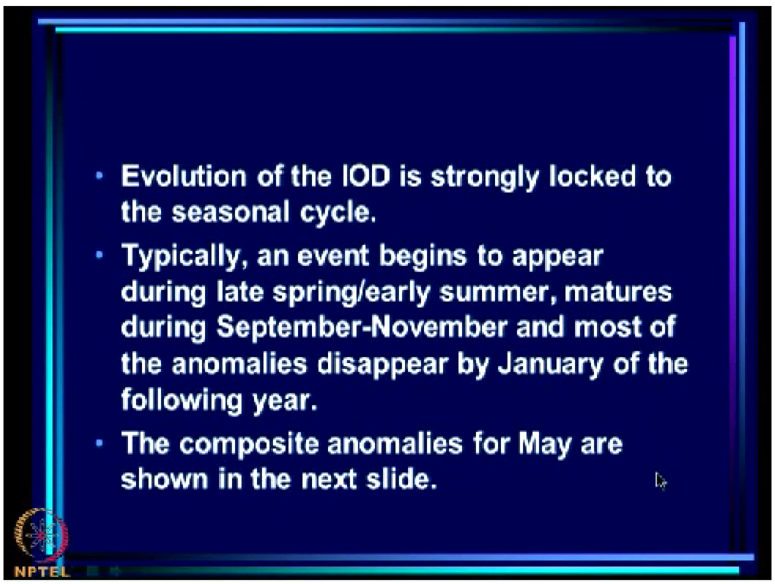

Now I am going to talk about evolution of IOD. Also look at atmospheric component of IOD separately in the next lecture and then we will look at how these modes or the coupled Indian Ocean dipole mode, its atmospheric and oceanic components, are they in any way linked to variability of the monsoon. Thank you.