The Monsoon and Its Variability
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Lecture – 32
Indian Ocean Dipole – Part 1

Today, I want to continue our discussion on the Indian Ocean Dipole mode which we began in the last class.

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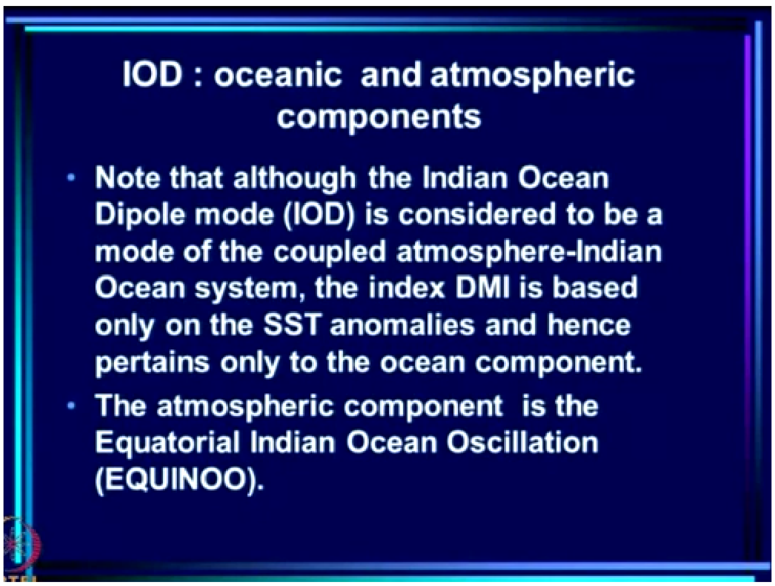

This is Indian Ocean Dipole mode called IOD and as we noted last time, it has an oceanic component as well as an atmospheric component; however, although the Indian Ocean Dipole mode is considered to be a mode of the coupled atmosphere-Indian Ocean system, the index DMI which we defined in the last class which was actually the difference of the SST anomalies of the West and East equatorial Indian Ocean.

So, the DMI is based only on the SST anomalies and hence pertains only to the ocean component. The atmospheric component of this Indian Ocean Dipole mode is the equatorial Indian Ocean oscillation or what we call EQUINOO.

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Now, suppression of convection over the eastern equatorial Indian Ocean tends to be associated with enhancement of convection over WEIO and vice versa.

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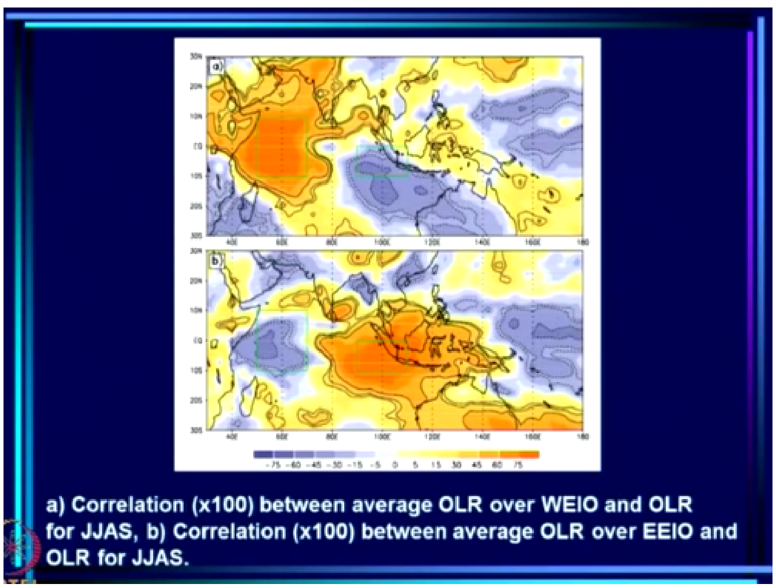

Now, what you see here is the correlation between the average OLR. On top is the average OLR of WEIO (Western Equatorial Indian Ocean) with OLR everywhere and you can see that the OLR here is highly positively correlated with OLR here. So, rainfall here would be highly positively correlated with rainfall here, but what I am pointing out now is more importantly that there is a seesaw in convection between the West and the East.

You can see that the OLR correlation between the West average WEIO OLR is highly negatively correlated with the OLR over the Eastern Equatorial Indian Ocean. Similarly, if we look at the correlation related to the average over the East box which is shown here. Then, you see that it is negatively correlated with the OLR over the West box. So, there is a seesaw in convection between the East and the West, right.

So, the seesaw is what leads to this Equatorial Indian Ocean Oscillation. It is a signature of the Equatorial Indian Ocean Oscillation. EQUINOO is the oscillation of a state with enhanced convection over the West and reduced convection over the East. So, EQUINOO is an oscillation of state for which the OLR anomalies would look something like this, enhanced convection here and suppressed convection here.

And the opposite which means enhanced convection over East and suppressed convection here. So, EQUINOO is the oscillation between these 2 states of a state with enhanced convection over WEIO and reduced convection over EEIO which we call the positive phase. In fact, I just mentioned that this is one kind of thing, one state of the Equatorial Indian Ocean Oscillation. Now, if you look at July 1997, the OLR anomaly corresponds to very big suppression over the East and enhanced over the West.

So, this is what is referred to as the positive phase of the Equatorial Indian Ocean Oscillation and the opposite which means that the anomaly of OLR over WEIO is positive, i.e., to say convection is suppressed over WEIO and enhanced over EEIO is the opposite phase or the negative phase which we can see corresponds to 2002 case.

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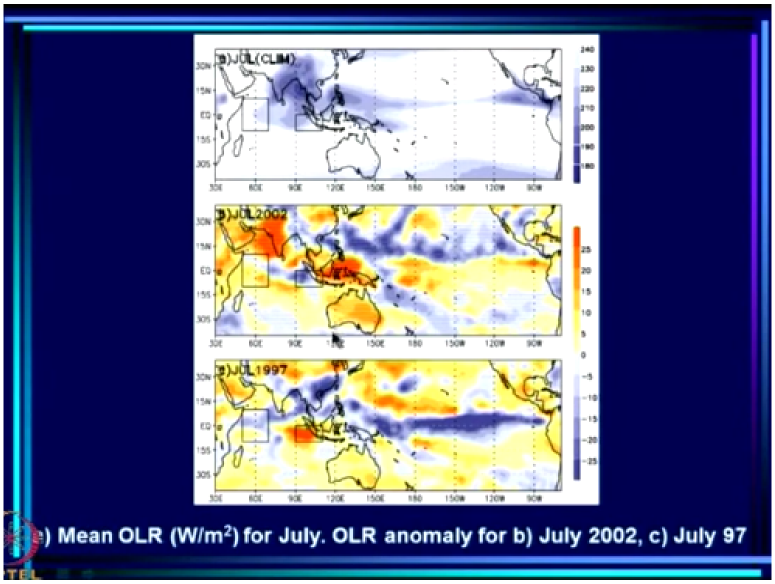

You can see the convection over the East box is enhanced, convection over the West box is suppressed. So, EQUINOO corresponds to oscillation between these 2 states, positive phase and negative phase. Up here is the climatology, okay. We have already noted that the OLR over the Indian region is positively correlated with OLR over WEIO. If you look at OLR over the Indian region, it is positively correlated with OLR of WEIO and negatively with OLR of EEIO. Now, if we compare the mean July pattern with that of July 2002.

See is the mean OLR for July and you can see that in the mean pattern also there is more convection over the East than there is over the West, okay. If we look at July 2002, that same tendency has been strengthened. So, it is like strengthening of the gradients which are already there in the mean pattern or the climatological pattern.

So, negative phase corresponds to strengthening of climatological gradients, whereas positive phase corresponds to reversal of those gradients, whereas here East is more convective than the West. In the positive phase, East is suppressed and the West is enhanced. So, it is of the opposite sign.

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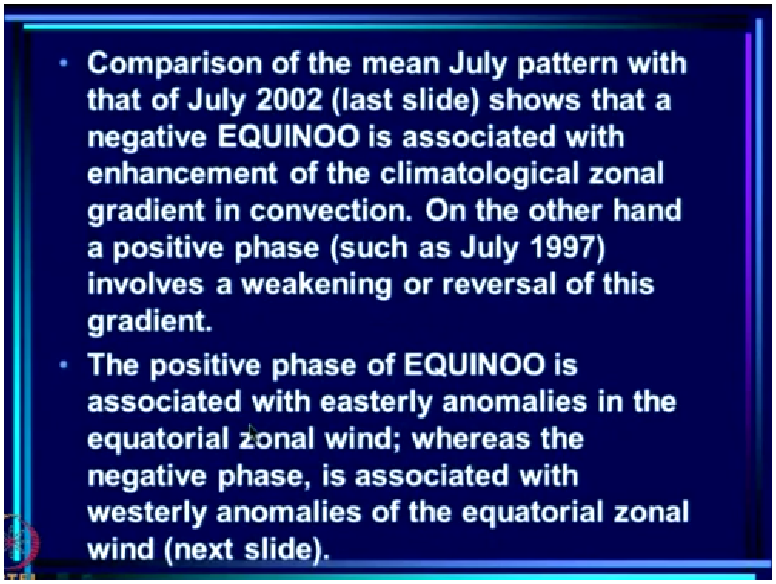

So, negative EQUINOO is associated with enhancement of the climatological zonal gradient in convection. On the other hand, a positive phase such as July 1997 involves weakening or reversal of this gradient. The positive phase of EQUINOO is associated with Easterly anomalies in the equatorial zonal wind, whereas negative phase is associated with Westerly anomalies.

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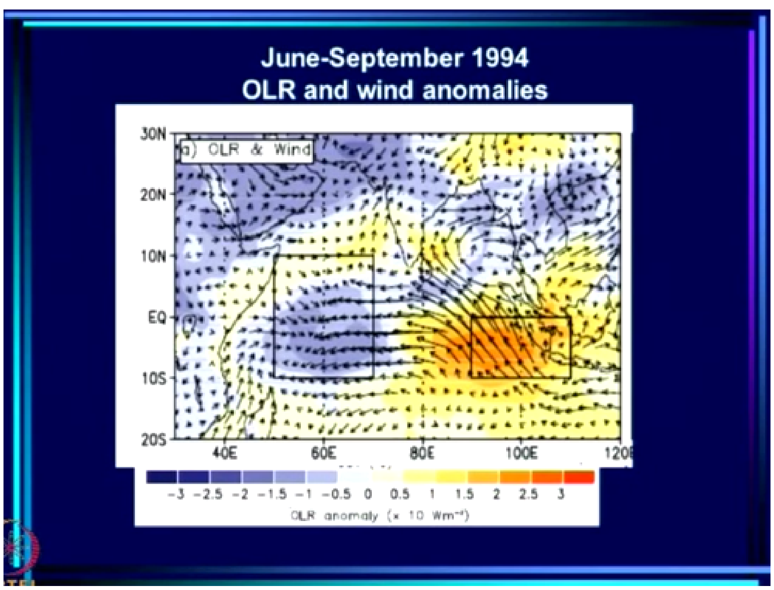

Let see an example of a positive phase. Positive phase, these are all anomalies. You see that convection is suppressed here, OLR anomalies are positive. Convection is enhanced here, OLR anomalies are negative and you can see the wind is going towards the region where convection is enhanced, that is to say the anomaly is from the East or Easterly. Now, if opposite were the case then the anomaly would be from the West going towards the place where convection is more and therefore it would be westerly.

So, positive phase of EQUINOO is associated with Easterly anomalies in the equatorial zonal wind, whereas negative phrase is associated with Westerly anomalies. In fact, we use an index of the EQUINOO based on the anomaly of the zonal component of surface wind over the Central Equatorial Indian Ocean which is between the 2 boxes which is highly correlated with the difference between the OLR of WEIO and EEIO.

So, we use as an index of EQUINOO, winds over the Central Equatorial Indian Ocean here which in fact is highly correlated with the difference in the OLR between these 2.

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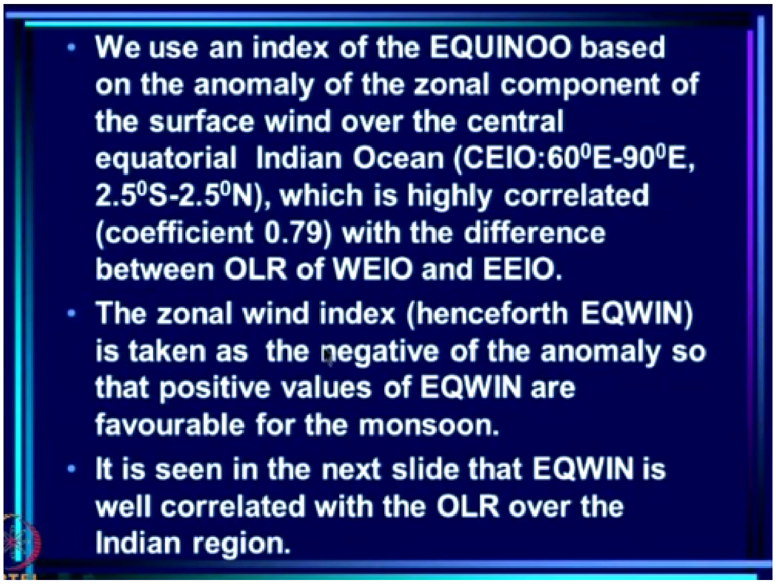

So, the zonal wind index which we call EQWIN is taken as a negative of the anomaly, so that positive values of the EQWIN are favourable for the monsoon. Now, you can see that this is what is favourable for the monsoon. You can see that there is negative OLR anomaly here and negative OLR anomaly over the Indian monsoon zone; and during that time, in fact the anomaly of the winds is from the East to the West or easterly.

Now, you know zonal wind is taken as positive when it is West to East. So, what we would like to do is to call EQWIN the index as positive when it is favourable for the monsoon. So, we multiply this anomaly that we get here over the Central Equatorial Indian Ocean with -1. So, zonal wind index is taken as the negative of the anomaly so that positive values of EQWIN are favourable for the monsoon.

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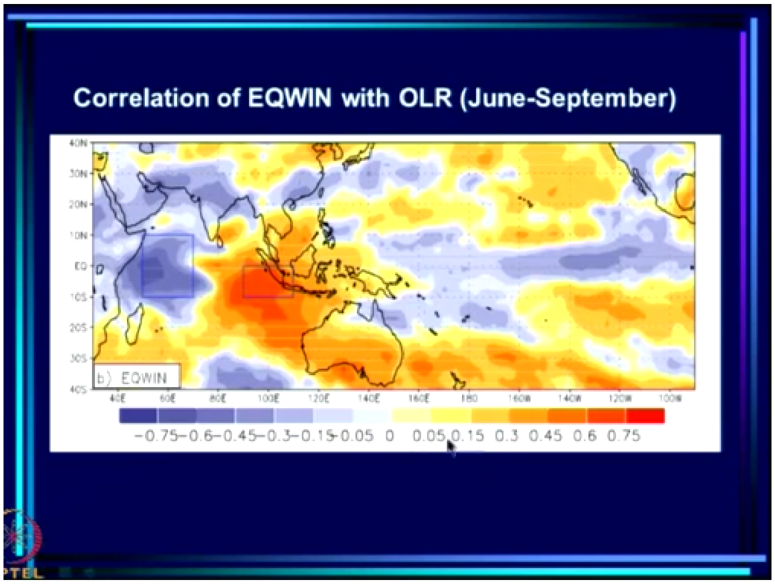

Now, let us see what is the correlation of this index EQWIN with OLR for June to September and what you find is that EQWIN leads to positive EQWIN implies high convection over WEIO as well as the Indian region and suppression of convection over here. So, this is the pattern here. Notice also that EQWIN is also related to convection anomalies over the Pacific.

This has to be borne in mind that the modes over the Ocean and the mode over Pacific which is then so are not independent of one another, in fact they are mutually interactive systems which we will come to a little later.

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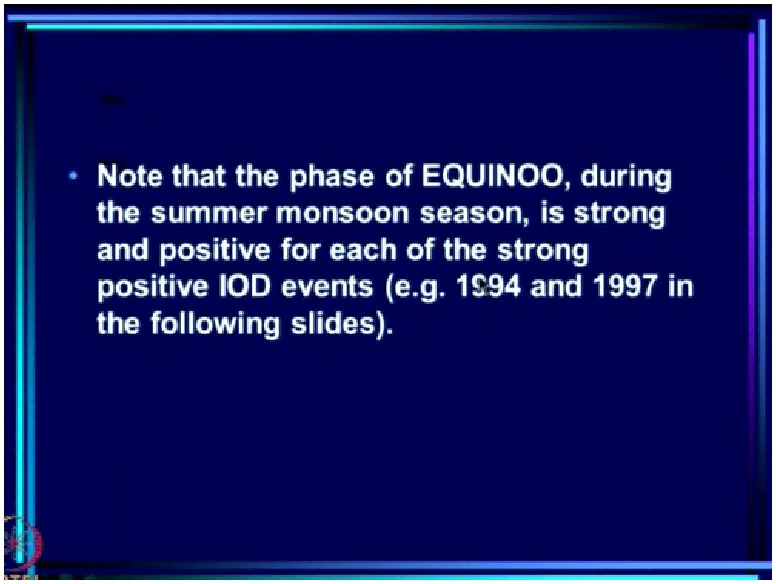

Note that the phase of EQUINOO during the summer monsoon season is strong and positive for each of the positive IOD events, okay. So, IOD events we have actually identified based on DMI. DMI remember is an index which is an oceanic index. It depends on the sea surface temperature anomalies, but now let us see.

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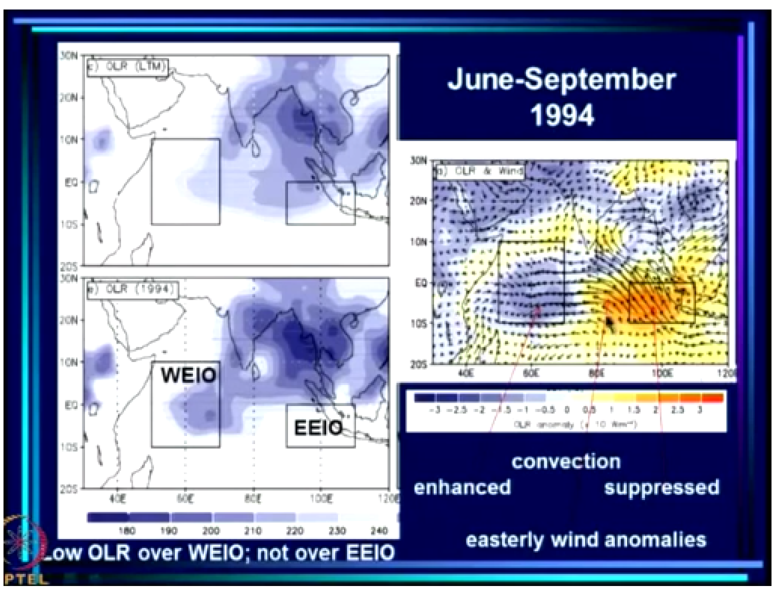

This is June to September 1994 identified as a positive IOD in the event because DMI is very large that is to say SST anomaly of WEIO is much larger than that of EEIO. This is positive SST anomaly; this is negative SST anomaly for the event of 94. What you see here is actually the OLR pattern and the winds, okay and you see that associated with positive SST anomaly here, you have enhanced convection associated with negative SST anomaly here, you have depressed convection, suppressed convection and you have easterly winds here.

So, in this case, in the case of strong positive IOD events, in fact the SST anomalies and the OLR anomalies go hand-in-hand. SST anomaly positive and OLR negative over WEIO and opposite signs over EEIO. So, the atmosphere and ocean seem to behave as if they are tightly coupled.

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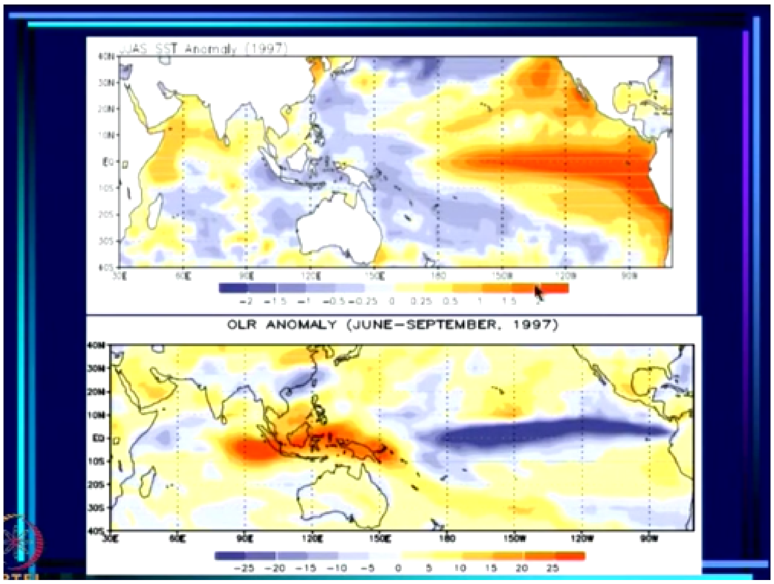

Now, same thing with 1997. 1997, this is the SST anomaly now. You see it is much colder over the East, much warmer over the West. The convection is suppressed. This is the OLR anomaly. Convection is suppressed over the East and enhanced over the West. So, for strong positive IOD events during the summer monsoon, in fact we get strong phase of EQUINOO as you can see here. Very strong winds and very big gradient, strong positive phase of EQUINOO is what you get.

This you can see here from the OLR anomaly patterns. Very strong phase of EQUINOO, positive phase.

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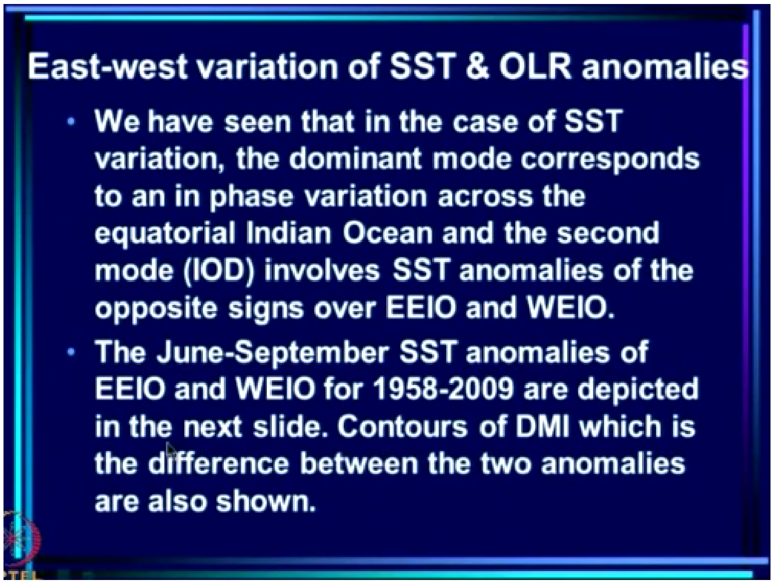

Now, let us look again at East-West variation of SST and OLR anomalies. See in the case of SST when we discuss the variation of SST over the Indian Ocean region, we pointed out that if this SST variability is analysed, then the dominant mode corresponds to an in phase variation across the Equatorial Indian Ocean which means either the entire region is getting warm, positive SST anomaly or the entire Equatorial Indian Ocean is getting colder which is negative SST anomaly.

These are in phase variation that was the dominant mode and the second mode involved an anomaly of positive on the West and negative on the East or vice versa. So, anomalies of opposite sign over West and East corresponded to the second mode of SST variability. Now, the June to September SST anomalies of EEIO and WEIO, we see in the next slide.

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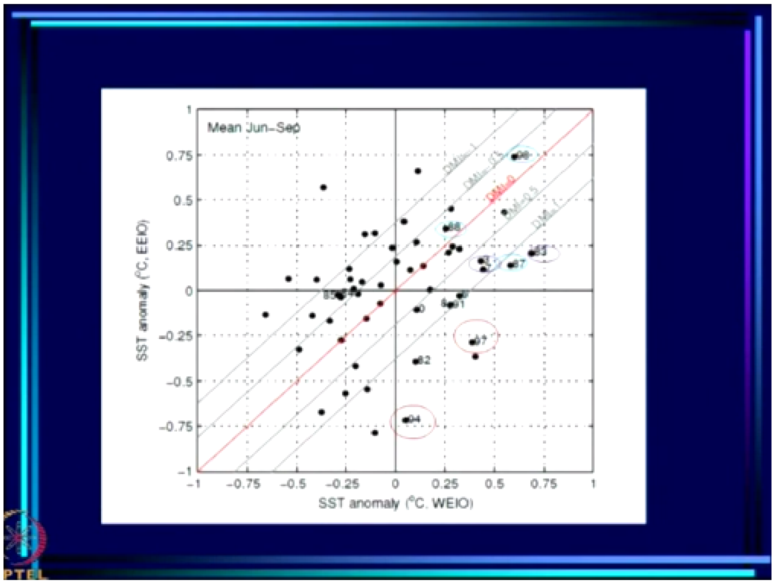

What you will see here is, see this is the SST anomaly of WEIO. This is the SST anomaly of EEIO. So, now when they are of the same sign, the points are in this quadrant here. So, for some years, they are both positive. For some years they are both negative. This is the in phase variation which we saw and most points in fact correspond to in phase variation. But there are quite a few points in which the variation is out of phase.

In other words, anomalies of WEIO are SST anomalies or opposite sign to SST anomalies of EEIO. Here WEIO SST anomaly i positive and EEIO SST anomaly is negative. This corresponds to positive phase of the dipole and this corresponds to negative phase of the dipole. Now, since DMI is simply the difference between the 2 anomalies, we can plot contours of DMI on this and what you see here is contours of DMI.

This is DMI 0, okay. This is DMI -0.5, +5 and +1. Now, important thing to notice is, although we has DMI > 1, means it is an IOD event or an Indian Ocean Dipole with a fairly strong amplitude but actually there are years such as here. This is 1983 and this is 1987 in which both the anomalies are of the same sign and yet DMI is > 1.

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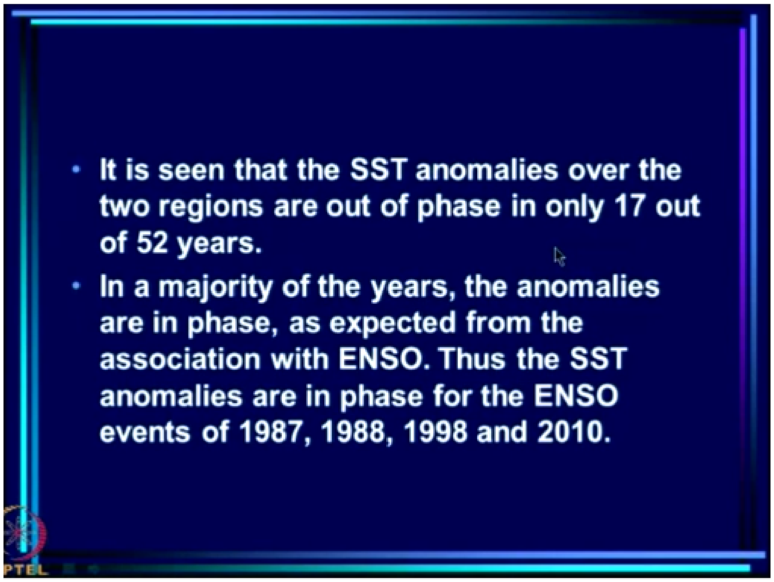

So, this is a point to be noted that first of all that the SST anomalies over the 2 regions are out of phase only in 17 out of 52 years. Most of the years, SST anomalies of the 2 regions are in phase. They are either in this quadrant with + + or in this quadrant with - - SST anomalies in both cases. Only in a few years they are out of phase. In fact, roughly one third of the years they are out of phase.

In the majority of the year, the anomalies are in phase and this is expected from the association with ENSO. We have already seen that when you have El Nino, the entire region tends to get warmed up and when you have La Lina, the entire region becomes cooler and in fact you have a signature of this as well in this, okay. So, we have SST anomalies are in phase for 1987, 1988, 1998 and 2010.

So, we have 1987, they are in phase and 1998 also they are in phase and 1988 also they are in phase, okay. Of the seasons associated with negative SST anomalies of EEIO and positive SST anomalies of WEIO, DMI and the SST anomaly of EEIO are large for 1994 and 1997, you have seen this. These are the 2 positive IOD events and you see that here 1994 and 1997, EEIO SST is very much suppressed. These are the 2 years in which they are opposite.

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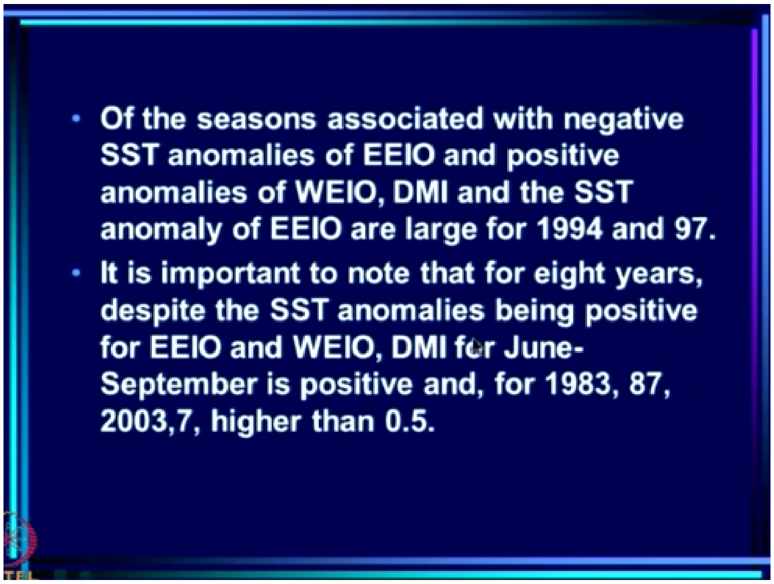

Now, it is important note that for eight years despite the SST anomalies being positive for the EEIO and WEIO, DMI for June to September is positive and for 1983, 1987, 2003 and 2007, higher than 0.5. So, remember we had used DMI as a measure of Indian Ocean Dipole intensity but you see here for several years, it is positive and larger than 1. This is 2007, 2003, 1983 and 1987. So, you do have a case of DMI being larger than 0.5.

Although anomalies are both positive here. This is to be kept in mind. So, for some years actually DMI is > 0.5, although SST anomalies are positive over both the regions.

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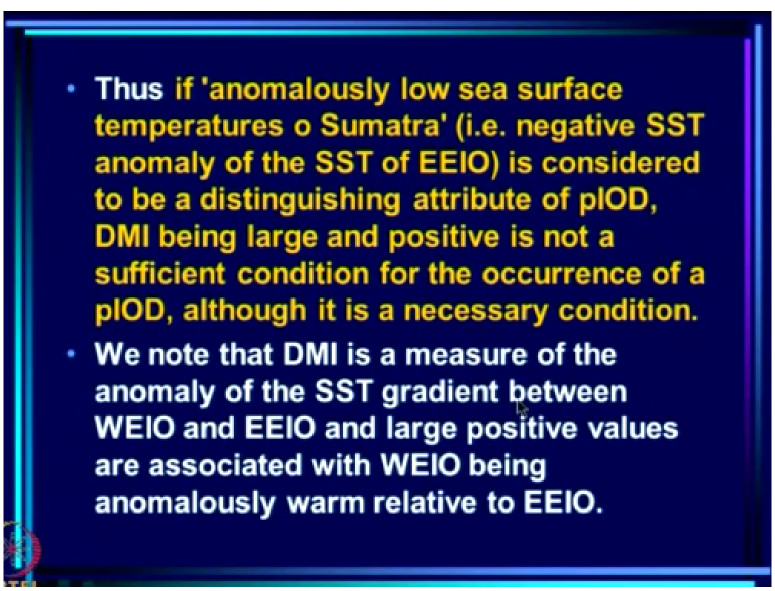

Now, when Saji et al originally defined the Indian Ocean Dipole mode, they had said if anomalously low sea surface temperature of Sumatra, i.e., negative SST anomaly of the SST of EEIO is considered to be a distinguishing attribute of pIOD, DMI being large and positive is not a sufficient condition for the occurrence of pIOD, although it is a necessary condition. So, we believe that the IOD must have SST anomalies of opposite sign, then simply DMI being greater than some quantity does not give uniquely only IOD events.

It is necessary that DMI should be large, that the SST anomaly of WEIO should be larger than that of EEIO but it is not sufficient because even when it is large, you have cases even for DMI > 1, you have cases in which both the SST anomalies are positive. So, simply identifying IODs by looking at DMI does not make sense. These are what can be considered more as a zonal mode, because this is a mode in which the entire region is getting warmer.

So, this is more of a zonal mode there has been a big debate in the literature about whether what we see over the Indian Ocean is a dipole mode meaning with opposing anomalies over the 2 regions or a zonal mode. So, DMI is a measure of the anomaly of the SST gradient between WEIO and EEIO and large positive values are associated with WEIO being anomalously warm relative to EEIO, but does not mean they have to be of opposite sign.

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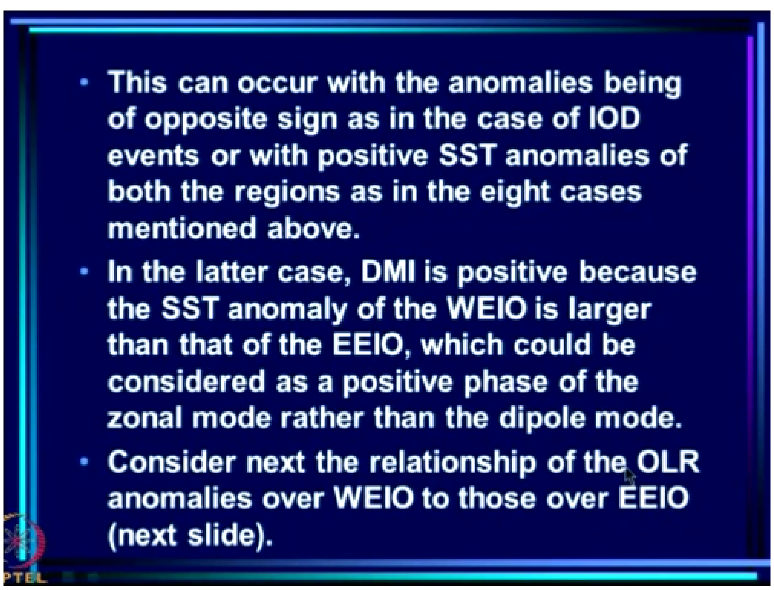

This can occur with the anomalies being of opposite sign as in the case of IOD events or with positive SST anomalies of both the regions as in the eight cases mentioned above. In the latter case, DMI is positive because the SST anomaly of WEIO is larger than that of the EEIO which could be considered as a positive phase of the zonal mode rather than the dipole mode. This is exactly what I mentioned. Consider next, the relationship between the OLR anomalies. See so far we looked at how are the SST anomalies over the East and West related.

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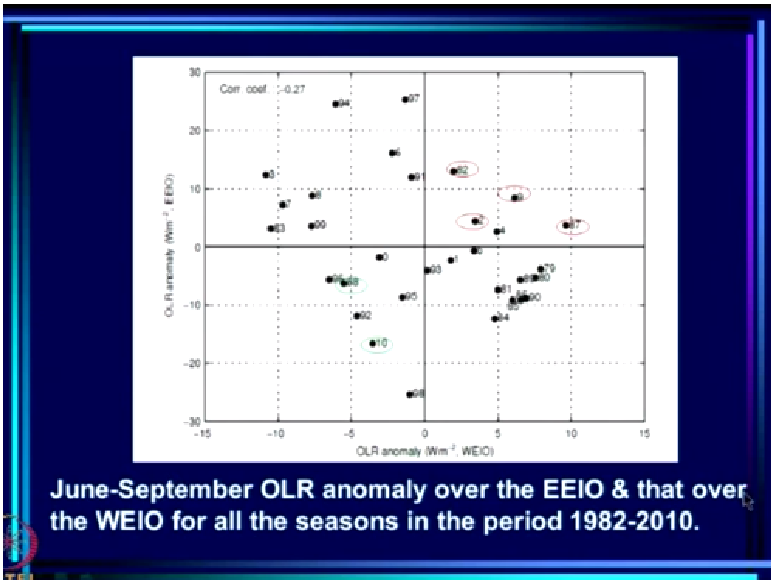

Now, let us look at the OLR anomalies. Now, June to September OLR anomaly over the EEIO and over WEIO for all seasons in the period 1982 to 2010 are shown here and what you see is again there are several seasons in which both the anomalies are of the same sign, the anomaly over WEIO is same sign as anomaly over EEIO and they are positive here which means that you get suppression of convection over both the regions and here you get enhancement of convection over both the regions.

So, there are some points in which there is in phase variation across the equatorial Indian Ocean in OLR but then, there are also cases of EQUINOO in which case the anomalies are of opposite sign which will be in these quadrants here.

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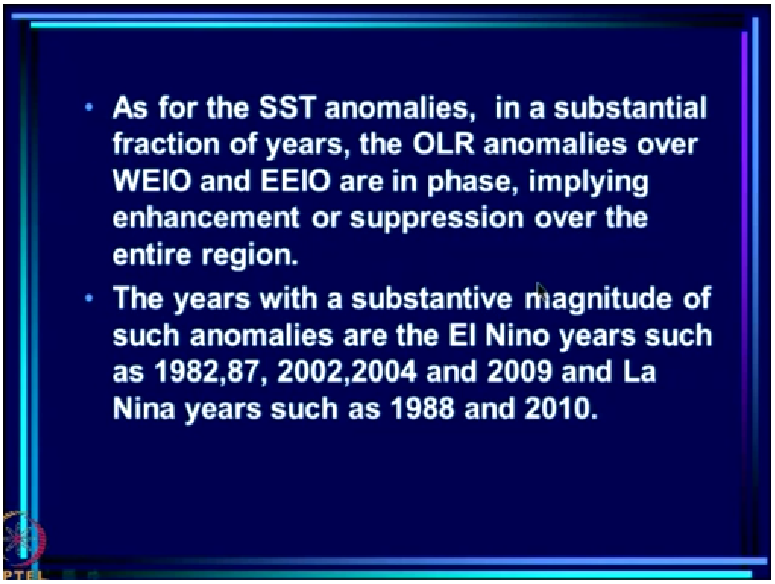

So, as for the SST anomalies in a substantial fraction of years, the OLR anomalies over WEIO and EEIO are in phase implying that enhancement or suppression over the entire region. The years with a substantive magnitude of such anomalies are El Nino years. El Nino years are here as I said before. El Nino years, the SST anomaly tends to be positives. So, you have 1982, 2002, 2009 and 1987.

These are the El Nino years, whereas negative anomalies correspond to 1988 and 2010, these are La Nina years. So, these are generally El Nino years and these are generally La Nina years that you get when you have in phase separation or enhancement of convection, okay. So, years with substantive magnitude of such anomalies are the El Nino years which I just pointed out and the La Nina years.

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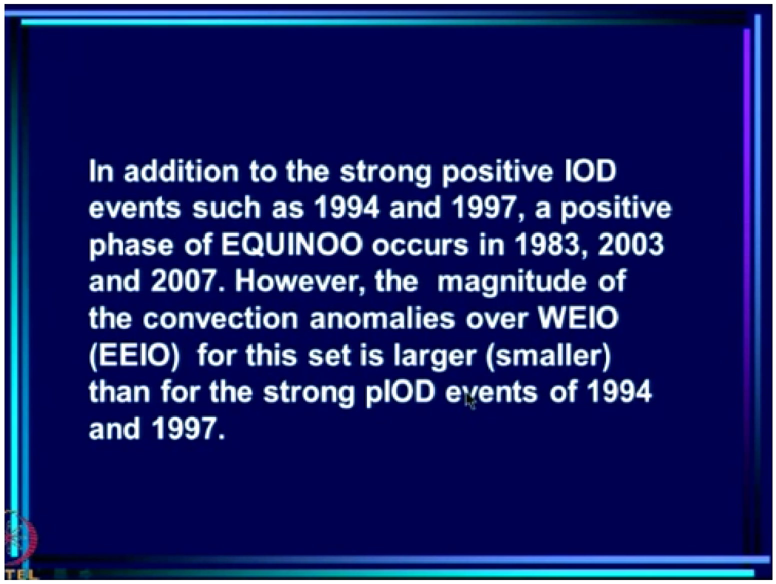

Now, in addition to the strong positive IOD events such as 1994 and 1997, a positive phase of EQUINOO occurs in 1983, 2003 and 2007. So, let us look at those, okay. So, now we have this is the case in which we have suppression of convection, OLR anomaly being positive due to El Nino, enhancement due to La Nina and then years this is 1994 and 1997. These are 2 strong positive IOD years.

But in addition to that in the same quadrant years like 2003, 2007 and 1983, they also have a negative OLR anomaly over the West and a positive OLR anomaly over the East. So, these are also positive EQUINOO years. So, in addition to the positive IOD years, there are years here which are also positive EQUINOO years.

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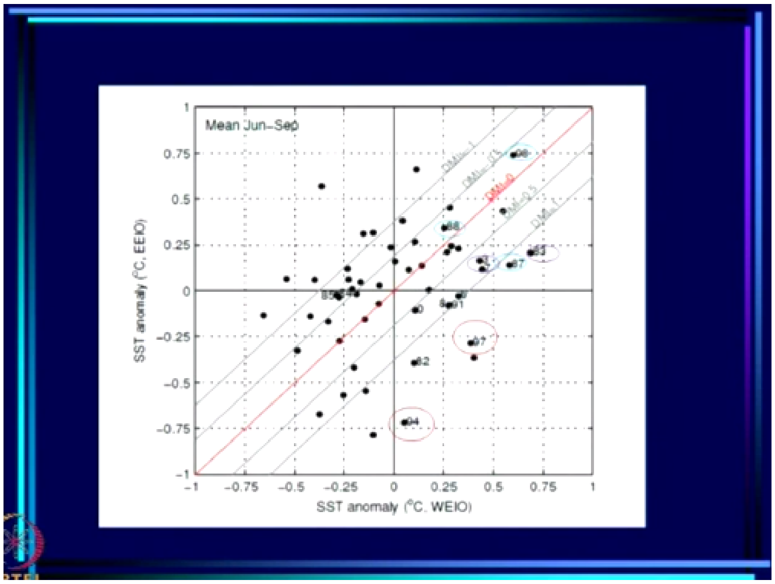

You may remember that I had pointed out earlier which we can just see again that 2003, 2007 and 1983 where years in which the SST anomalies are both positive. So, we do have EQUINOO in a positive phase but here we cannot talk of an IOD for these years in terms of the ocean component, because their SST anomalies are in the same, okay. So, positive phase of EQUINOO occurs in 1983, 2003 and 2007; however, the magnitude of convection anomalies over WEIO is larger and this we have.

You can just quickly see that for these years 2003, 2007 and 1983, you can see 1994, 1997 are here, the enhancement of convection over the West is not very large but 2007, 2007, 1983, it is very large. Whereas, the pIOD (the positive IOD events are characterized by intense suppression of the East, whereas for these events the suppression of the East is not so intense suppression of convection over the East is not so intense.

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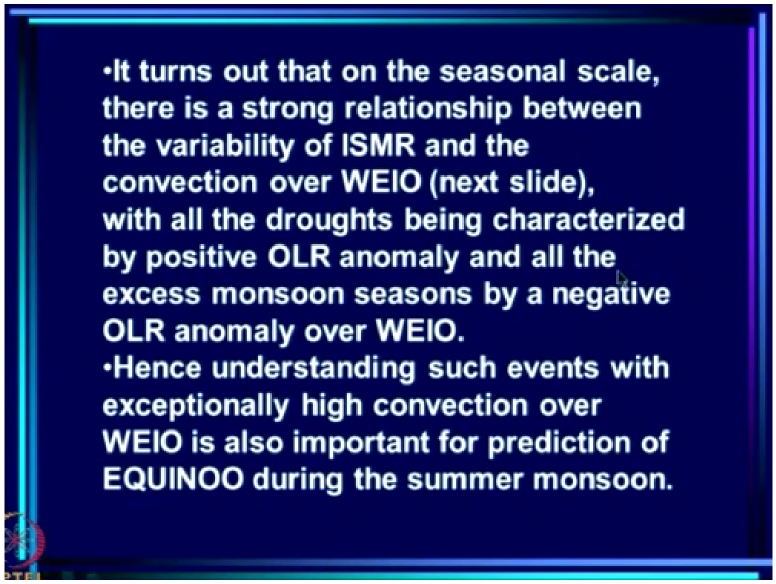

Now, why is this interest. Why is EQUINOO per se of interest, we will discuss that even further in the next lecture, but here let me just point out that it turns out that on the seasonal scale, there is a strong relationship between the variability of the all India summer monsoon rainfall and the convection over the western equatorial Indian Ocean.

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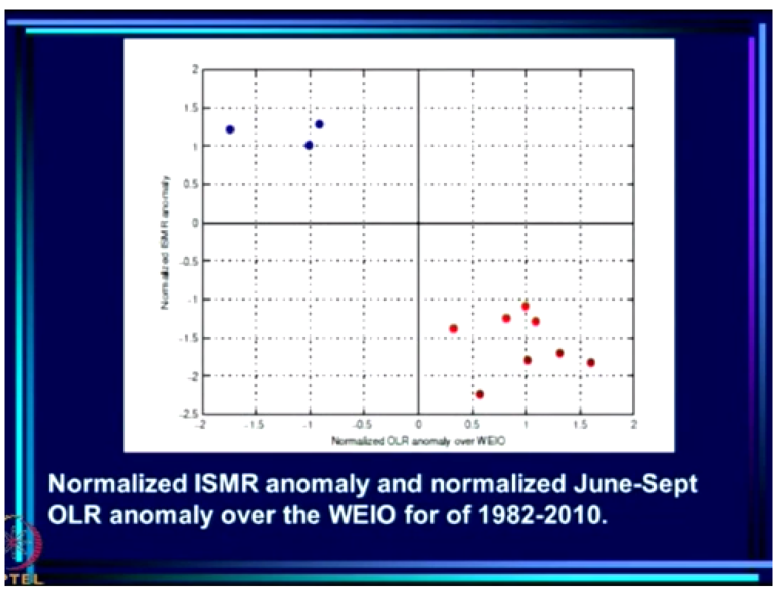

Now, now we look at only the droughts and excess rainfall years of all India monsoon rainfall and these are the ordinary droughts and these are more severe droughts and these are the excess rainfall years and what you see is this is the ISMR anomaly and you can see that this is more than -1 and ISMR anomaly deficit be more than 1.5 standard deviation, these are the severe droughts, these are droughts and these are excess monsoon seasons, excess rainfall seasons.

What you see is these are all in this quadrant which means for these the convection over the West is suppressed. For these, the convection over the West is enhanced. So, the best equatorial Indian Ocean does seem to play a very important role in determining how high the monsoon rainfall would be on the Indian region because if the convection over the West is suppressed, all the droughts belong to the case in which the convection over the West is suppressed.

All excess rainfall season belong to a state in which the convection over the West is enhanced. This is important to keep in mind.

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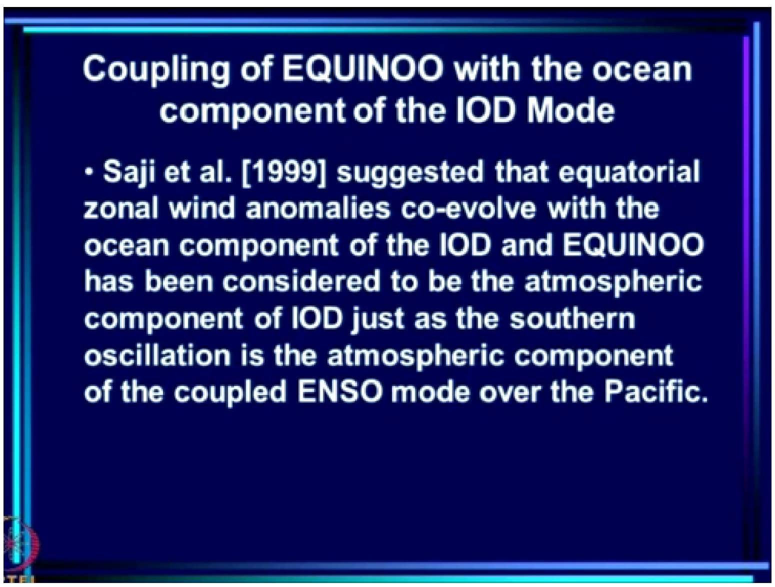

Now, we have already seen that for certain years, we have a hint that the coupling may not be so strong and we mentioned years like 2003, 2007 and 1983 for which it was really a zonal mode not an IOD, so that in fact SST anomalies were positive on West as well as East but the OLR anomalies were such that OLR anomalies were of opposite sign. So, that you had a very strong positive phase of EQUINOO.

So, we had a hint that the coupling may not be so strong and we will test it. Actually, Saji et al. really looked at primarily the positive IOD events and they suggested that equatorial zonal wind anomalies co-evolve with the ocean component of the IOD and EQUINOO they suggested was the atmospheric component of IOD just as the Southern oscillation is the atmospheric component of the coupled El Niño Southern Oscillation mode over the Pacific. So, this is what was suggested in the original paper by Saji et al.

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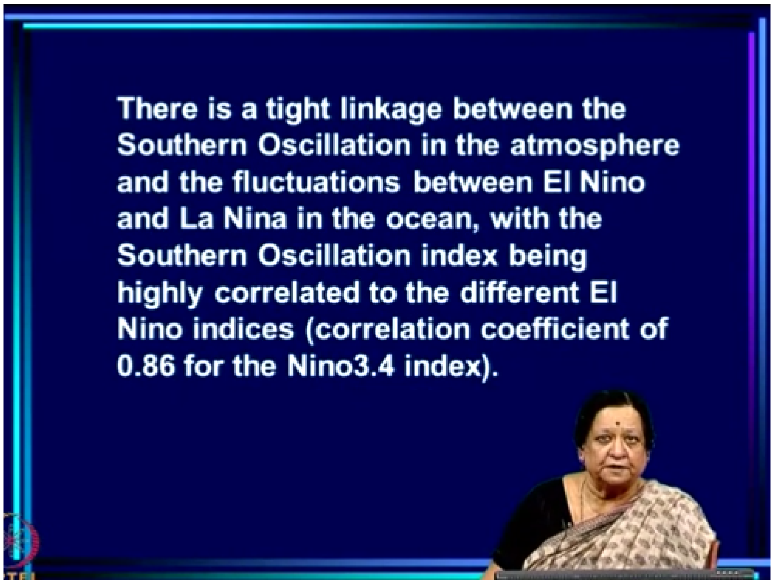

But we have to note that there is a tight linkage between Southern oscillation in the atmosphere and the fluctuations between El Nino and La Nina in the ocean with the Southern oscillation index being highly correlated to the different indices. So, for example correlation coefficient of the Southern oscillation index with Nino 3.4 is 0.86. So, this is a very tightly coupled system over the Pacific.

It turns out that the relationship between DMI which in an index for the ocean component of IOD and EQWIN in the summer monsoon season is not strong and you will see that here.

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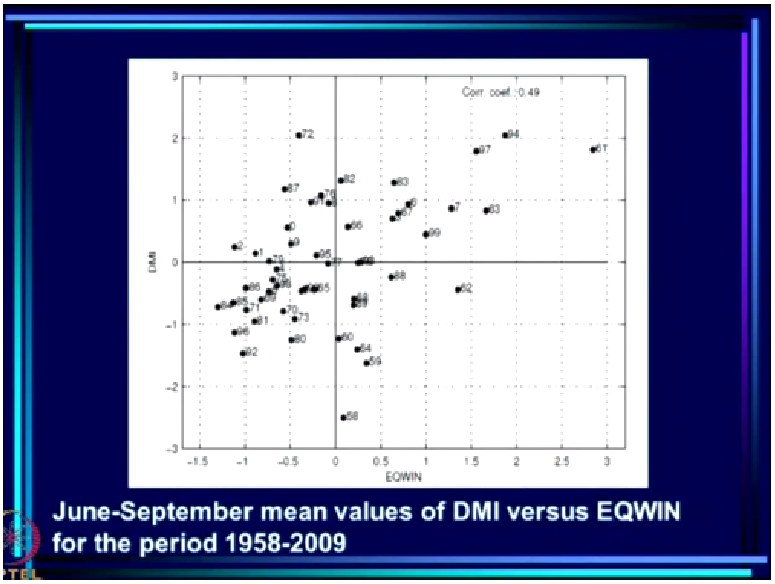

In fact, these are all values between 1958 and 2009 and what you see is that the correlation is somewhat poor. It is only 0.49, whereas remember (()) (28:21) it was 0.86 and irrespective of what index you take it is of that order and in fact there are many points in the wrong quadrant so to speak. Many points when the signs of DMI and EQWIN are different. These are points in the wrong quadrants.

These are points in the right quadrant where you would expect if it was highly positively correlated most of the points would be in these 2 quadrants here, but that is not the case at all.

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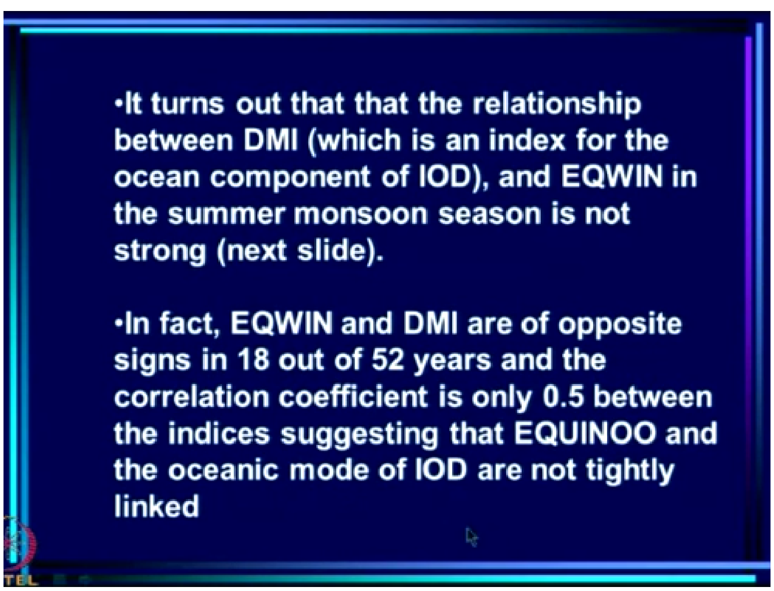

So, in fact EQWIN and DMI are of opposite signs in 88 out of 52 years and the correlation is only about 0.5 between the indexes suggesting that EQUINOO and the oceanic mode of IOD are not tightly linked.

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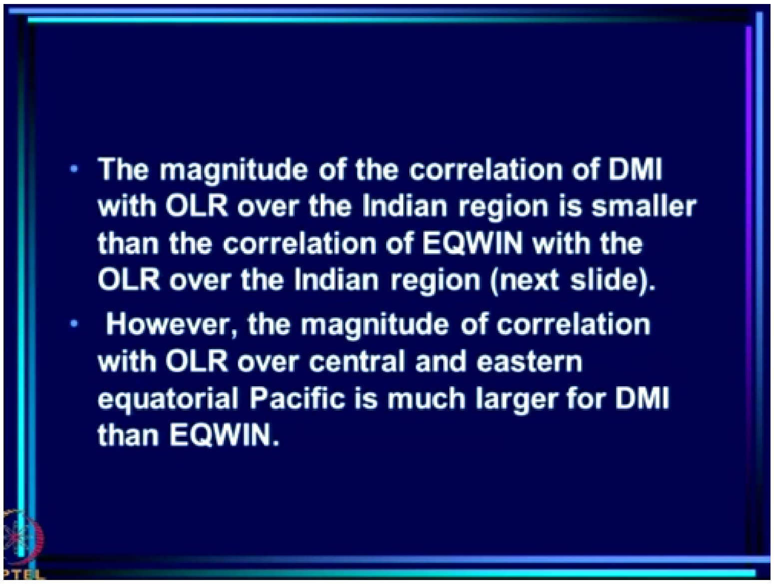

Now, the magnitude of the correlation of DMI with OLR over the Indian region is smaller than the correlation of EQWIN with the OLR over the Indian region.

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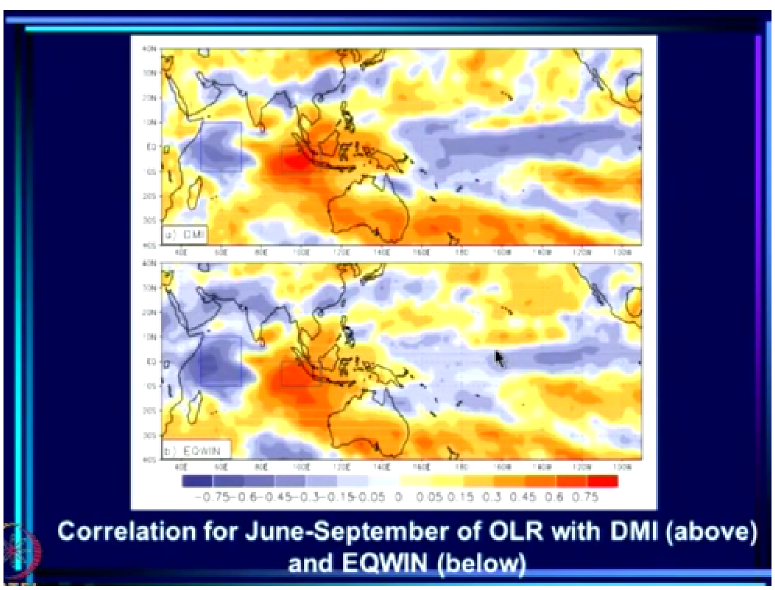

Correlation for June-September of OLR with DMI (above) and EQWIN (below)

Now, actually in the original paper of Saji et al, they have plotted a correlation for the whole year and they show that the correlation is primarily with rainfall over Africa, but now here we see a comparison of correlation with EQWIN of OLR everywhere and this is the correlation with DMI of OLR everywhere and this is the correlation with EQWIN. You can see that correlation with

DMI is more or less similar to correlation with EQWIN over the equatorial Indian Ocean.

But importantly DMI is not so well correlated with rainfall over India as EQWIN is and furthermore DMI seems to be highly correlated with events in the Pacific, whereas EQWIN is not so highly correlated. The patterns are somewhat similar which is not surprising but the coalition with the atmospheric component of the rainfall over the Indian region is much higher than the correlation with the ocean component of IOD. This has to be borne in mind.

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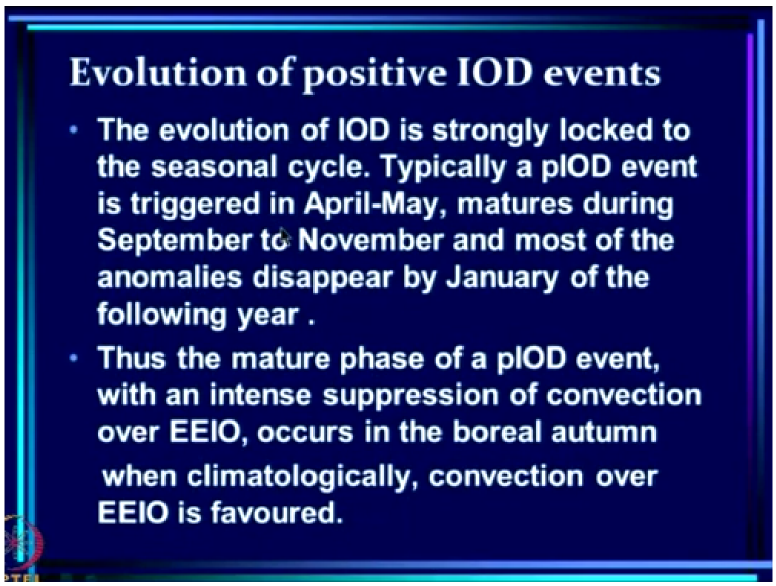

Now, so far we have been talking of Indian Ocean Dipole mode and the 2 phases of the dipole more, the 2 phases of the ocean component of the dipole mode of the atmospheric component of the dipole mode namely EQUINOO and so on. But there is a great deal of interest in the positive IOD events.

The strong positive Indian Ocean Dipole events like those of 1994 and 1997 and so on, because these are cases in which the climatological gradients are reversed, that is to say the SST gradient, East-West gradients of SST of convection and so on are reversed from that in the climatology or the mean picture. So, there has been a lot of attention to this and naturally one is interested in finding out how does the state evolved because it has signatures of East-West gradients which are opposite to those that are observed in the climatology.

So, evolution of positive IOD events has been focus of many studies since the discovery of IOD in 1999. The evolution of IOD is strongly locked to the seasonal cycle. This was pointed out in the very first paper by Saji et al. Typically, a positive IOD event is triggered in April-May, matures during September to November and most of the anomalies disappear by January of the following year.

So, this is a typical evolution and so the mature phase of a positive IOD events with an intense suppression of convection over EEIO occurs in the boreal autumn when climatologically convection over EEIO is favoured.

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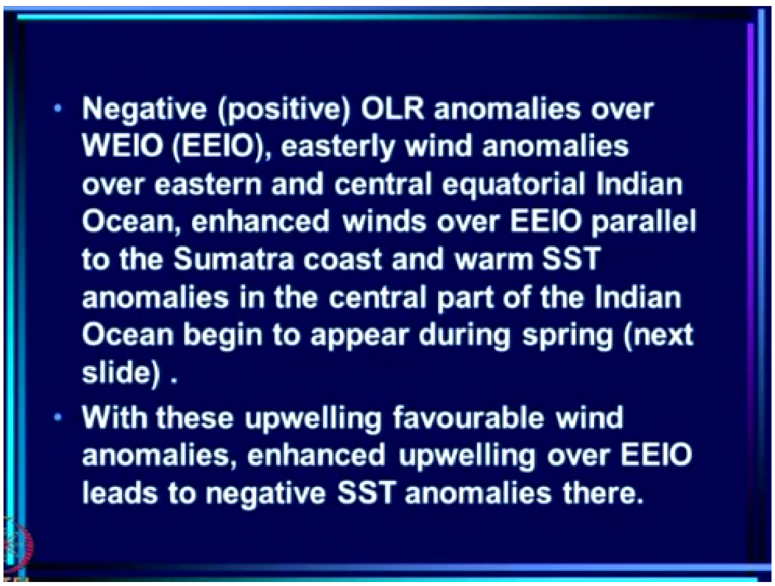

Now, this is something we had seen in the last class that climatologically convection over EEIO is very much favoured during September to November and it is at that time that the convection gets suppressed during a positive IOD event. So, that is the mature phase of IOD. Now, negative OLR anomalies over WEIO, easterly wind anomalies over eastern and central equatorial Indian Ocean, enhancements over EEIO parallel to the Sumatra coast and warm SST anomalies in the central part of the Indian Ocean begin to appear during spring.

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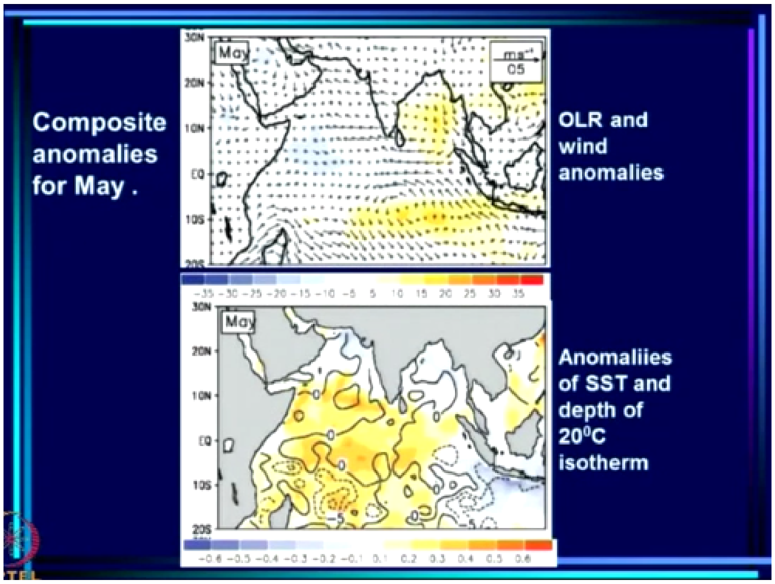

So, let us see what happens. We are now trying to see how do the OLR anomalies evolve, how do the anomalies of different fields evolve by taking composites over several positive IOD events and what you see here is these are the OLR and wind anomalies and you can see that already in April-May you are beginning to see first of all a trace of negative OLR here and winds which are and easterly here.

So, already you are beginning to see this and in terms of the sea surface temperature which is in colours, we are beginning to see cooler SSTs here, that is to say negative SST anomaly, positive SST anomalies everywhere else and furthermore the depth of the thermocline is shallower here. Remember climatologically, you have to remember that the thermocline depth is deeper here, thermocline is deeper in the East than in the West.

But now because this is a positive IOD event in fact you have negative anomalies of thermocline depth near the East and positive anomalies near the West.

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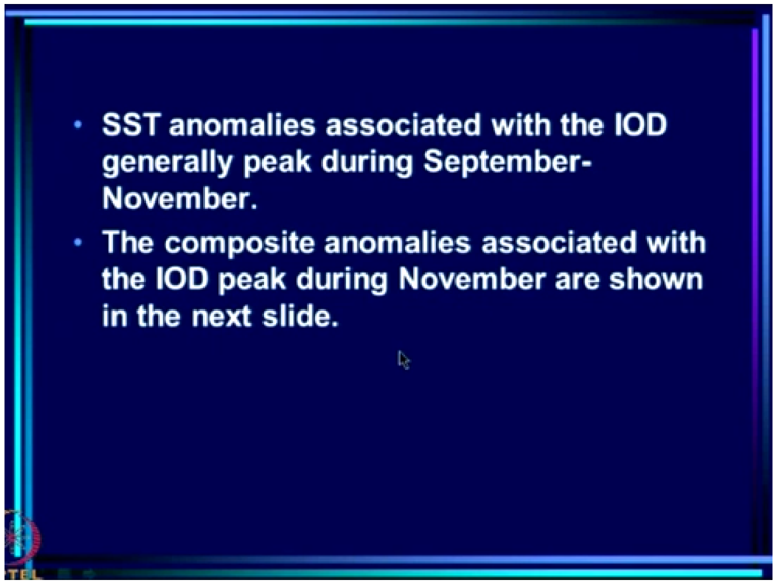

So, these things begin in April-May itself. SST anomalies associated with the IOD generally peak during September-November. The composite anomalies with the IOD peak in November is shown here.

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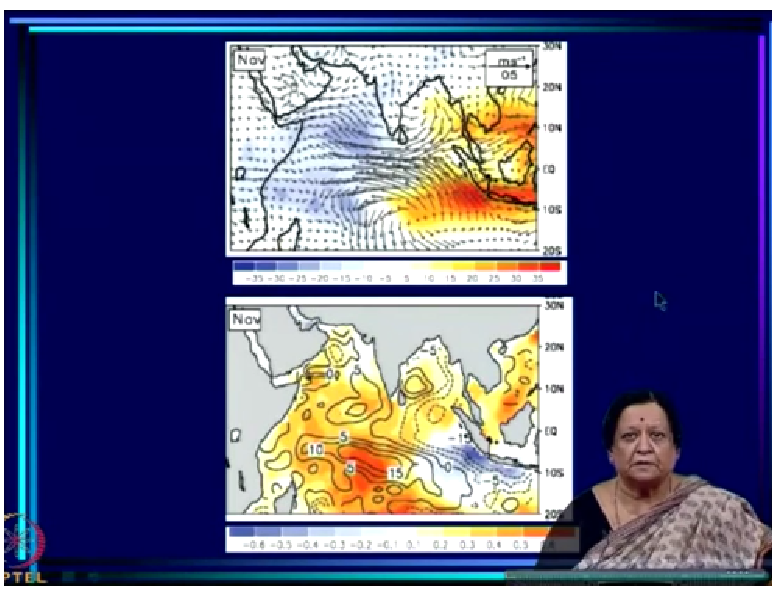

What you see is intense suppression of convection here associated with cold SST anomalies here, these are the blues. Enhancement of convection here, warm SSTs here and you can see very strong easterly wind anomalies here going towards the region which is convecting more.

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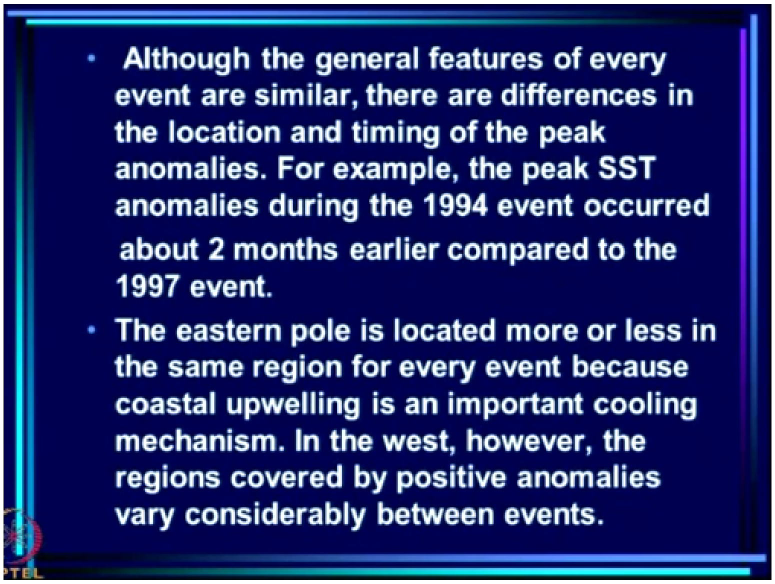

So, this is the general picture, then you begin to see signals that an IOD is going to develop in April-May in OLR, in winds, in SST, in everything. As the IOD evolves, it matures generally around September to November at which point all these anomalies have very large amplitude. Now, although the general features of every event are similar, there are differences in the location and timing of the peak anomalies.

For example, the peak SST anomalies during 94 event occurred about 2 months earlier compared to the 1997 event. So, this is a matter of difference in timing. There is also a difference in the locations like Eastern pole is located more or less in the same region for every event because of coastal upwelling is an important cooling mechanism. In the West, however, the regions covered were positive anomalies vary considerably between the events, they are talking here of SST anomalies of course.

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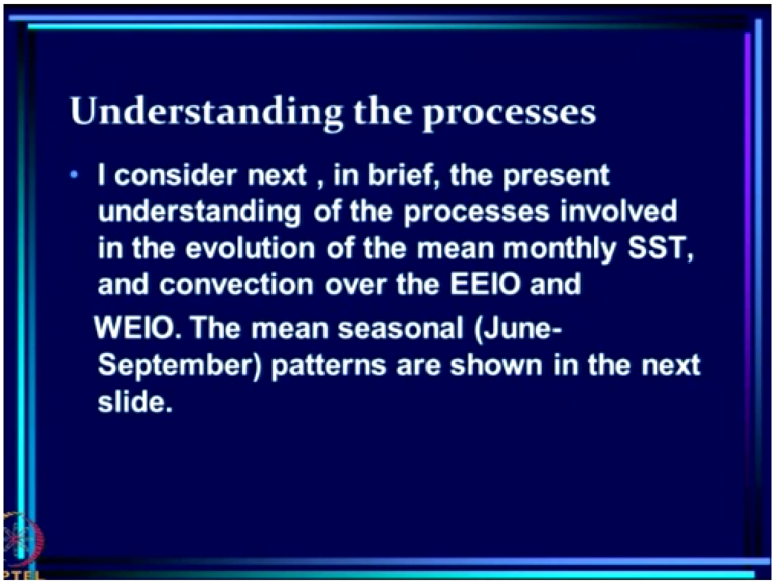

Now, so far we have really described what are the different states between which the Indian Ocean tends to oscillate and the atmosphere over Indian Ocean tends to oscillate, but we need to understand the processes only then we can model properly and then eventually predict these. So, let me now present what is the present understanding or what are the processes involved. So, first let use consider the processes involved in the evolution of the mean monthly patterns itself over East and West which are the 2 poles of IOD.

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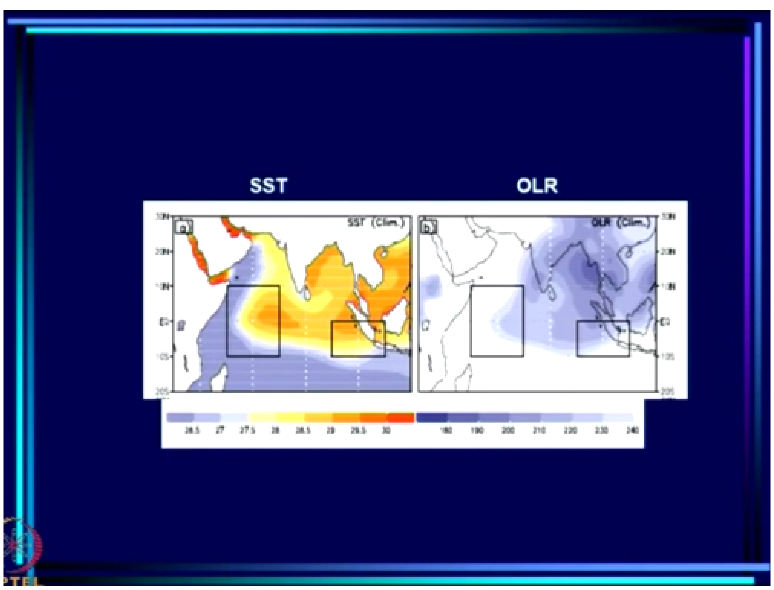

So, the mean seasonal patterns are here. This is the SST and this is the OLR. These are the mean seasonal patterns. So, what we are going to see is how do these evolve, okay because we have seen that in the seasonal pattern, you have more convection over the East box than over the West box, okay.

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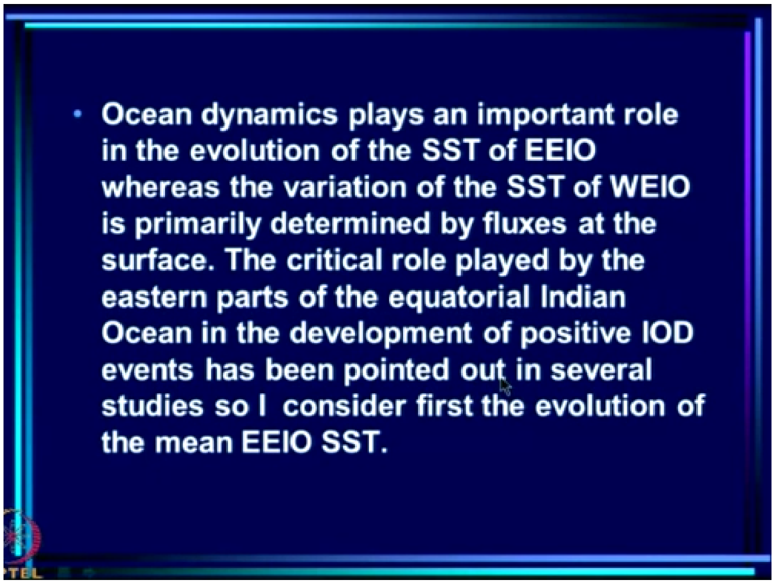

Now, ocean dynamics plays an important role in the evolution of the SST of EEIO, whereas the variation of the SST of WEIO is primarily determined by fluxes at the surface. The critical role played by the Eastern parts of the equatorial Indian Ocean in the development of positive IOD events has been pointed out in several studies. So, I consider first the evolution of EEIO SST. This is considered the critical poll in most of the studies of the evolution of IOD.

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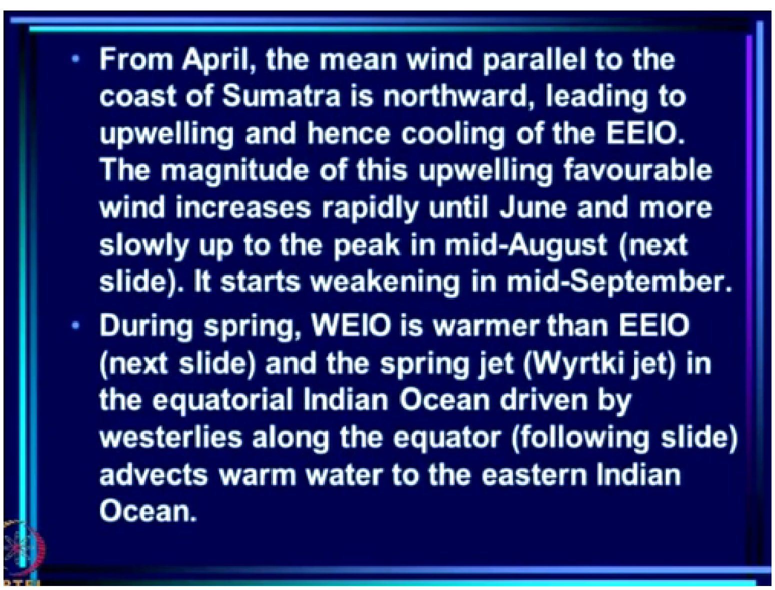

So, let us look at that and as I said ocean dynamics plays a very critical role in that. Now, from April, the mean wind parallel to the coast of Sumatra is northward leading to upwelling and hence cooling selectors look at April winds.

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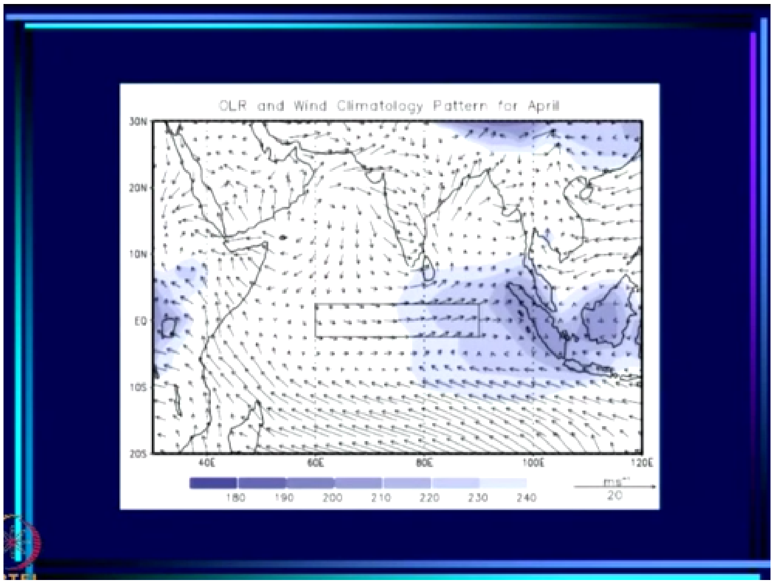

This is the pattern in April and what you notice is that the mean wind here is parallel to the coast of Sumatra.

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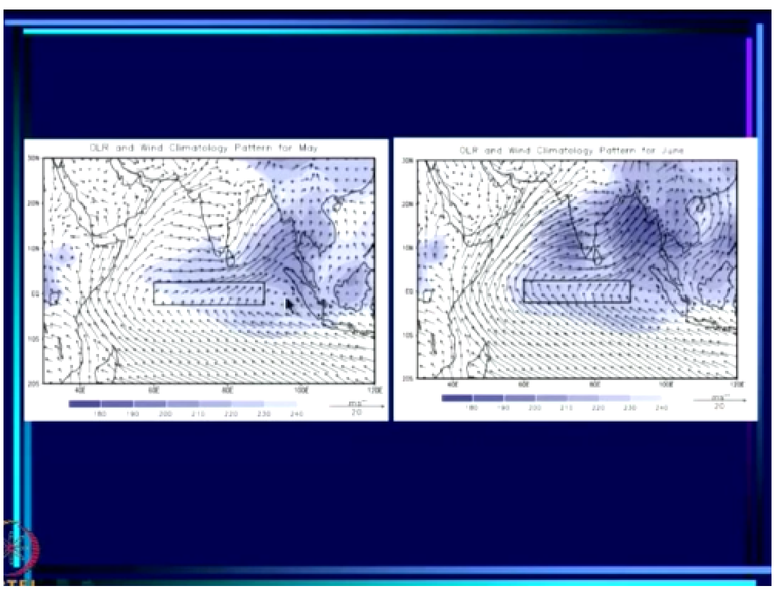

In fact, this is May and this is June.

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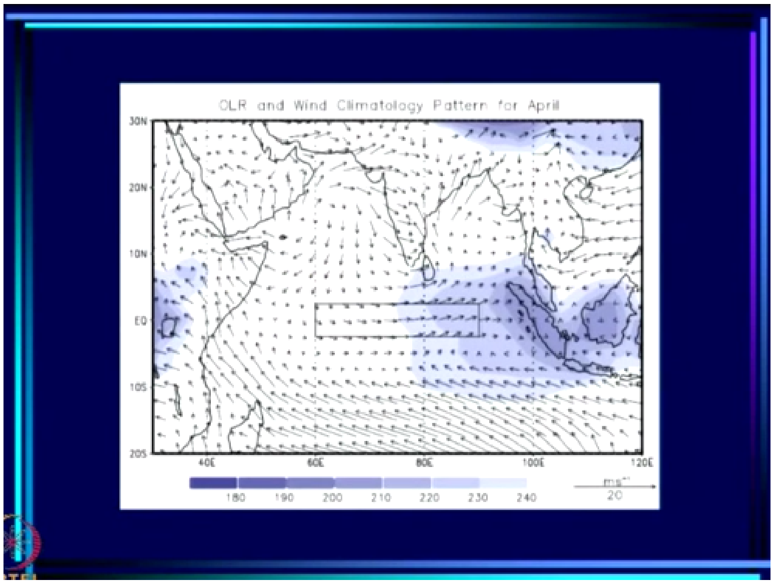

So, it begins in April. Now, remember we are in the southern hemisphere here. This is the equator. So, in the southern hemisphere, the mean wind is parallel to the coast, then Ekman drift would be at 90 degrees to its left, right because we are in the southern hemisphere which means that wind coming from the south parallel to Sumatra coast is an upwelling favourable wind because in Ekman layer, the transport will be towards this direction.

So the upper water of Ekman layer will have to be replenished by water coming from below. So, this is a region of upwelling, here. So, from April the mean wind parallel to the coast of Sumatra is northward leading to upwelling and hence cooling of EEIO. The magnitude of this upwelling favourable wind increases rapidly until June and more slowly up to the peak in mid-August.

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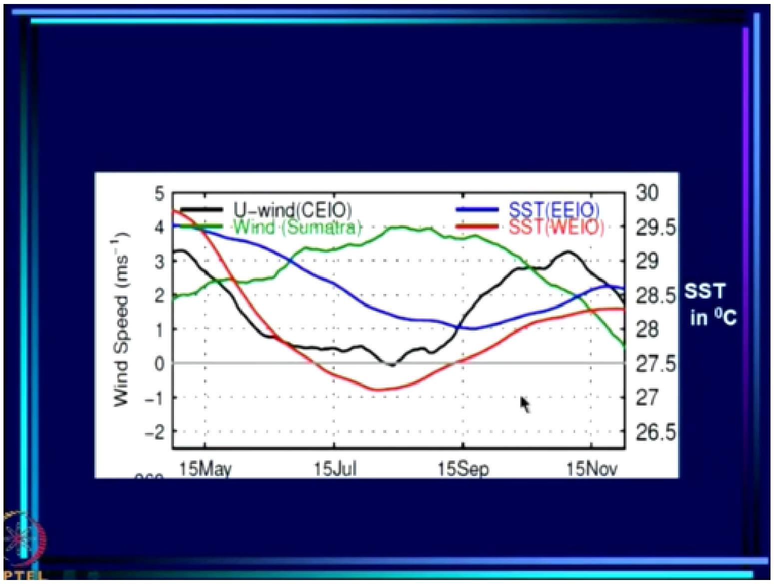

What we have plotted here now is the wind parallel to Sumatra coast which is in green here. You can see it is plotted only from first of May and it has begun to build up in April, continues to build-up, okay until about August, 15 of August or so. So, until mid-August, you have the wind parallel to the Sumatra coast building up. This means that since this is a wind favourable for upwelling, this will have a tendency to cool EEIO. So, this is the wind that is building up, okay.

Magnitude of this upwelling favourable wind increases rapidly until June and more slowly up to the peak in mid-August which we have seen. Initially, it increases more rapidly here. Here it increases more rapidly and then slowly till it reaches its peak and it starts weakening in September, that you can see here. By September it starts slowly weakening and finally it becomes very weak by end of November.

So, this is the way the wind parallel to the Sumatra coast evolves during the season. Remember we are talking of mean values here, okay. Now during spring, the WEIO SST is larger than EEIO SST and the spring jet (Wyrtki jet) in the equatorial Indian Ocean driven by westerlies along the equator advects warm water to the East. So, let us see this now. You see SST of EEIO here is in blue.

So, this is SST of the East and red is SST of the west and you can see that up to about end of May, West is warmer than the East. So, this begins in April itself. The west is warmer than East from before April and it continues to be warm till end of May, relative to the east. So, you have West being warmer than the East.

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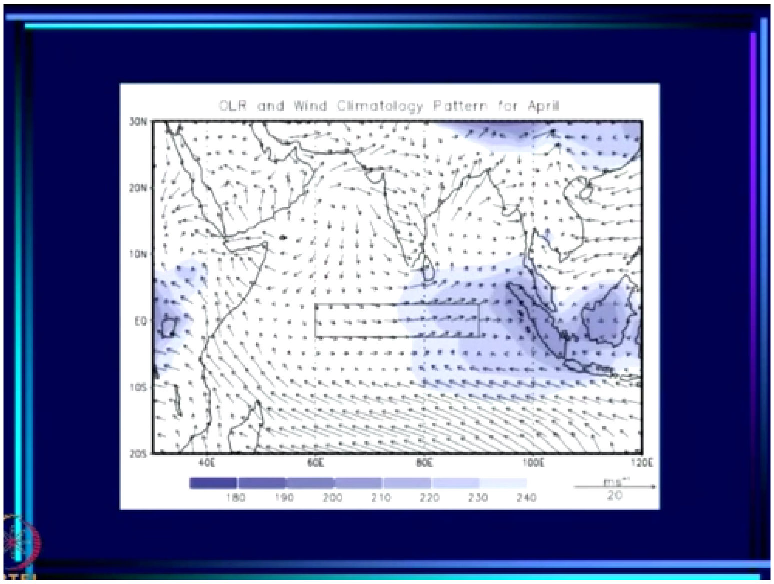

In addition to that, you have a strong, you can see here, over the central equatorial Indian Ocean, you have very strong winds coming from West to East here. So, this part is warmer than the eastern part and then you have winds which will drive the currents in this direction from West to East. These are Wyrtki jet that we talked about when we looked at the Indian Ocean. So, what happens is this Wyrtki jet will bring warm water from West to the East.

So, during spring, West is warmer than East and the spring jet in the equatorial Indian Ocean driven by westerlies along the equator advects warm water to the eastern Indian Ocean.

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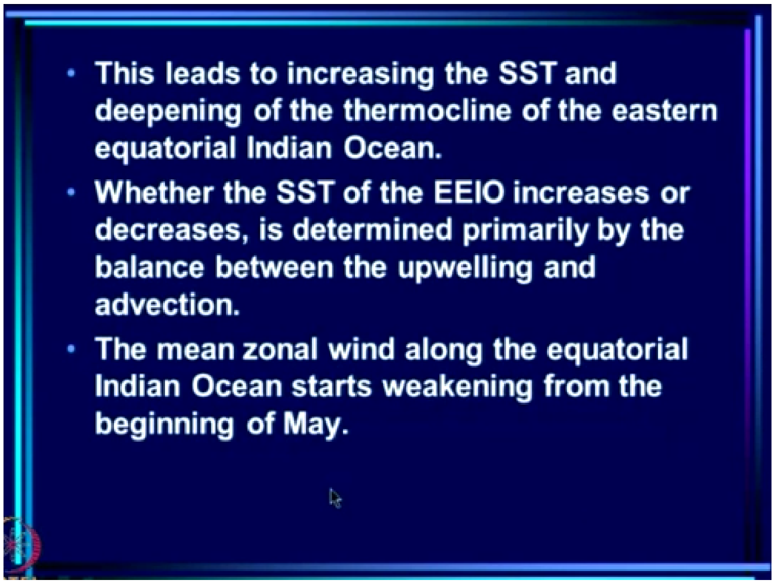

Now, what will this do. This leads to increasing the SST and deepening of the thermocline of the eastern equatorial Indian Ocean. See, this is similar to what happens in the Pacific where the trends drive a lot of warm water towards the West and deepen the thermocline here. Here what is happening is Wyrtki jet are driving a lot of warm water to the East and deepening the thermocline there. So, there are 2 competing forces.

There is winds which cause upwelling, these are winds parallel to Sumatra which will cause cooling of EEIO and winds which lead to deepening of the thermocline and warming by advection of warm water. Now, whether the SST of the EEIO increases or decreases is determined primarily by the balance between the upwelling and advection. So, which of the 2 forces is more important determines what will happen.

Now, the mean zonal wind along the equatorial Indian Ocean starts weakening from the beginning of May.

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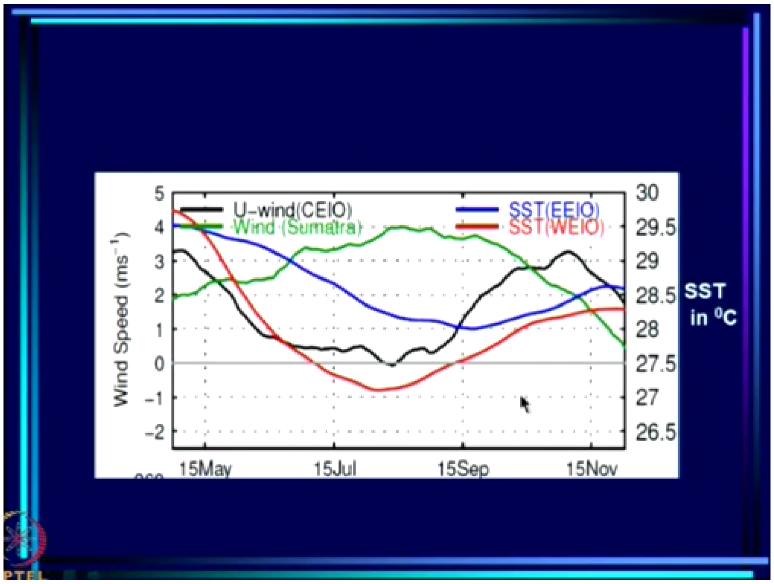

Now, here the zonal wind is also plotted, that is the line in black here this one and what you see is from the beginning of May it has started decreasing and it decreases more and more and more and starts picking up only in September. So, the mean zonal wind along the equatorial Indian Ocean starts weakening from beginning of May which means the warming that it contributes also will become less.

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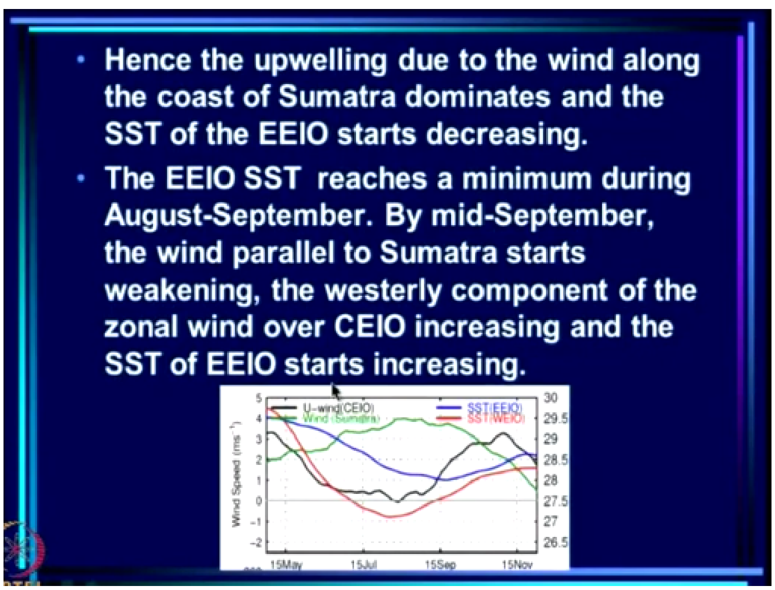

So, the upwelling due to the wind along the coast of Sumatra dominates. So, what is happening is here the mean wind which will lead to warming is weakening and the wind that leads to upwelling is strengthening. This is the wind parallel to Sumatra. So, upwelling winds the warm and in fact EEIO SST starts decreasing which you see here. This is the blue. So, SST of EEIO starts decreasing throughout and it reaches the minimum around here, just about the time when the wind parallel to Sumatra reaches a maximum.

Just around then, this reaches a plateau and then start slowly increasing as the wind drops here, okay. So, EEIO SST reaches a minimum during August-September. By mid-September, the wind parallel to Sumatra starts weakening. The westerly component of the zonal wind over CEIO is increasing which you see here, the westerly component which is the black one here that has started increasing. In fact, Wyrtki jets occur generally in the seasons between the 2 monsoons as they say.

So, during April-May and then again during fall, that is when we have strong westerly winds. So, the EEIO reaches a minimum during August-September. By mid-September the win parallel to Sumatra coast starts weakening, westerly component of the zonal wind over CEIO increasing and SST over EEIO also starts increasing. So, in this phase, the upwelling wind is decreasing and the one that advects warm water is increasing. So, you have EEIO beginning to increase.

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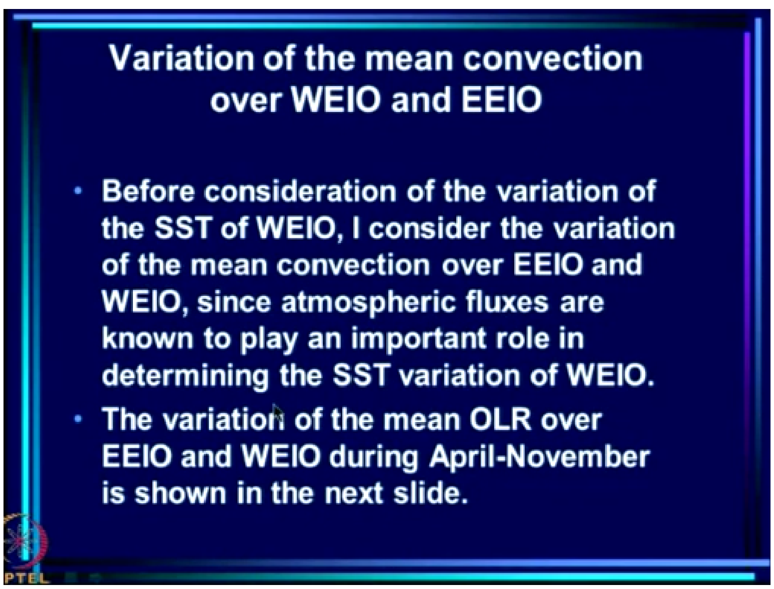

Now, to understand what happens to the sea surface temperature of the western equatorial Indian Ocean, we have to look at convection first because SST of the West equatorial Indian Ocean is very much dependent on the fluxes of the atmosphere. So, OLR or whether there is convection or not is a very important factor in determining what sort of fluxes are driving the sea surface temperature of the west.

So, let us now digress for a minute and look at how does the convection evolves over the west. So, before consideration of variation of SST of WEIO, I consider the variation of the mean convection over both EEIO and WEIO since atmospheric fluxes are known to play an important role in determining the SST variation of WEIO. The variation of the mean OLR over EEIO and WEIO during April to November, we see here.

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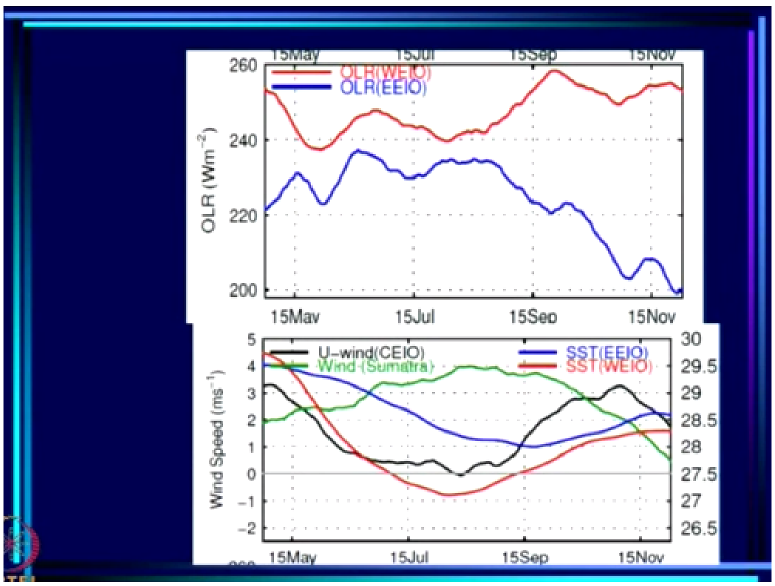

So, this is now the mean average over the boxes that you know WEIO and EEIO and you can say that these are very, very close together. Remember that if we look at monthly scales 240 is a very good measure of convection. On daily scale, it should be somewhat lower than 240 of course, much more like 200 watts per meter square will determine whether there is convection or not but you can see that the mean convection over these large regions are very, very close from around middle of May till around here which is middle of August.

After which, they start diverging very much with the convection oven EEIO becoming very much more dominant, okay.

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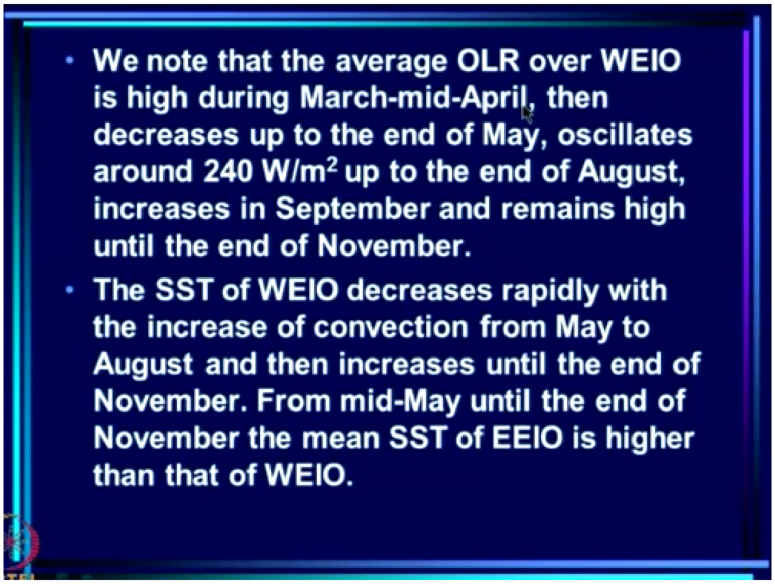

So, average OLR of WEIO is high during March to mid-April and then decreases up to here. See, average OLR of WEIO which is the red curve is high here and then decreases here up to about which means convection is building up. Then, decreases up to the end of May with convection building up, then oscillates around 240 watts per meter square up to the end of August, which we have seen and increases. See, it just oscillates around here and then increases from about September.

Then, remains high until the end. Now, SST of WEIO decreases rapidly with the increase of convection from May to August and then increases until the end of November. From mid-May until the end of November, the mean SST of EEIO is higher than that. Now, we will have to see the SST is here. This is the SST of EEIO which is decreasing rapidly with the convection here. Remember OLR is decreasing which means convection is building up.

With that, the SST of WEIO is decreased, okay, below that of EEIO from May to August and then increases, okay. So, SST here decreases from May to August and then as convection starts decreasing which is seen by OLR increasing, we find SST begins to increase. So, as convection builds up, SST of the West decreases to well below SST of the East and then starts building up to when the convection is suppressed here.

But remember that in all this time, the SST of EEIO is higher than SST of WEIO, almost through this entire period. So, from mid-May until end of November, the mean SST of EEIO is higher than that of the WEIO.

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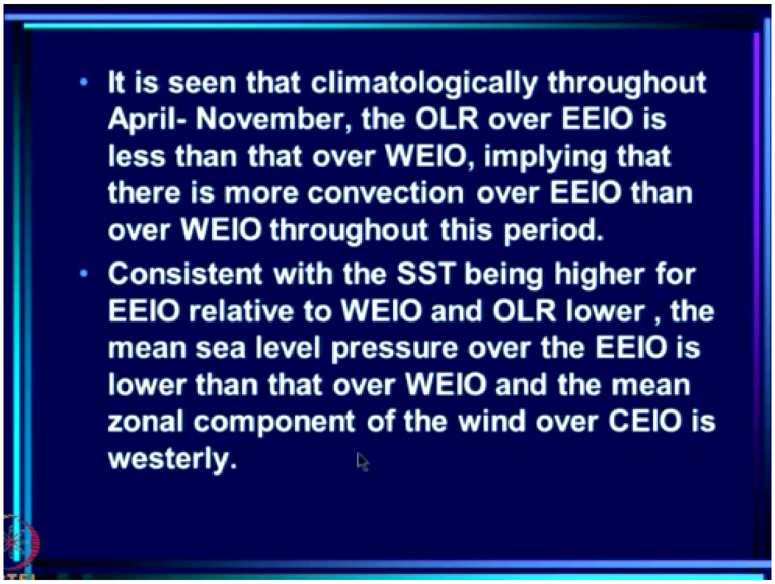

It is seen that climatologically throughout April to November, the OLR over EEIO is < that over WEIO implying there is more convection over EEIO than WEIO. See, this we have seen that throughout, OLR of EEIO is < OLR of WEIO. So, definitely, there is more average convection over EEIO than over WEIO throughout this period. Now, consistent with the SST being higher for EEIO related to WEIO and OLR lower, okay.

So, now what is the situation between East and West. SST of East is higher and OLR is lower which means there is much more mid-tropospheric heating generated by clouds. So, you will have a lower pressure over the East relative to the West. Remember, this is very similar story to what we had over the Pacific, except what happens over Western Pacific happens over Eastern Equatorial Indian Ocean.

We have to West to East when we come to the Indian Ocean. So, consistent with the SST being higher for EEIO relative to WEIO and OLR lower, the mean sea level pressure over EEIO is lower than that over WEIO and the mean zonal component of the wind is towards EEIO, that is to say westerly.

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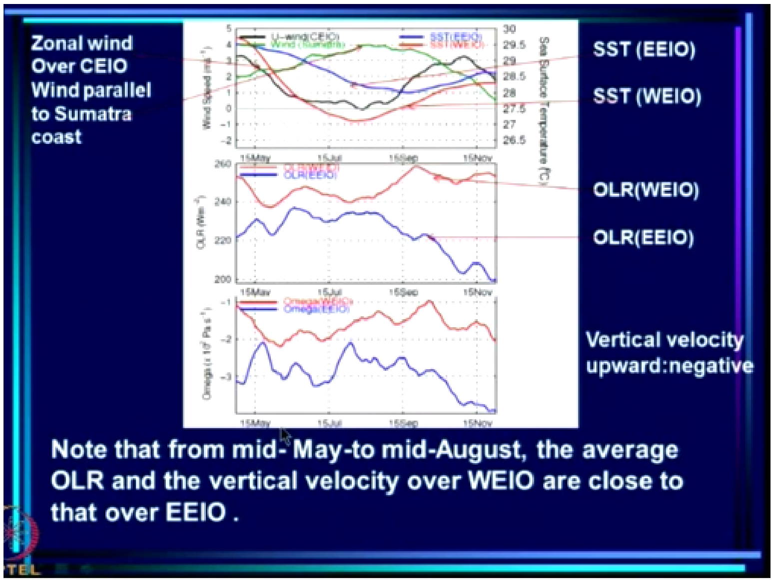

So, this is what is happening that the mean zonal wind is always westerly. This is the mean zonal wind and this is 0. You can say that it decreases quite a bit when the OLR of the 2 regions is closing. It begins by being rather high, decreases and then picks up again. Again, this is the other Wyrtki jet for the other season. So, from mid-May to mid-August, now this is the average OLR and this is the vertical velocity.

So, from mid-May to mid-August, this is the period in which average OLR of both the regions is similar and average vertical velocity is halfway through the troposphere is also rather similar.

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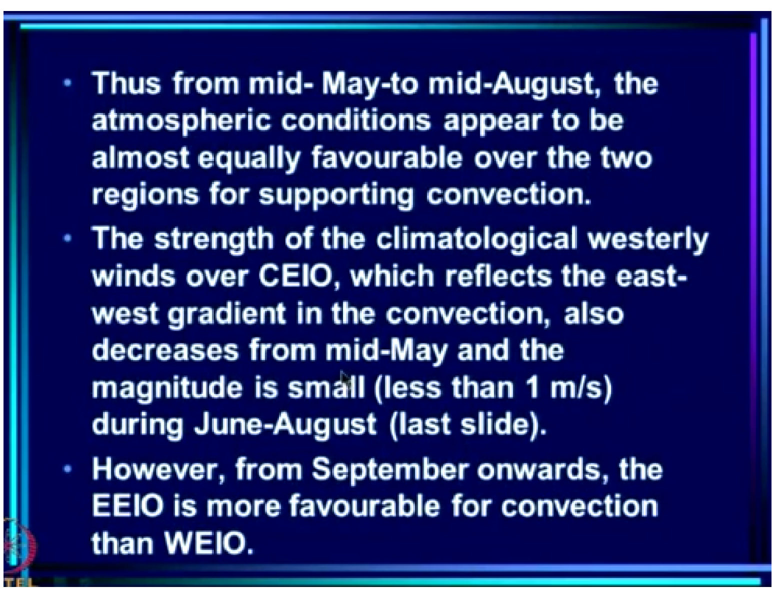

Thus, from mid-May-to mid-August, the atmospheric conditions appear to be almost equally favourable over the 2 regions for supporting convection. The strength of the climatological westerly winds over CEIO which reflects the East-West gradient and convection also decreases in mid-May in this time and only from September onwards these become favourable.

Now, we will have 2 stop here the discussion. We have some idea now as to how the convection and the SST EEIO and WEIO evolve. Now, we will have to see in the next class, what happens to these mean patterns and how does an IOD event get triggered and evolve, that we will look at in the next class.