The Monsoon and Its Variability
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Lecture – 33
Indian Ocean Dipole – Part 2

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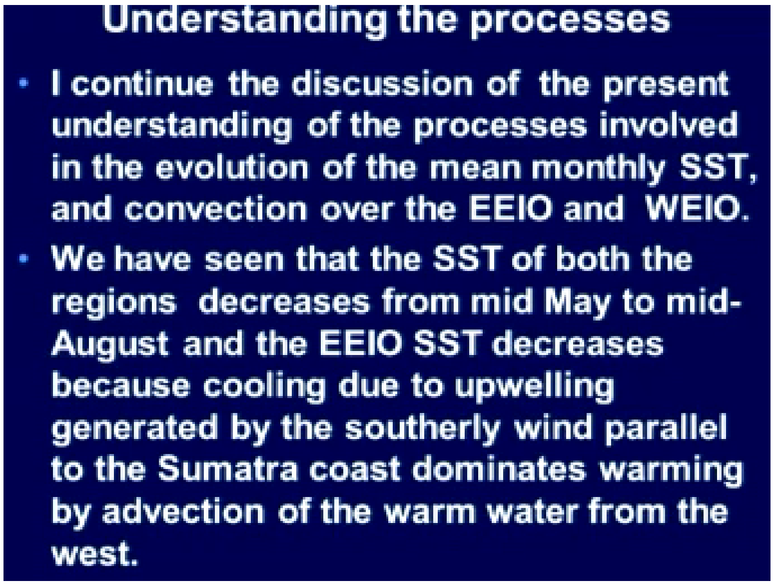

So, today I will continue our discussion on the Indian Ocean dipole, which we began in the last class. We were discussing processes that lead to the mean patterns of variations and then we will go to what leads to the formation of the IOD events. So, I continued the discussion of the present understanding of the processes involved in the evolution of the mean monthly SST and convection over the EEIO and WEIO.

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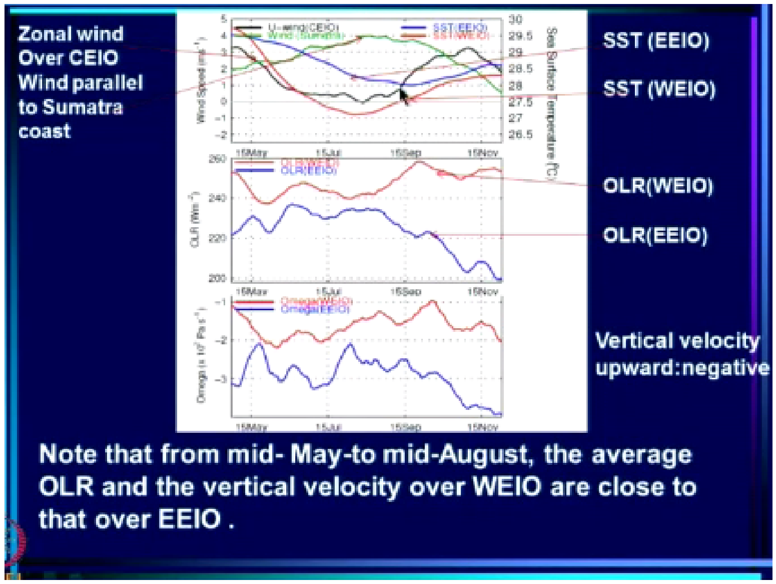

Now, we have seen that the SST of both the regions decreases from mid-May to mid-August and that again; I show you here again that the SST of both the regions, this blue is EEIO and red is WEIO. Both of the regions starts; the SST starts decreasing from mid-May right up to this point here mid-August or so and then both start increasing after mid-September.

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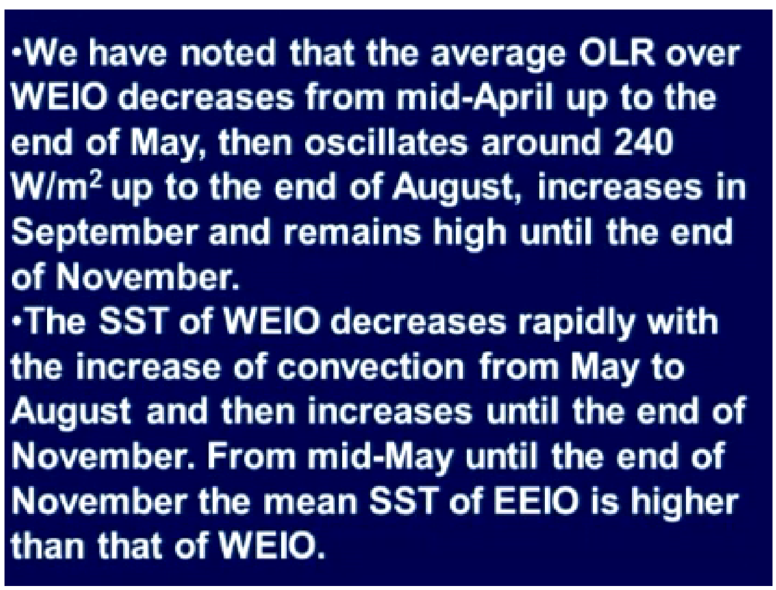

So, we have seen that SST of both the regions decreases that from mid-May to mid-August and the EEIO decreases because cooling due to upwelling generated by southerly winds parallel to the Sumatra coast dominates the warming by advection of the warm water from the West. We have seen this last time. We have noted that the average OLR over WEIO decreases from mid-

April up to end of May and then oscillates around 240 watts per metre square up to the end of August, okay.

So, now we are looking at what is happening to OLR over WEIO and that is in red here, so it initially decreasing here which means convection is building up and then up to mid-August, it simply oscillates around 240 watts per metre square, then it increases in September and remains high until the end of the season. That means convection starts disappearing from here and then it just remains; suppressed in this part of the year.

From about mid-September onwards, the convection over WEIO is suppressed and OLR of WEIO is high. Now, the SST of WEIO, we have said before that the WEIO SST response primarily to fluxes from the atmosphere and SST of WEIO decreases rapidly with the increase of convection, so here we have; when the convection increases, SST of WEIO which is here, decreases very rapidly here up to about mid-June till; when the convection build up.

So, the SST decreases rapidly because of the radiation cut off by the clouds and then increases until the end of November once the clouds go away, so from mid-May until end of November, the mean SST of EEIO is higher than that of WEIO, so we have from about throughout from mid-May up to end of November, the SST of EEIO is higher than that of WEIO. Because WEIO decreases very much more rapidly in the first part of this season with the build-up of the convection here, okay.

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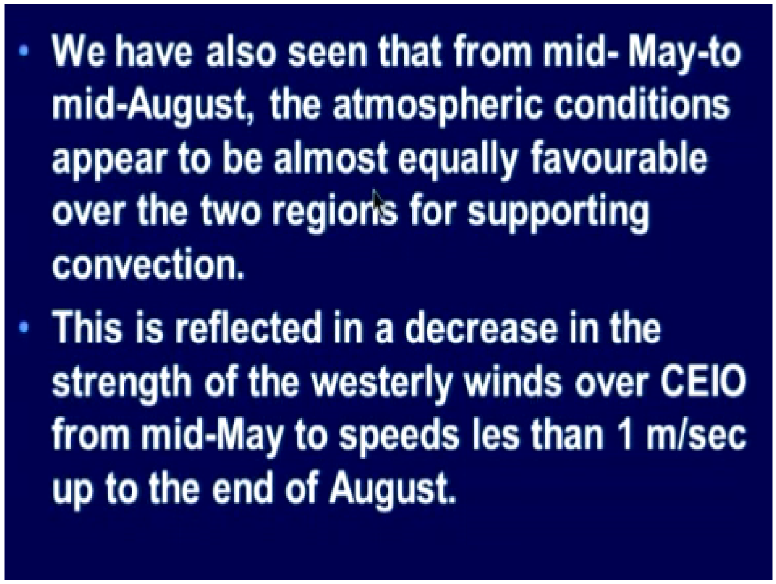

So, now what is the situation then? We also seen that from mid-May to mid-August the atmospheric conditions appear to be almost equally favourable over the 2 regions for supporting convection, so what does that imply? This implies a decrease in the strength of the westerly winds over CEIO from mid-May to; onwards. So, now you have the westerly wind is denoted by black here and you can see decreases rapidly.

As the convection probabilities in the 2 regions become similar, you have less of a gradient and therefore less of a westerly wind and then from here to here, which is to say from mid-June to about September, it remains very low, lower than 1 meter per second, see this is the reflection of the fact that the convection over the 2 regions is very close, so we have low westerly winds in that period, okay.

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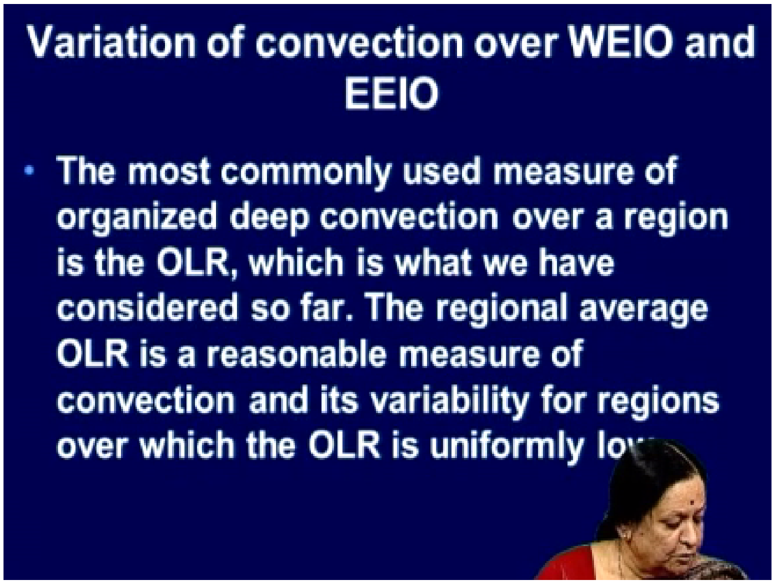

Now, let us consider the variation of convection over WEIO and EEIO, see the most commonly used measure of organised deep convection over the region is the outgoing long wave radiation OLR which is what we have considered so far. Now, the regional average of OLR is a reasonable measure of convection and its variability for regions over which it is uniformly low. So, if you have a region filled with a grid points with low OLR, then there is convection over all of them.

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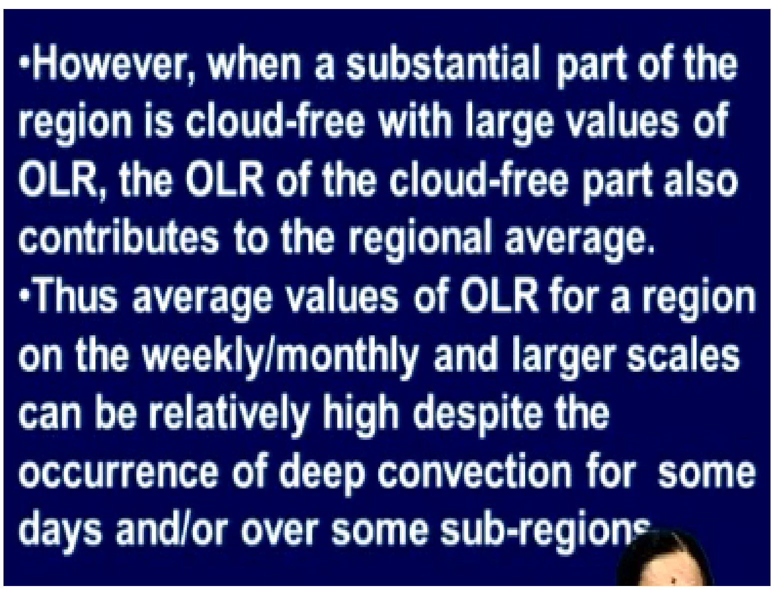

And then the average OLR makes sense, average OLR is representative of convection in the region. However, when a substantial part of the region is cloud-free with large values of OLR, the OLR of the cloud-free part also contributes to the regional average, so the average values of

OLR for a region with; on the weekly or monthly and larger scales can be relatively high, despite the occurrence of deep convection for some days and or over some regions.

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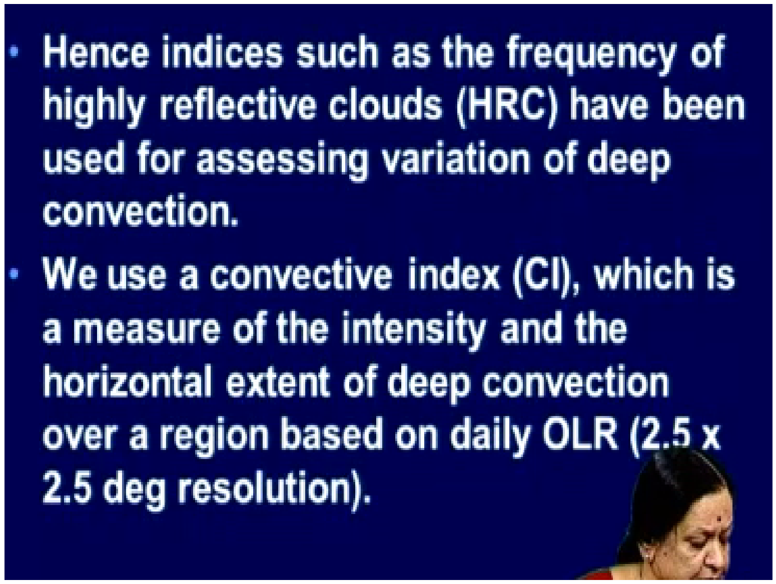

So, on a single day, part of the region may be clouded will have less OLR but it will not get reflected in the average OLR, if the other part overwhelms this region, the cloud-free part. So, but what we are interested in is really not the variation of OLR but the variation of convection, so it is important to focus on, where the convection is and how large is the extent of the region with convection.

This is why indices such as the frequency of highly reflective clouds, you know so far, we have been talking of long wave radiation and another thing, the satellite measures is the Albedo and you know deep clouds are highly reflective clouds and this is measured in the visible, in the albedo. So, there has been work done in actually consolidating data on frequency of highly reflective clouds and Atlas has been generated.

And this has been used as a measure of convection. Now, is we have using frequency of highly reflective clouds, what we can do is, we can use a convective index CI, which is a measure of the intensity and horizontal extent of deep convection over a region based on daily OLR 2.5 degree/ 2.5 degree resolution, that is to say we do not go to a smaller units of space than 2.5/2.5, we asked the question is that mean OLR of every grid point 2 .5 / 2.5, is it low enough to have convection there.

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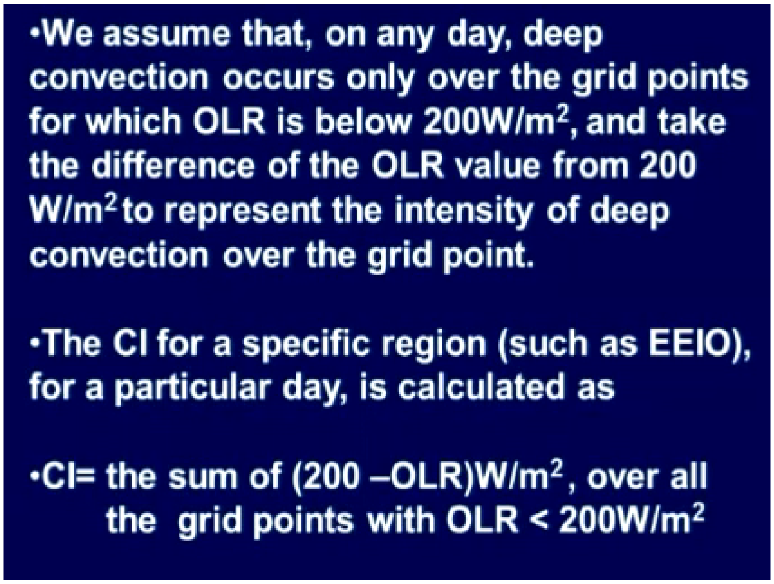

And from, such grid wise analysis generator convective index, so that we do? We assume that on any day, deep convection occurs only over the grid points for which OLR is below 200 watts per metre square and take the difference of the OLR value from 200 watts per metre square to represent the intensity of deep convection, that is to say, how much lower is the OLR, then 200 watts per metre square.

So, if it is 180, the difference will be 20, if it is 16, the difference will be 40 and so on. So, that gives the measure of the intensity of cloudy. Now, the CI for a specific region such as EEIO, which compresses typically several grid points, for a particular day is calculated as following. See what we see is, over how many grids on that day was the OLR< 200, we take only those grids.

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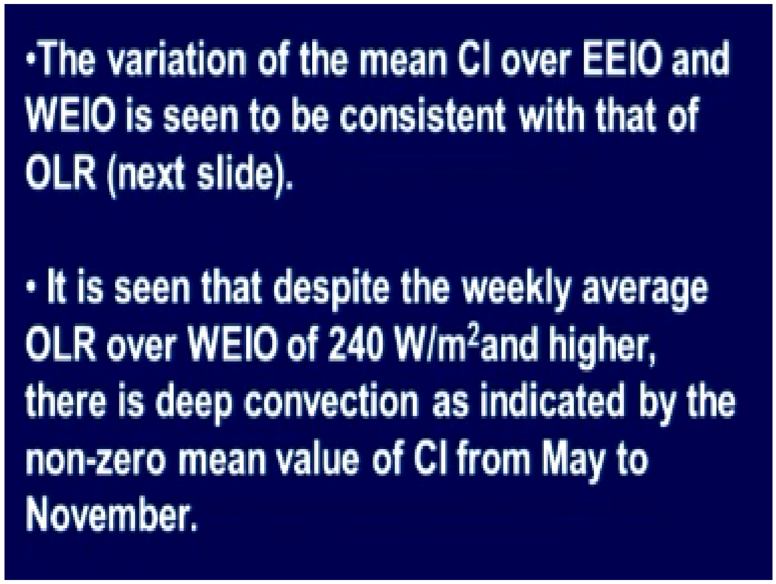

For those grids, compute the intensity as 200 - OLR and some over all those grids that is to say CI is the sum of 200 - OLR over all the grid points for which OLR is < 200, all the grid points which support deep convection. Now, the variation of the mean CI over EEIO and WEIO is actually not surprisingly consistent with variation of OLR.

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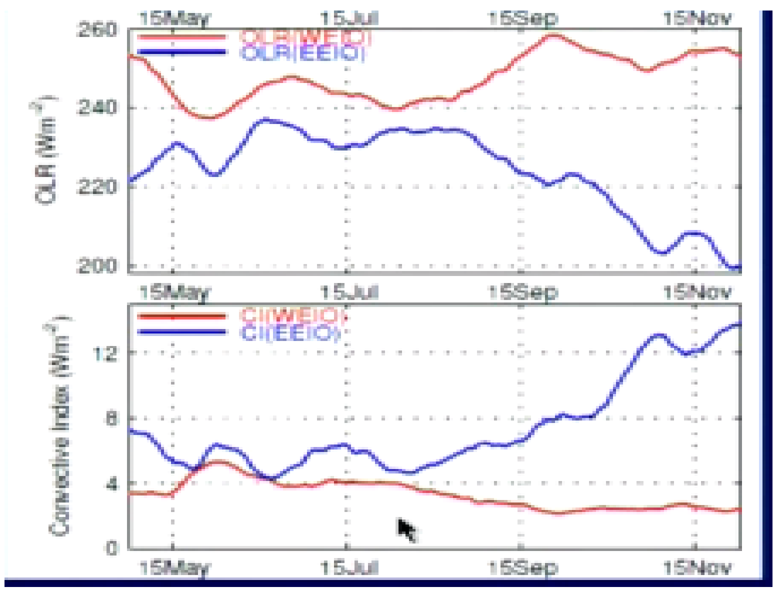

So, we have here, OLR variation, which we had before and we have the variation of CI. Now, we had seen that OLR of EEIO is lower than that of WEIO, and indeed CI of WEIO is lower than that of EEIO, the thing is consistent, even the variation is generally consistent; variation of CI generally consistent with this. However, when we talk of 240, being a reasonable limit, so that if OLR is below 240, we can say that the region is convecting.

We have here regions or days on which WEIO is about 240 but even then you see it has non 0 values of CI. This is a exactly reflective what I said before that there is a considerable cloud-free region which is leading to high values of OLR but actually it is not indicating; it is not an absence of convection which is what we would think of, if we looked at only the mean OLR, in fact, there is convection of the order of 4; convective index of about 4 in this case.

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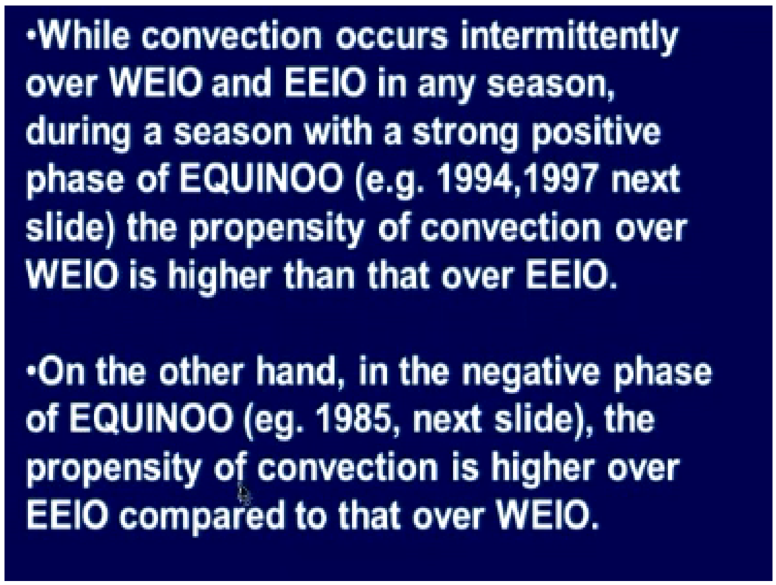

So, in fact the conductive index is never 0 which is saying that there is always some convection going on in the mean over some part of WEIO and some part of EEIO. So, while the convection occurs intermittently over WEIO and EEIO in any season, during a season with a strong positive phase of EQUINOO such as 94, 97 and so on. The propensity of convection over WEIO is higher than that over EEIO, because there is a strong IOD event there.

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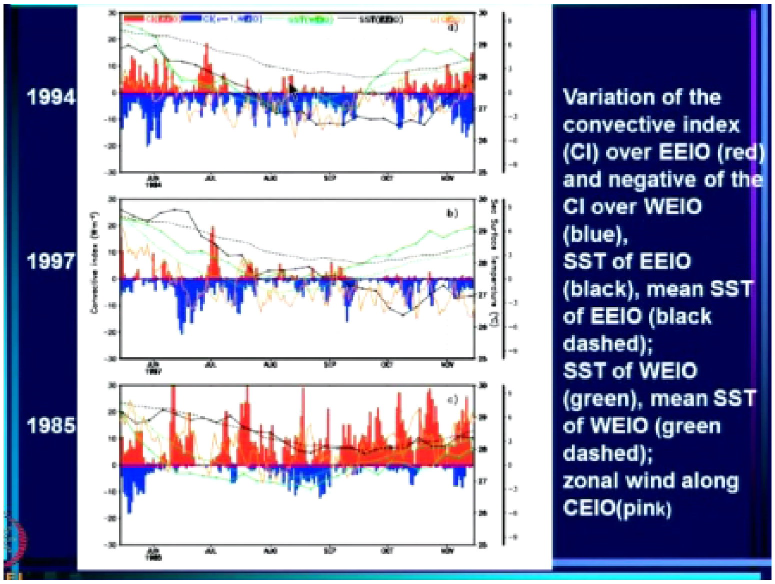

On the other hand, in the negative side of EQUINOO, which again we will see. The propensity of convection is highly for EEIO. So, what you see here is a somewhat complicated figure but I will explain to you what it is. These towers represent convection over WEIO and this is the convection over EEIO. The convection over WEIO, the convection over EEIO is red convection over WEIO; we multiply that by -1, the CI value.

So, that we can see it because otherwise, there would be too much overlap of the towers, so this is the convection over WEIO and imagine that this means lot of convection and this means less convection. So, we have simply inverted to access, so to speak for convection over WEIO, so this is CI for EEIO, the red towers and blue towers are for WEIO. Now, what you see here is the SST of EEIO, SST of WEIO and various other parameters.

There is also; this is the SST of EEIO and WEIO and you can see that in this case, these are the dipole event, so SST of the West actually is larger than SST of the East over a large part of the region; this is a reflection of it being a dipole. So, what do we see for 94 and 97, that initially there is convection over EEIO but then it is largely suppressed here, you see the red towers are very few here and same thing here.

It is the blue towers dominate the red when you have positive IUD events and exactly the opposite occurs in the negative EQUINOO phase, where you have a EEIO convection dominating the WEIO convection but note that it is and as if convection is totally 0, rather the propensity of convection is less over WEIO in negative phase and less over EEIO in the positive phase of EQUINOO, this is to be borne in mind.

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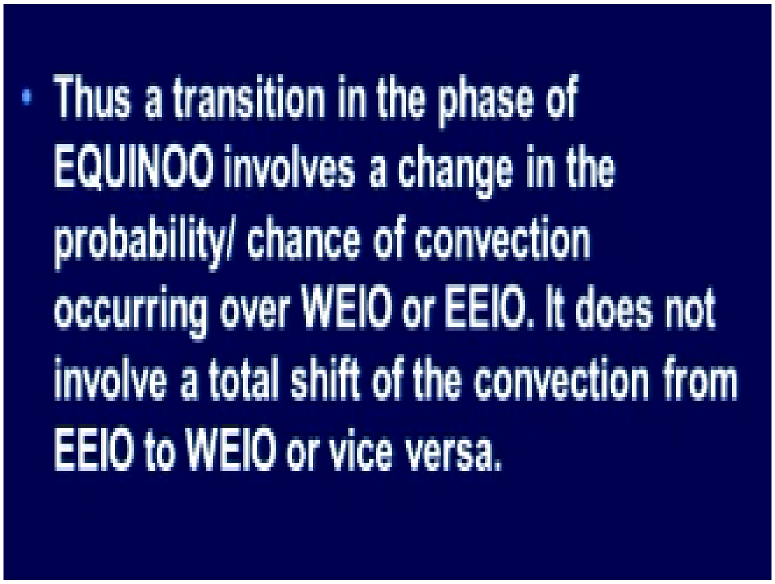

So, a transition in the phase of EQUINOO involves a change in the probability or chance of convection occurring over WEIO or EEIO. It does not involve a total shift of the convection from EEIO to WEIO or vice versa. This is something very important to remember that it is and as an entirely new regime has come into a place when we have an IOD event rather the probabilities are shifted from what they were.

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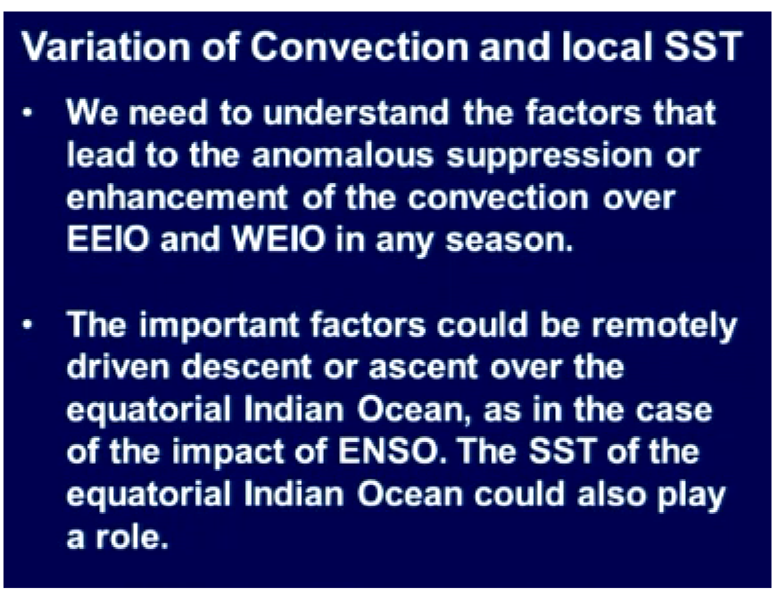

So, now it is important to understand what other factors that leads to variation of convection. So, let us consider one of the factors suggested how does the convection vary with local SST, in particular we need to understand the relationship between the EEIO convection and SST because we need to understand the factors that lead to the anomalous suppression or enhancement of the convection over EEIO and WEIO in any season.

Now, important factors could be remotely driven descent and ascent over the equatorial Indian Ocean. For example, we know that phenomena like El Nino do drive descent or ascent over the Indian Ocean and so, the suppression or enhancement could be a manifestation of remote factors operating on the region. However, the SST of the equatorial Indian Ocean could also play a role.

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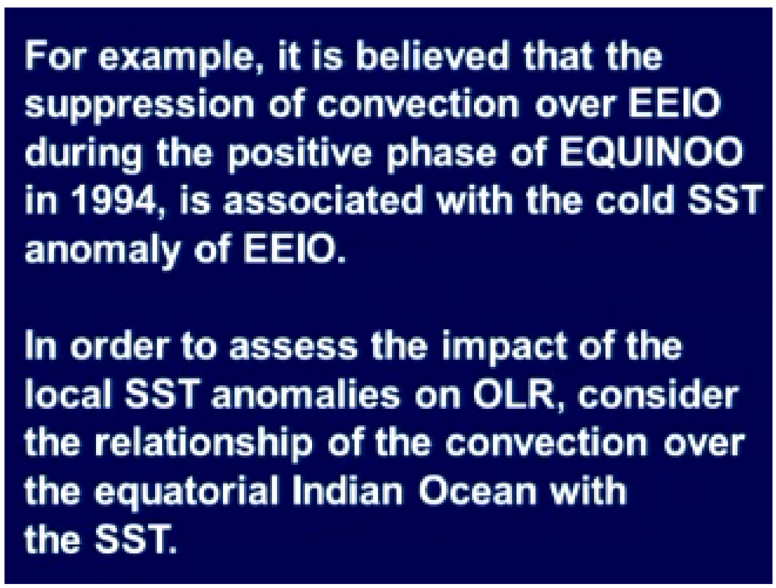

For example, it is believed that the separation of convection over EEIO during the positive phase of the EQUINOO of in 1994 is associated with the cold SST anomaly of EEIO. Because even in the original paper of Saji et al and in all the succeeding literature, it is very clearly stated that the suppression of convection over EEIO and the cold SST anomalies go hand in hand for positive IOD events.

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•The variation of the monthly OLR anomaly over EEIO with the SST of EEIO for all the months in the period 1982-2009, is depicted in the next slide.

•It is seen that for SSTs above the threshold, there is a large spread with OLR anomalies ranging from 30 W/m^2 to -30 W/m^2, suggesting that variation of convection is not linked with the variation of the SST when it is above the threshold.

So, let us now look at the relationship between OLR over EEIO and the average SST of EEIO. The variation of the monthly OLR over EEIO with the SST of EEIO, for all the months in the period 82 to 2009.

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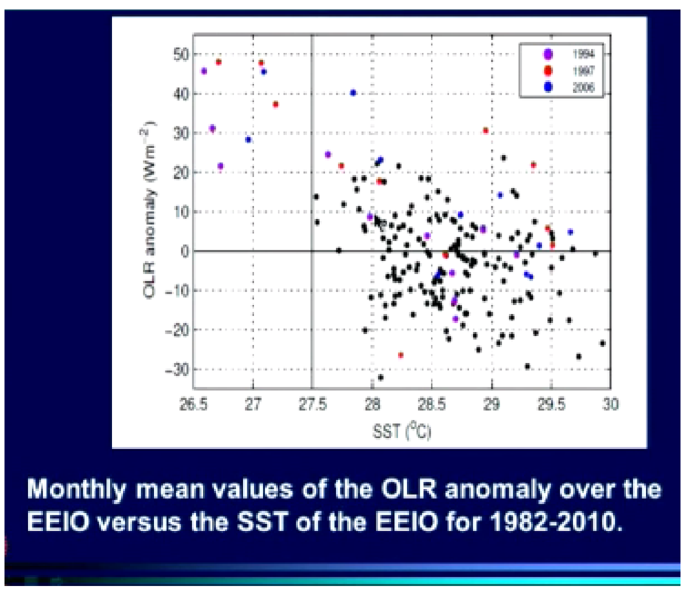

Monthly mean values of the OLR anomaly over the EEIO versus the SST of the EEIO for 1982-2010.

We see here, so what is this? Each of these points represents one month and for example, for this point this is a specific month in that period and for this period, the average EEIO, SST is about 27.5 and the average OLR anomaly is about 15 watts per metre square. So, this is how all the data, for all the months between 82 and 2010 are plotted because each month is characterised by a pair of values; one for the SST and the other for the OLR anomaly.

Now, when we plot, what do we see? 27.5 is a threshold here for convection and what we see is once the SST is above the threshold, it is a big mess, you now you could either have a suppressed convection or you could have enhanced convection, there is large range of variation particularly above 28 degree but once it is below 27.5, you see all the points positive OLR anomaly, that means once it is below the threshold of 27.5 convection is suppressed.

Now, to what extent varies, it could be suppressed with an OLR anomaly of about 20 watts per metre square or it could be very much more suppressed with OLR anomalies between 40 and 50 watts per metre square. So, the extent does vary here but there is no month in which the OLR anomaly is even within 20 are negative. So, this is a very clear (()) (17:07) if you wish or a threshold of 27.5 which seems to be operating in determining, what is the kind of convection that is possible for a given SSD range of EEIO.

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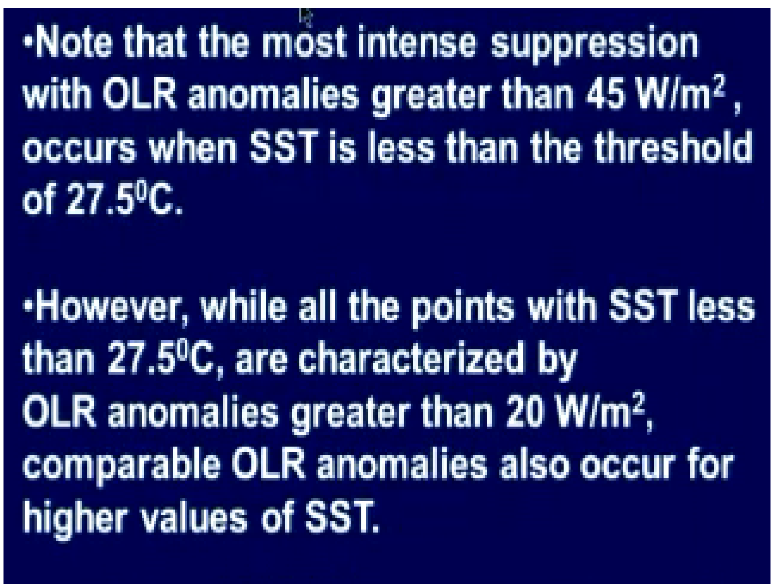

So, we have noted that the most intense suppression with OLR anomaly is > 45 watts per metre square occurs when SSD here, this is the most intense suppression, this occurs when SST is < 27.5. However, while all the points with SST < 27.5 are characterised by OLR anomaly is > 20 watts per metre square which we saw comparable anomalies also occur for other SST.

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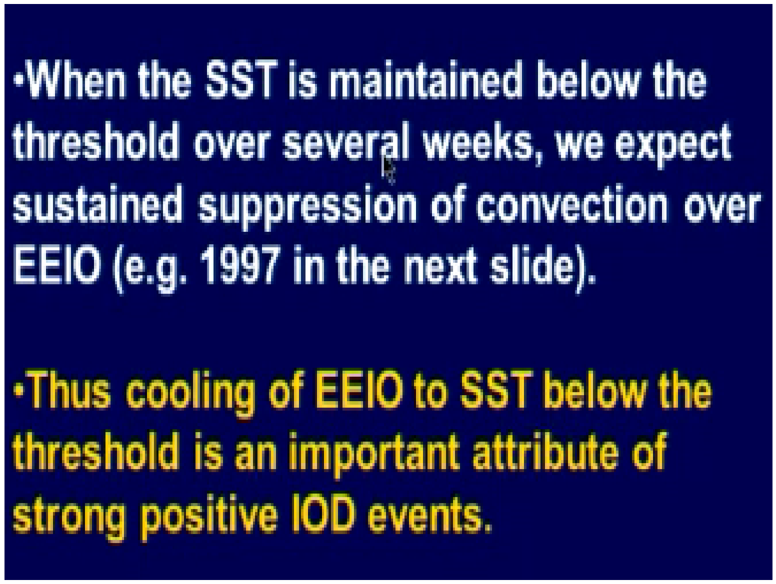

So, you have here; you know points like this and comparable anomalies here occur also for much warmer SSTs here, you see that, so it is difficult to give in a OLR anomaly to say what the SST range would be unless, of course the OLR anomaly is so large as +45 or so, watts per meter square. In that case, we can say the SST is definitely below 27.5. So, now all the coloured dots here represent IOD events.

Purple is 94, all the IOD events in that period, red is 97 and blue is 2006, so you can see that certainly for some months, in each of the IOD years, SST goes below the threshold and that is where you have sustained suppression of convection over EEIO but you can also see that in the other months, before IOD has attained a mature stage, in fact the SST is higher than the threshold for these IODs, but with cooling, it goes below the threshold.

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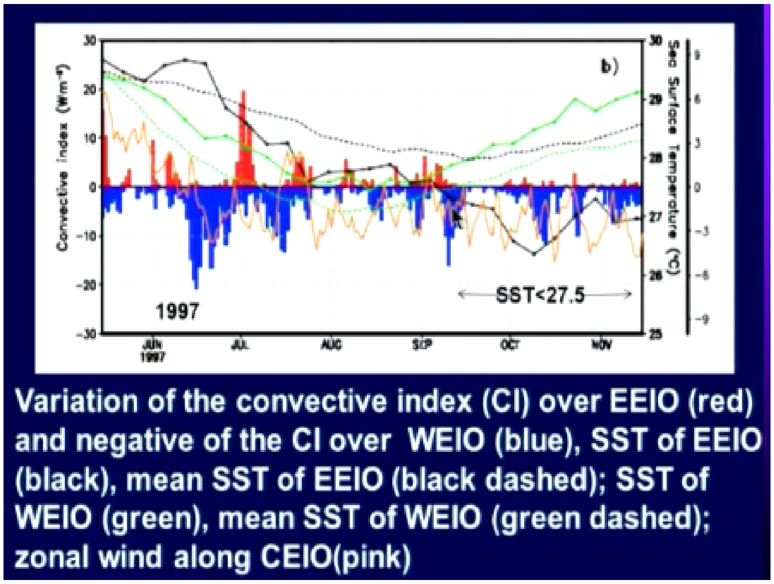

So, when the SST is below the threshold for several weeks what happens? We expect sustained suppression of convection over the EEIO and you see that here, this is the case of 97 okay, again this black line corresponds to SST of EEIO, red towers are the EEIO convection, blue towers are the WEIO convection and what you see here is actually that the SST of EEIO decreases rather rapidly here and then crosses the threshold around here.

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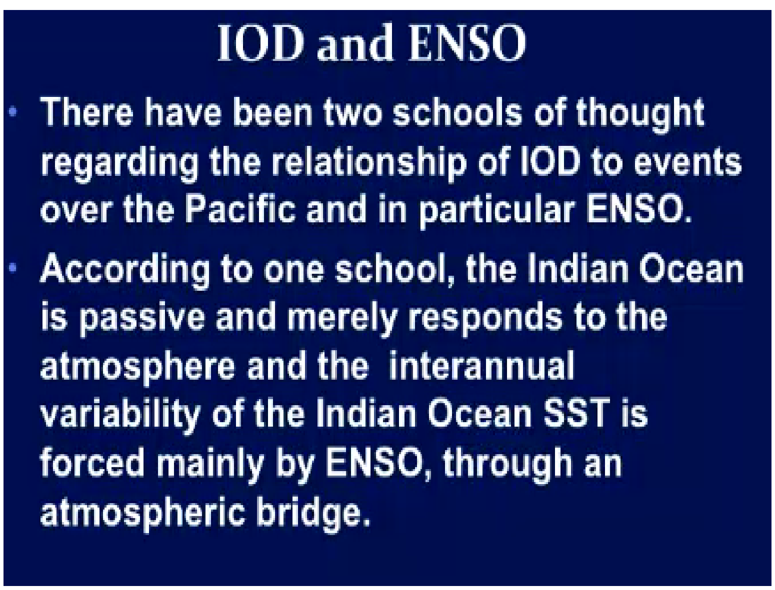

And once it crosses the threshold, then there is hardly any days with a convective activity over EEIO. So, you can see the kind of suppression; sustained suppression that occurs when SST is below the threshold. So, cooling of EEIO to SST below the threshold appears to be a very important attribute of strong positive IOD events. Now, you know ever since the papers of Saji et al and Webster et al in 1999 which first talked about the Indian Ocean dipole more, there have been lots of studies of the relationship of IOD and ENSO.

Now, there is one school of thought, which feels that the Indian Ocean is passive and nearly response to the atmosphere and inter annual variability of the Indian Ocean SST are forced mainly by ENSO through an atmospheric bridge, so what they believe is that there are lots of activities over the Pacific namely ENSO. This ENSO through the atmospheric bridge has an impact on the atmosphere over the Indian region and equatorial Indian Ocean.

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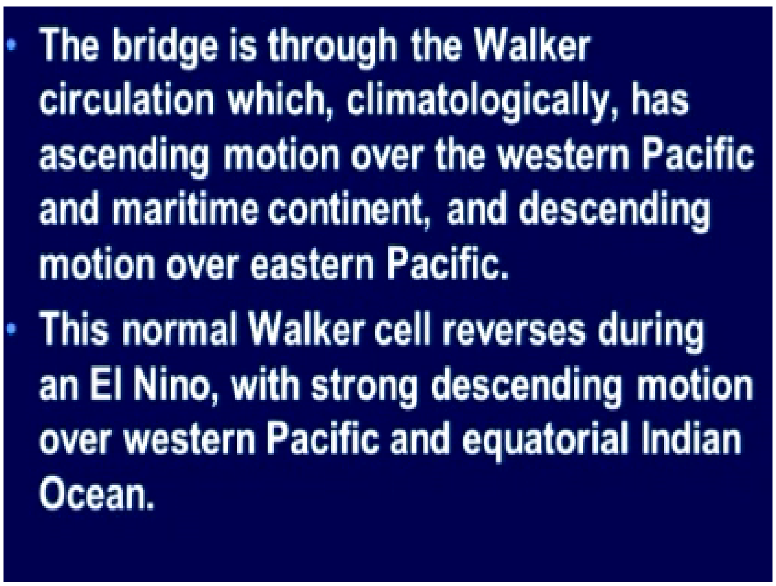

And through that influences the Indian Ocean SST, so it believes that most of the events of the Indian Ocean are actually remotely forced Indian Ocean is passively responding to that and the bridge is through Walker circulation which as we know, climatologically we have as ascending motion over West Pacific and descending motion over East Pacific which is the Walker circulation.

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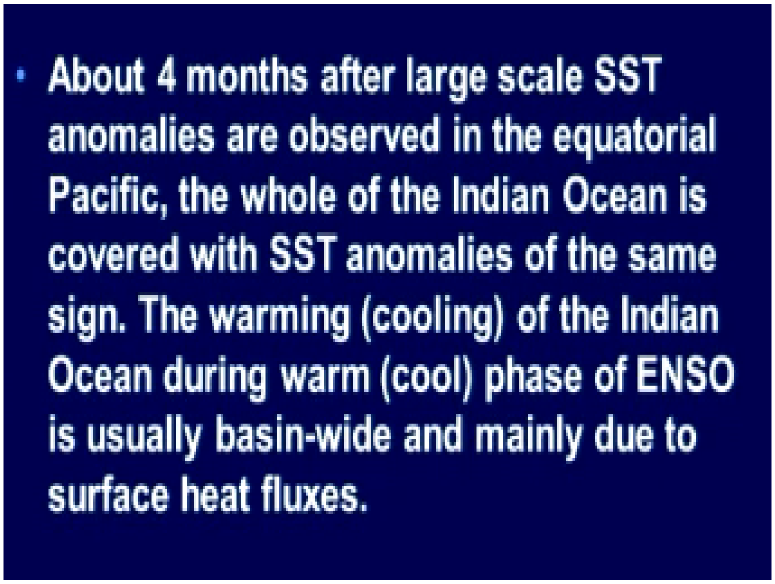

But this circulation changes during EL Nino and what we get is descending motion over West specific as well as eastern part of equatorial Indian Ocean. Now, about 4 months after large scale SST anomalies are observed in the equatorial Pacific, the whole of the Indian Ocean is covered with SST anomalies of the same sign. This we have seen, in fact that when we looked at SST anomalies even of WEIO and EEIO, we could see in the ++ or -- quadrants, that is to say in the quadrant in which both the anomalies were positive, that quadrant was dominated by El Ninos here.

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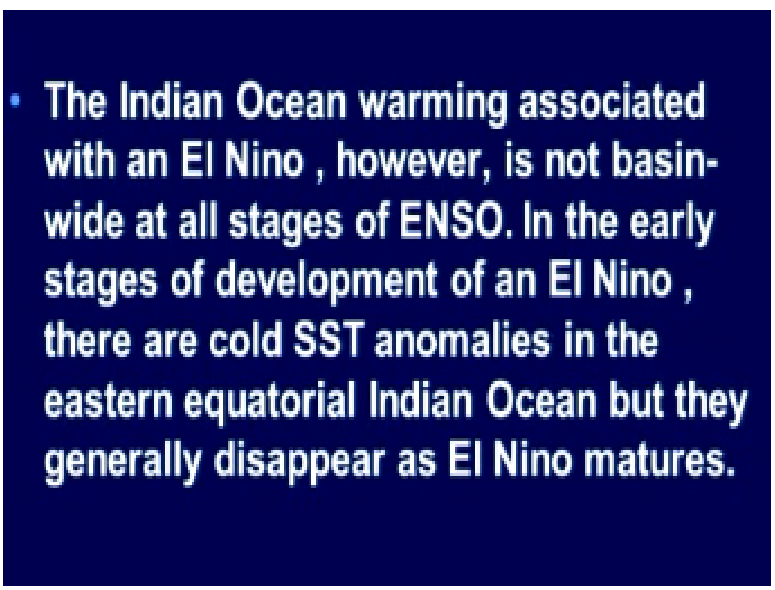

Because there is general warming of the Indian Ocean during El Nino and cooling during La Nina. Now, however, if that is the case then, why do they think that IOD is forced by El Nino because the Indian Ocean warming associated with an El Nino is not basin at all stages of ENSO. In the early stages of development of El Nino, there are cold SST anomalies in the eastern equatorial Indian Ocean.

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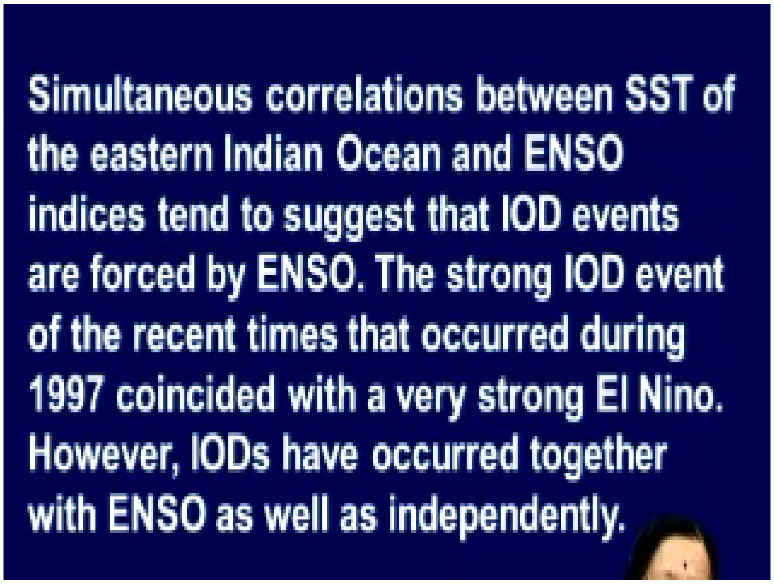

But they generally disappear as an El Nino matures, so as the El Nino is evolving, the one important feature is suppression of convection over eastern equatorial Indian Ocean this is what they talk of the Walker circulation being anomalous and also cold SST anomalies of EEIO. Now people; after the IOD papers came out, people look at simultaneous correlations between SST of the eastern equatorial Indian Ocean and ENSO indices.

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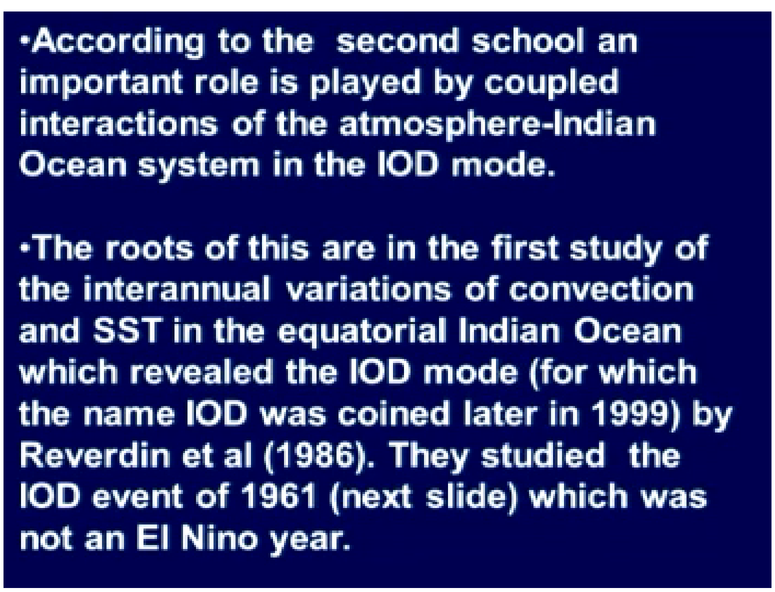

And these correlations tend to suggest that IOD events are forced by ENSO, that there is a correlation between the 2 and in fact, the strong IOD event of the recent types that occurred during 1997, coincided with a very strong El Nino, however it is important to note that IOD events have occurred together with ENSO as well as independently and in fact, according to the second school, an important role is played by the coupled interactions of the atmosphere Indian Ocean system in the IOD mode.

So, the fact that the Pacific will could and does have an influence on the Indian Ocean is not denied but the differences of the 2 schools are in what, how much importance to give to the role of the coupled Indian Ocean atmosphere system and the second school believes that that plays a very important role, so its Indian Ocean in not merely passive and but it is an active player in this; in the generation of an IOD mode, this is what the second school believes.

And in fact, the roots of the second school are in the very first study of the inter annual variations of convection and SST in the equatorial Indian Ocean which revealed the IOD mode however, it was then not called an IOD mode by the author, this was then by Reverdin et al from France and they are the once who actually reveal the structure of the IOD mode and this they did by studying on the basis of ship reports available, the IOD event of 1961.

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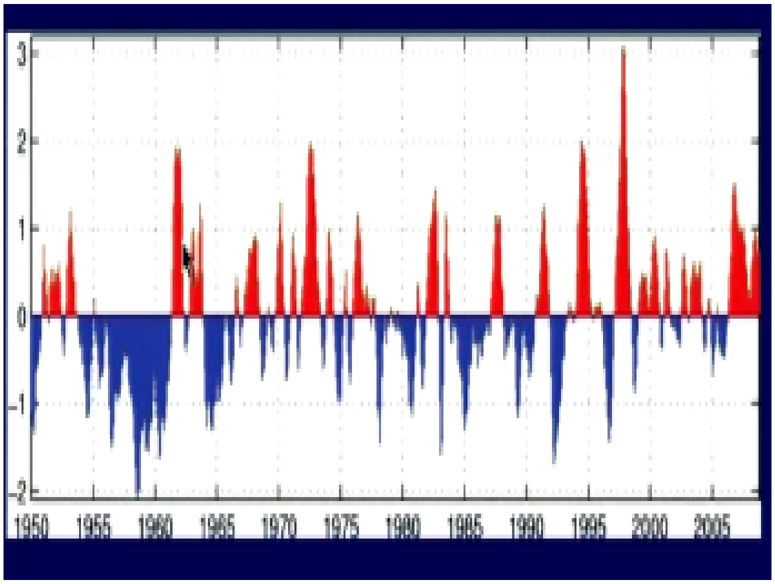

This is the picture of DMI now that you have seen before, DMI positive means positive IOD events and you can see here this is a major IOD event of 61, after which one occurred here and another occurred in 82 and then bigger occurred in 94 but the one in 61 is comparable to that of 94 and then 97 which was a very large IOD event.

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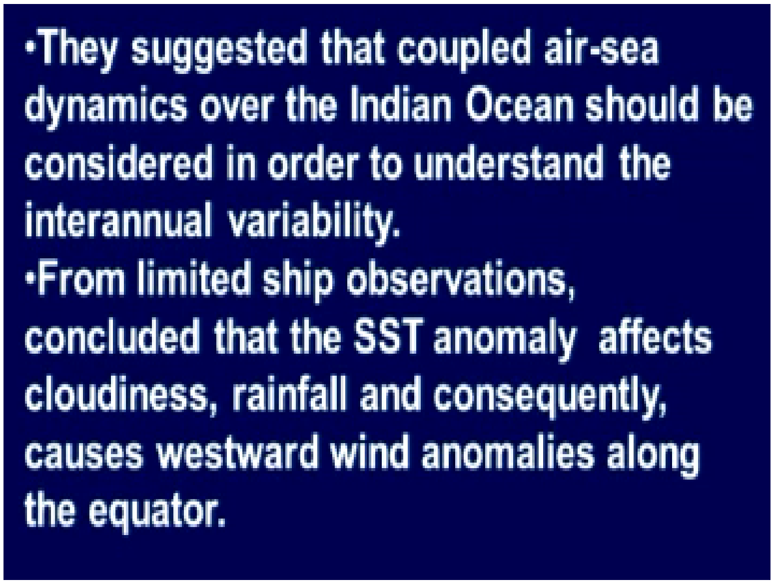

So, this IOD even of 61 is what revelled in another study and they suggested that coupled air sea dynamics over the Indian Ocean should be considered in order to understand the inter annual variability and from limited ship observations, they concluded that the SST anomaly affects cloudiness rainfall and consequently causes westward wind anomalies along the equator. See, this is a key element of positive EQUINOO and positive phase of the dipole in was the SST anomalies.

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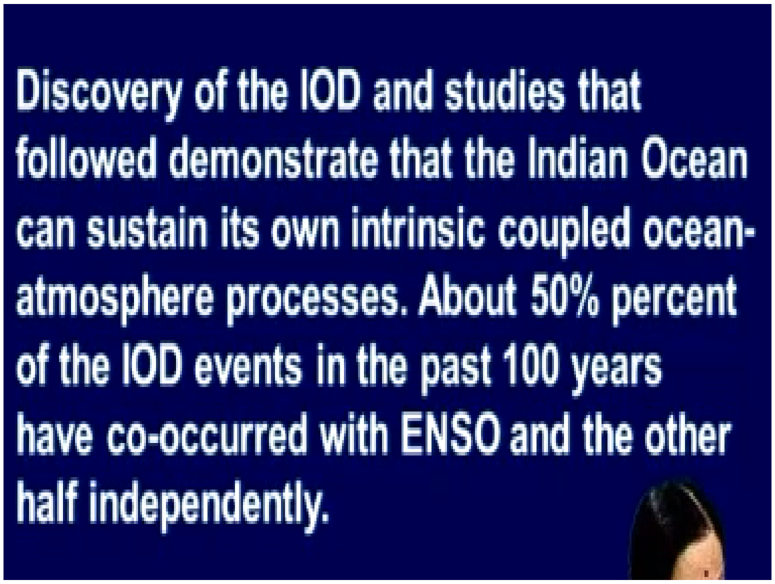

So, they actually talked about the coupled Indian Ocean atmosphere processes being important to the IOD event of 61. Now, subsequently there has been a lot of debate on this and so, the discovery of the IOD and studies that followed demonstrate that the Indian Ocean can sustain its own intrinsic coupled Ocean atmosphere processes. So, now it appears that we can say that it is true that the Indian Ocean is influenced by the Pacific but it can also sustain its own coupled ocean atmosphere processes.

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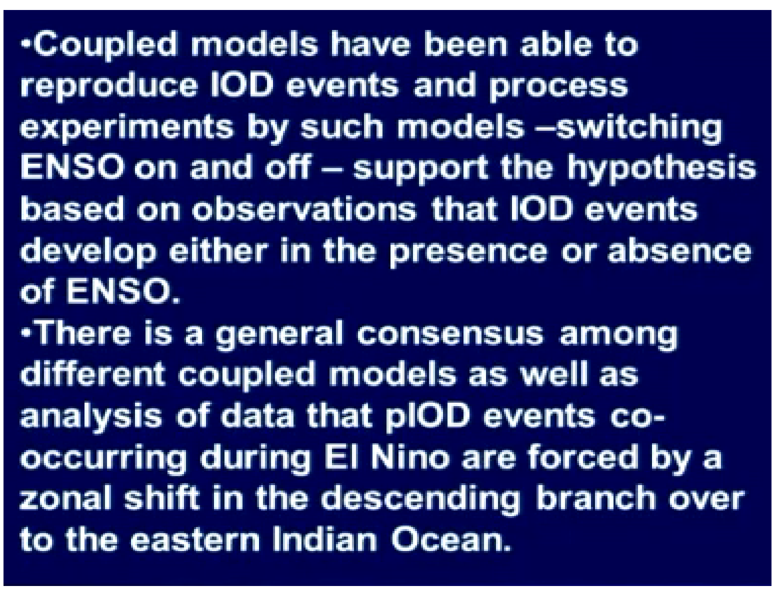

And about 50% of the IOD events in the past 100 years have occurred with and ENSO and the other half independently, so it is an, as if all the events are associated with ENSO. Actually, coupled models have been able to reproduce IOD events and process experiments by such models like switching and so on and off, support the hypothesis based on observations that IOD events developed either in the presence or absence of ENSO.

So, it is not necessary to have an El Niño developing in the Pacific for a positive IOD event to develop over the Indian Ocean. Now, there is general consensus among different coupled models as well as analysis of data that the pIOD events, that is to say positive IOD events, co-occurring during El Nino are forced by a zonal shift in the descending branch over the eastern Indian Ocean.

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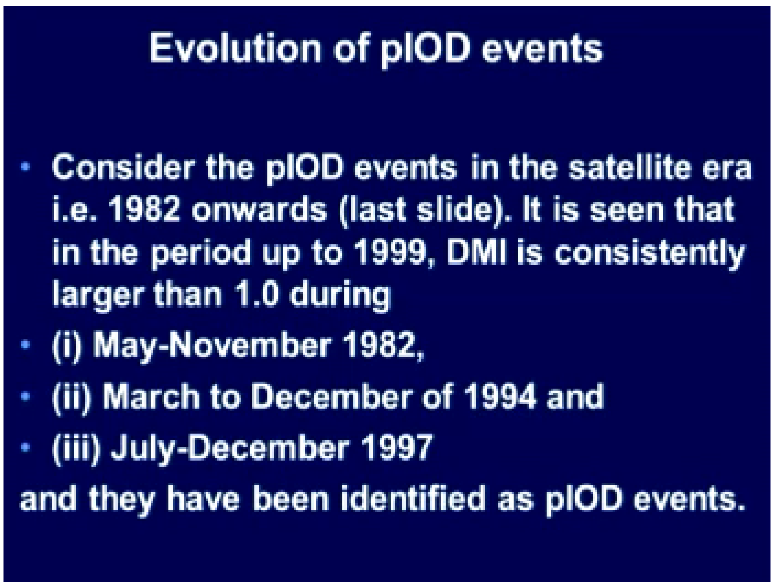

This is what I mentioned earlier, that the major at distinguishing attribute of El Nino is that the ascending limb of the Hadley cell shifts towards the Central Pacific and the anomalous vertical velocity over West Pacific is actually descending and it descends not only over West pacific but up to the eastern equatorial Indian Ocean okay. So, this is now the; after a lot of debate, it appears that if one looks objectively at what; the data available in the modelling done so far.

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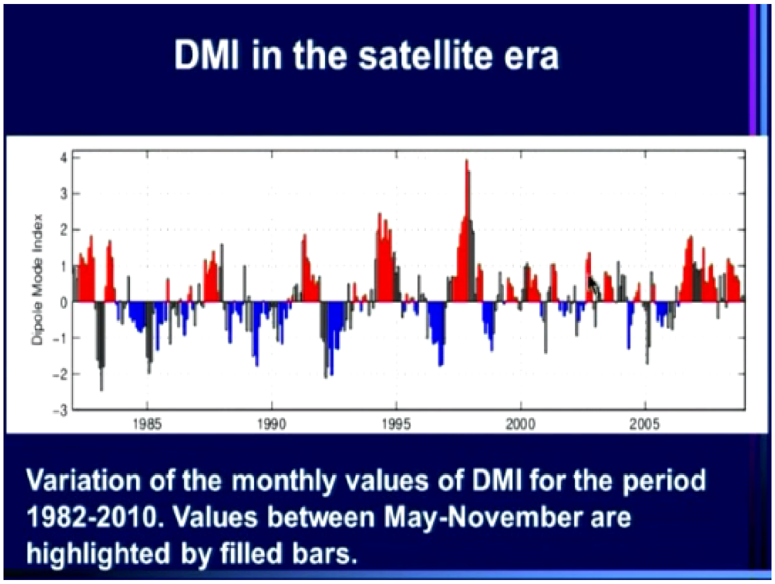

Then, one has to concede that the El Nino does have an impact, La Nina does have an impact, all this is very well known since the 80s but Indian Ocean by itself also can generate IOD events are important variability of the coupled ocean atmosphere system, this is the consensus now. Now, let us look at evolution of pIOD event. So, consider the pIOD events in the satellite era okay.

And which is here and what we see here again are the major events in the satellite era are 82 and then we had some here, 87, 92, 94, 97 and another in 2006, another interesting case is actually 2003, where we thought an IOD event is going to develop but it got aborted. So, we have the major IOD events are May to November 82, March to December 94 and July to December 97, so May to November 82, then 94 and 97.

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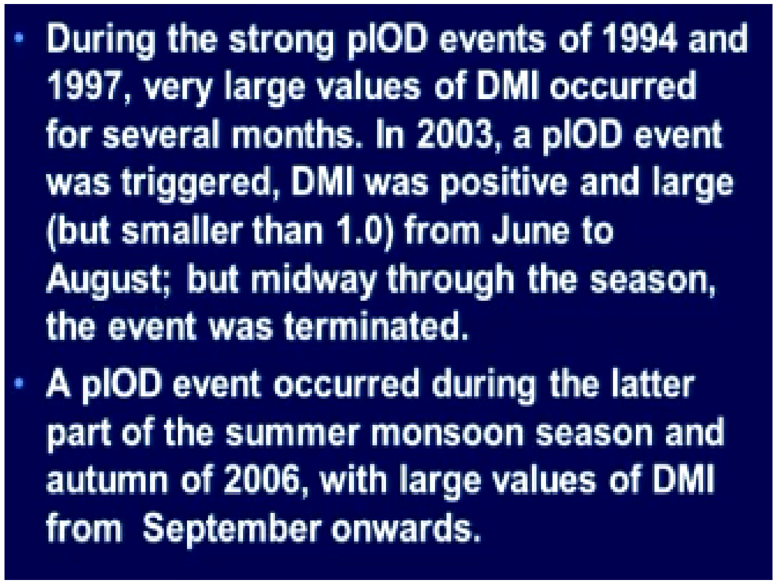

These are the major IOD events, where DMI is consistently larger than one for several months; these are the major IOD events. Now, during the strong pIOD events of 94 and 97, very large values of DMI occur for several months. In 2003, and I mention this before, a pIOD was triggered okay, DMI was positive and large from June to August but midway through the season, the event was terminated, that is the case of 2003.

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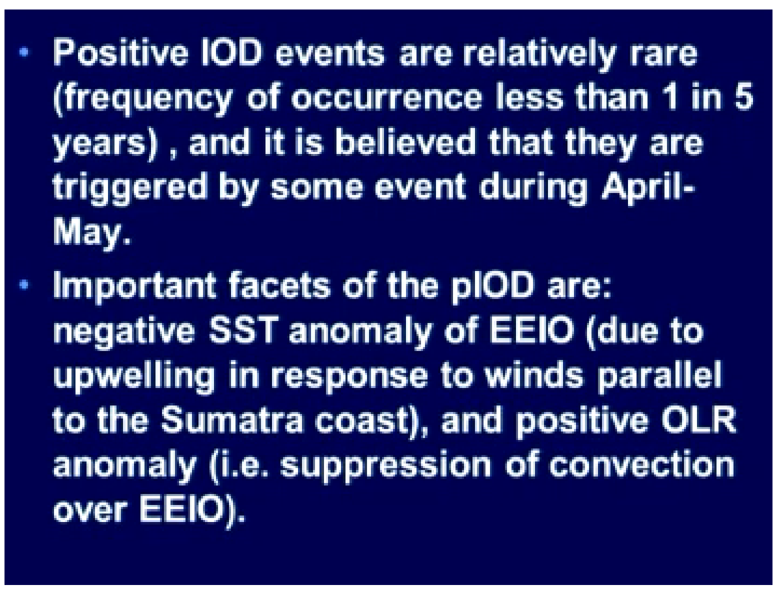

And you see here, midway through the season, this event simply got terminated okay. A pIOD occurred during the latter part of the summer monsoon season and autumn of 2006 with large values of DMI from September 2006 onwards and that is this event here, it is sort of developed a little late okay. Now, positive IOD events are relatively rare, frequency of occurrence is < 1 in 5 years and it is believed that `they are triggered by some event during April, May.

Important facets of the pIOD are, when we talk of triggering, we have to say, see what are the important facets of these events and the major facet of the IOD event is of course, negative SST anomaly of EEIO, which we know now occurs due to upwelling in response to winds parallel to the Sumatra coast and positive OLR anomaly that is to say, separation of convection over EEIO.

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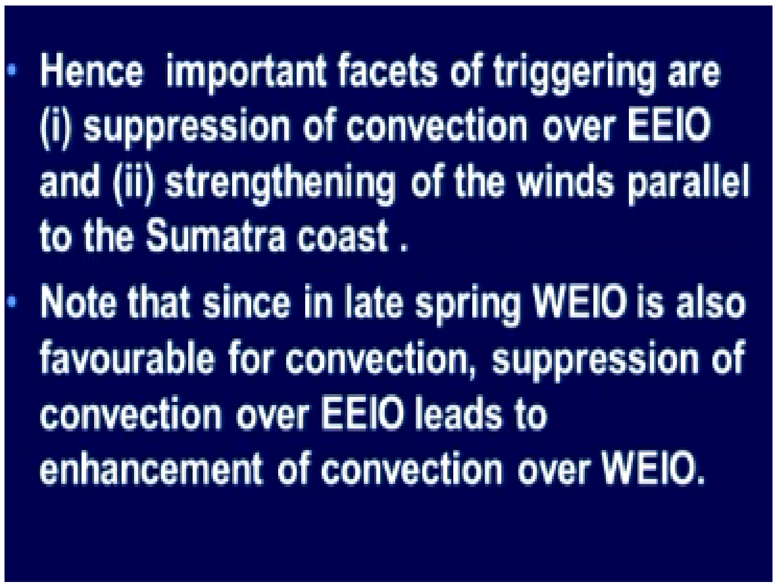

So, these are 2 very important features and we have to see how these features evolve. So, the important facets of triggering are the separation of convection over EEIO and strengthening of the winds parallel to the Sumatra coast which will lead to upwelling. Note that, since in late spring WEIO is also favourable for convection, this is what we have shown in the early part of today’s lecture that from May onwards up to August, both EEIO and WEIO are almost equally favourable for convection.

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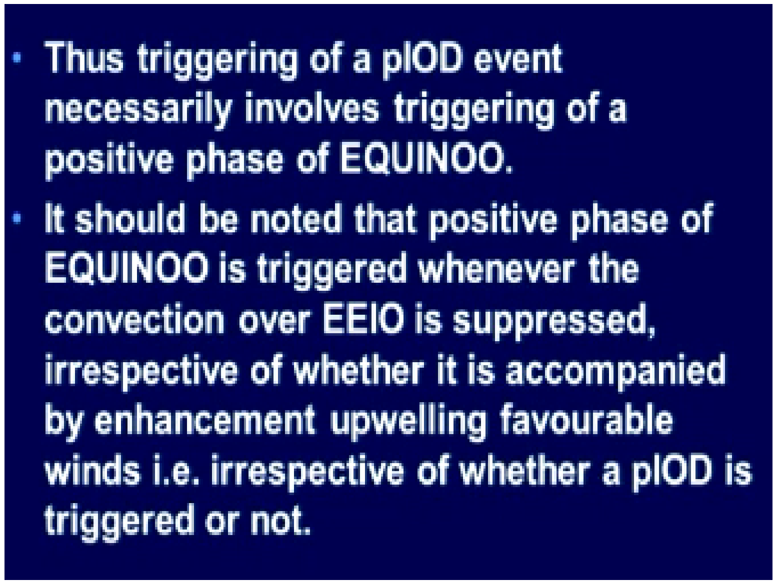

So, what happens? When we have separation of convection over EEIO, immediately you will get enhancement of convection over WEIO because there is a negative correlation between convection over EEIO and convection over WEIO, so separation over one will lead to enhancement of convection over the other. Thus, triggering of a pIOD event necessarily involves triggering of a positive phase of EQUINOO, so if we say, we say an event is triggered when the convection over EEIO is suppressed and those winds parallel to Sumatra are strengthened.

Then, as soon as the convection over EEIO is suppressed, necessarily convection over WEIO will get enhanced. This means that we get a positive phase of EQUINOO because positive phase of EQUINOO is characterised by having enhanced convection over the West and suppress convection over the east. So, triggering of a pIOD event necessarily involves triggering of a positive phase of EQUINOO.

Should be noted that positive phase of EQUINOO is triggered, whenever the convection over EEIO is suppressed, irrespective of whether it is accompanied by enhancement of upwelling favourable winds that is irrespective of whether a pIOD is triggered or not. So, this is something to remember when we look at variation of convection over East and West that irrespective of, what happens to the ocean?

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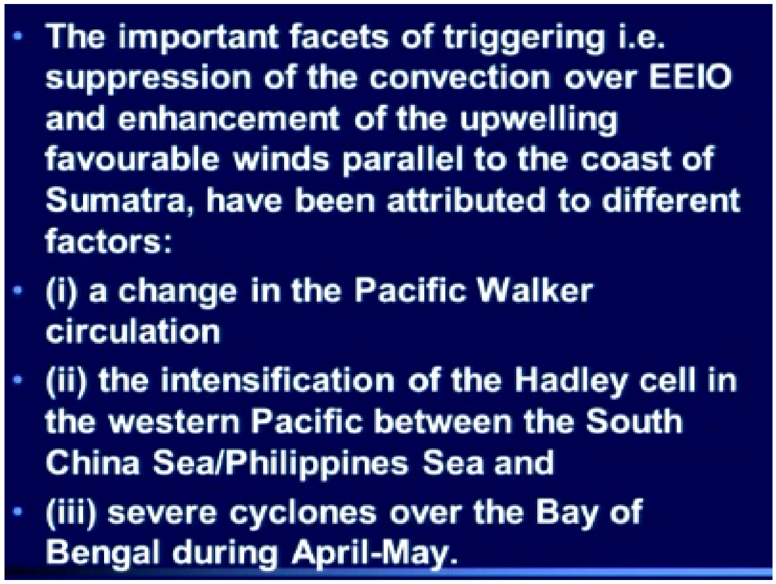

If some means, we ensure that the convection over EEIO is suppressed, then convection over WEIO will be enhanced, this is during May to August and this means, that a positive of EQUINOO will be triggered. Now, important facets of triggering, which is separation of convection over EEIO and enhancement of the upwelling favourable winds parallel to the coast of Sumatra have been attributed to different factors by different scientists among the many theories proposed.

The leading ones are changing the Pacific Walker circulation which I talked about. The intensification of Hadley cell in the Western Pacific between the South China Sea and Philippine Sea, so people have proposed that this intensification of the Hadley cell or intensification, if you wish are the tropical convection zone over South China Sea and Philippines will lead to triggering of positive IOD event. This is one of the theories proposed.

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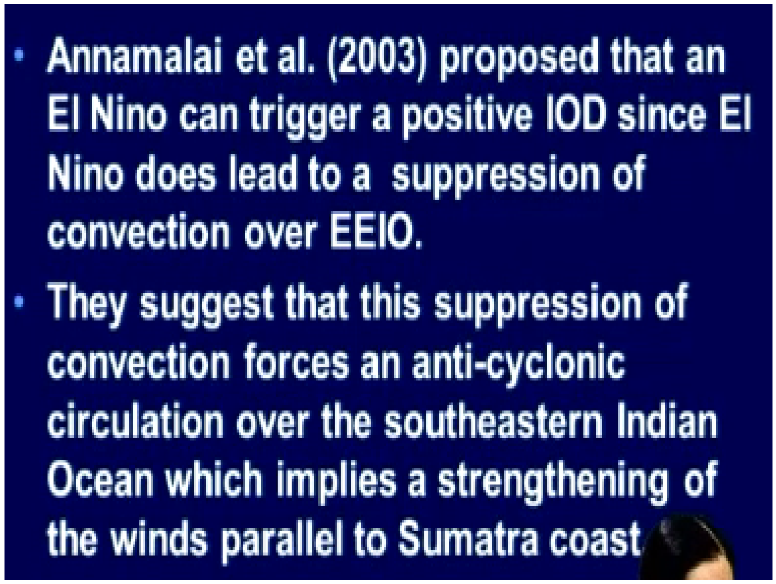

And there is also a theory which is somewhat different from the rest, in which it is suggested that severe cyclones over the Bay of Bengal during April and May can trigger an IOD event. Now, the proponents of the first school Annamalai et al, incidentally, they are also proponents of the theory that by and large Indian Ocean is a passive entity and obeys whatever orders are given from the Pacific.

So, Annamalai et al propose that an El Niño can trigger a positive IOD since, El Nino does lead to a suppression of convection over EEIO, this I have mention already. Now; but then, what about strengthening of the winds? So, they suggest that these separation of convection forces and anti-cyclonic circulation over the south eastern Indian Ocean, now one has to remember that in the southern hemisphere, anti-cyclonic is also anticlockwise.

So, if you have an anticlockwise circulation which is westward of Sumatra, then the circulation along Sumatra coast which corresponds to the limb from 6 o'clock to through 3 o'clock to 12 o'clock and this anticlockwise the direction is actually in the right direction causing upwelling, so we have winds which are south, coming from the south east or coming from the south parallel to the Sumatra coast.

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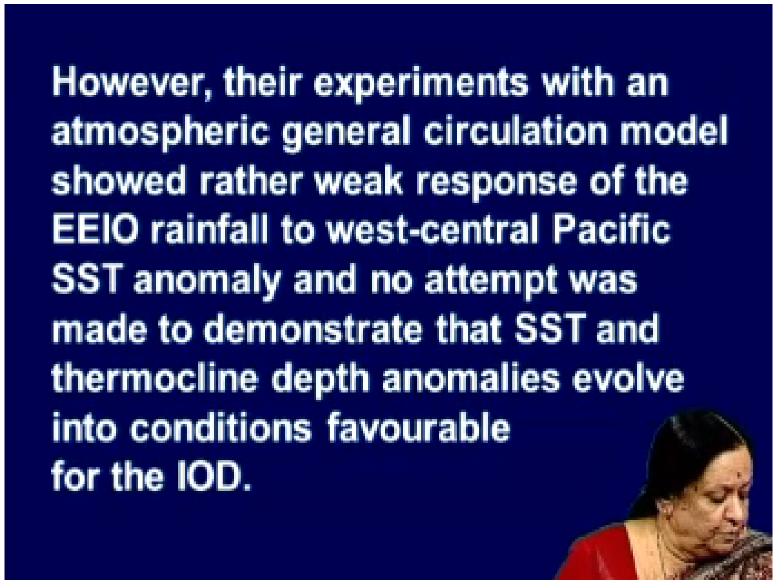

So, Annamalai et al proposed that actually this suppression of convection over EEIO associated with an El Niño leads to a circulation; anti-cyclonic circulation in near EEIO and to its west, such that we have strengthening of the winds which lead to upwelling; further strengthening of the upwelling of Sumatra coast. However, there are some problems with this theory, their experiments with an atmospheric general circulation model showed rather weak response of the EEIO rainfall to the West-Central Pacific SST anomaly.

See, they say that the El Niño, which is characterised by positive SST anomaly over West-Central Pacific is the one that leads to the separation of convection and rainfall over EEIO but their atmospheric model did not show a strong response over EEIO at all to West-Central Pacific SST anomaly, also no attempt was made to demonstrate that SST and thermocline depth anomalies evolve into conditions favourable for the IOD.

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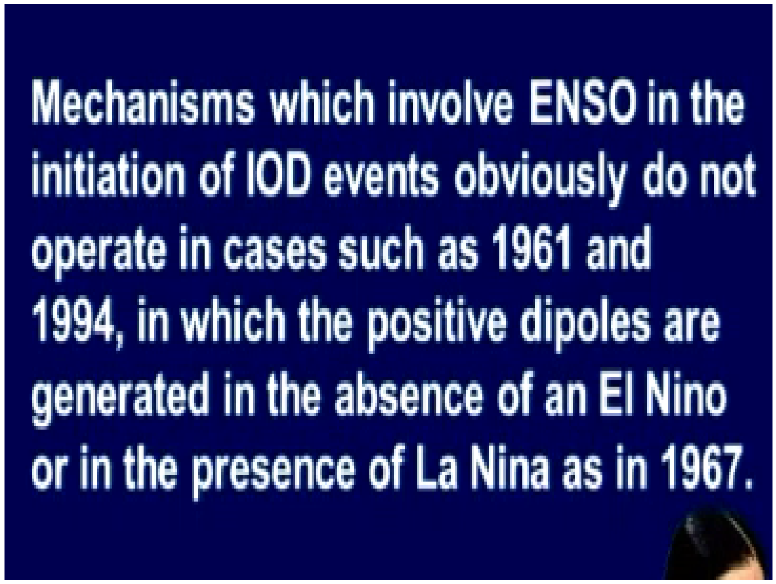

So, that part also was not convincingly demonstrated. One should also remember that mechanisms which involve ENSO in the initiation of IOD events obviously, do not operate in cases like 61, remember 61 is a case that revelled in studied, which first revealed the IOD and 94 in neither of the cases, did we have an El Niño over the Pacific. Secondly the mode in 1967, IOD event in 1967 occurred in the presence of La Nina.

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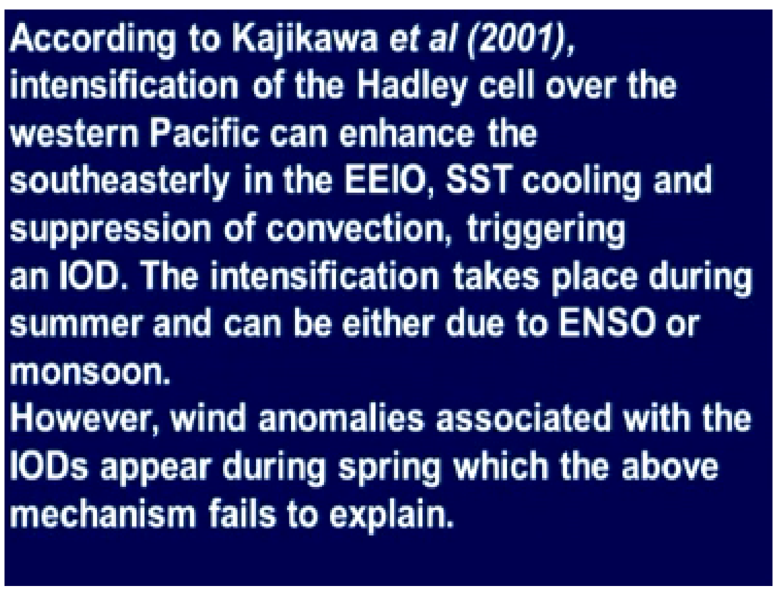

So, La Nina will have the opposite sign of anomalies in the Walker circulation, so it is not possible to explain all the observed IOD events, if we insist that they are generated by ENSO in the Pacific. Now, there was another theory proposed by Japanese, Kajikawa et al, which suggested that some of the convection over South China Sea which corresponds to intensification of Hadley cell over the Western Pacific can enhance a south easterly in EEIO, SST cooling and suppression of convection.

So, they are suggesting that if you have a lot of convection oversight China sea, then one can get this kind of a response and which; remember these are the factors that lead to triggering of an IOD, suppression of convection over EEIO and enhancement of the Southern south easterly winds off the coast of Sumatra. So, they claim that this can then lead to do the triggering of an IOD.

But the intensification that they are talking of take place during the summer, this is during June and July and can be either due to ENSO or monsoon, this is what they say. However, now it is well established that the wind anomalies associated with the IODs appear during spring, which the above mechanism fails to explain. See, they have suggested a mechanism which could have worked in terms of suppressing the convection over EEIO.

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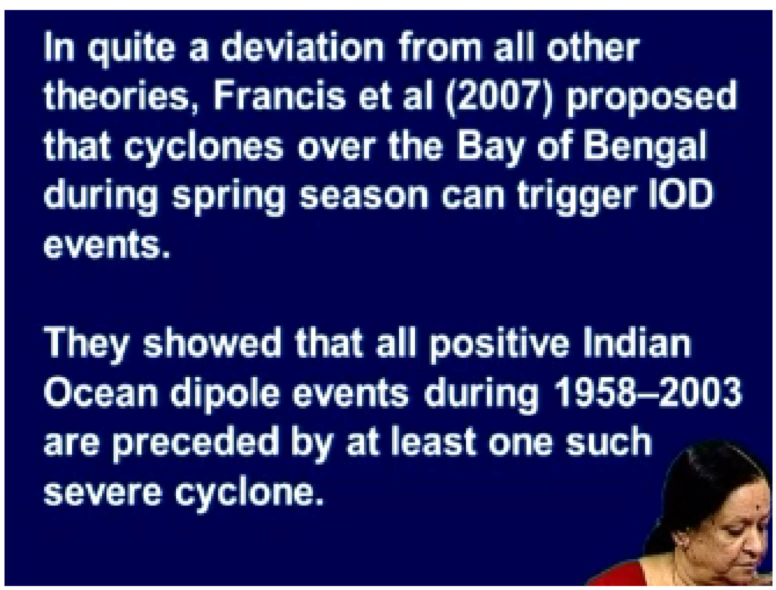

But the timing is wrong, if we compare with the observations. Now, so far people were talking about ENSO and its relationship to IOD and what happens to Hadley cell over West Pacific and its relationship to IOD. In quite a deviation from all other theories Francis et al in 2007 proposed a very different theory. They said severe cyclones over the Bay of Bengal during spring season can trigger IOD events.

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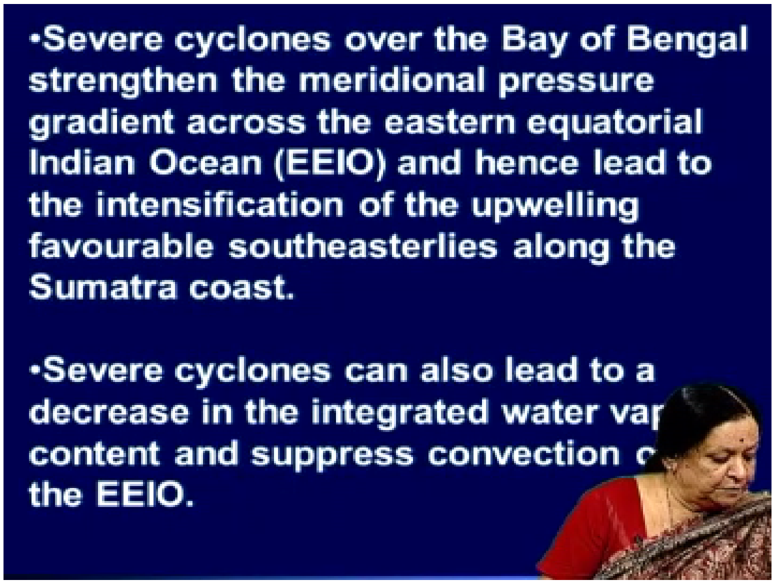

In fact, they showed that all positive IOD dipole event during 58 to 2003 are preceded by at least one such severe cyclone okay. Now, severe cyclones over the Bay of Bengal strengthened the meridional pressure gradient, why is that? Because severe cyclones imply that the pressure is very low over the Bay of Bengal related to the equatorial Indian Ocean, this means that the north south pressure gradient has enhanced.

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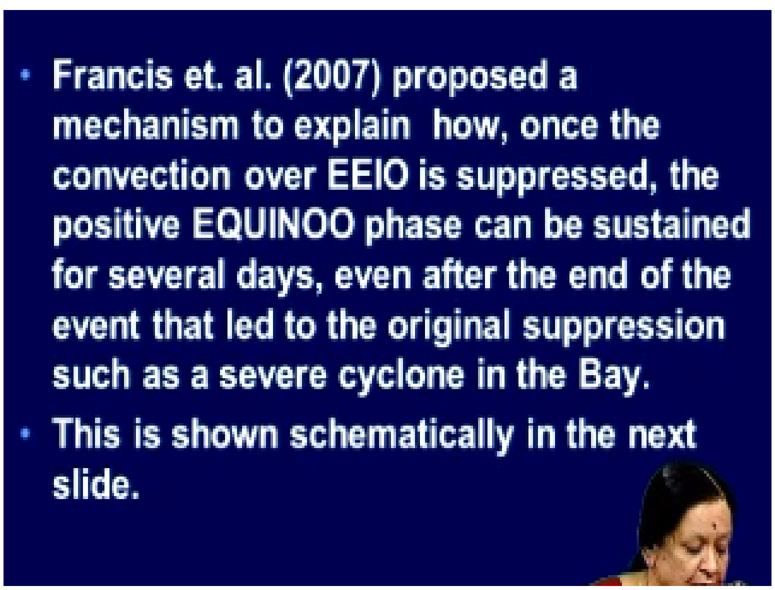

And that would lead to an intensification of up welling favourable south easterlies along the Sumatra coast. They also showed that severe cyclones can lead to a decrease in the integrated water vapour content over EEIO and suppress the convection there. So, they actually generate conditions, which are favourable for triggering. Now, I do not have the time to get into details about this.

But I would just like to mention, the jury is still out on what triggers the IOD events but what would be interesting to look at is a mechanism which Francis et all proposed to explain how once a convection over EEIO is suppressed, the positive EQUINOO phase can be sustained for several days even after the end of the event that led to the origin suppression such as the severe cyclone in the Bay.

So, this is an interesting problem in itself that you have an event; you have an event on the synoptic scale it could be intensification of convection over South China Sea as proposed by Kajikawa and others or it could be a severe cyclone in the Bay. Now, if this event has the kind of impact that has been suggested that is suppressing convection over EEIO and strengthening the south easterlies parallel to Sumatra coast.

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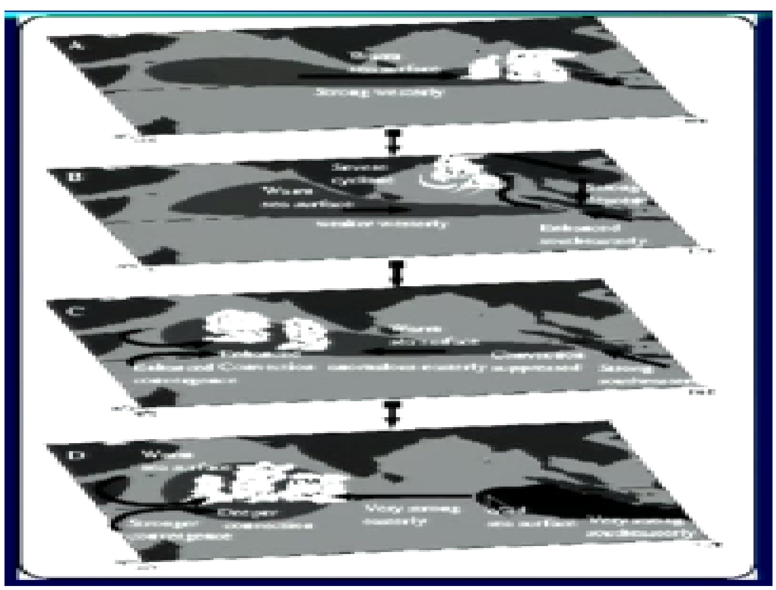

It should all end, once the event end, right because these events are only few days but for the triggering to take place, for the IOD event to be triggered, this has to be sustained for much longer than a synoptic scale at least for time scale of the order of weeks; question is, how does that happen? Now for this, Francis et al proposed a mechanism which is shown in this slide here schematically.

So, initially state is the following; initially, we have convection over EEIO and this is the entire warm sea surface remember, west is also warm, east is also warm and convection is over EEIO because that is where the propensity of convection is high, so we have strong westerly winds here and what happens? We get a severe cyclone here over the Bay, okay. Once we get a severe cyclone over the Bay, then it will enhance south easterly flow over the Sumatra; parallel to the Sumatra coast and it will also suppress convection over here okay.

Once its suppresses convection here, the pressure gradient decreases, so the flow becomes weaker westerly, so the equatorial winds become weaker westerly, EQUINOO is reduced the magnitude, so once we have a severe cyclone, this convection disappears and we have enhancement of up welling favourable winds and weakening of westerly winds okay. Now, once this convection is suppressed because this region is equally favourable and there is see saw in convection between these 2 regions which you have seen.

Once this cyclone forces, this convection over EEIO to be suppressed immediately convection will build up over WEIO. So, now we get a situation in which the convection builds up over WEIO and this means that you have now; the pressure gradient is switched, it is the low pressure on the equator is here, so the winds also; if it is in terms of anomalies, we get easterly anomalies here and eventually actually, in the development of an IOD, you get actually still easier, when there is sustained convection here.

So, the pictures here and what happens when you get convection here is that a positive feedback is set up. Because, now if we talk of anomalies, this anomalies convection drives winds to what is it; which are winds, which are easterly anomalies. Now, this means there is more convergence into this regions, more convergence means more convection and more convection means more convergence.

So, once the system gets set of here, it is so self-propagating, because it is so the system with a positive feedback which can lead to sustained increase in convergence and sustained increase in convection here and which is what happens. Then, this happens, actually what happens is, instead of just having easterly anomalies, you get easterly winds here, so strong convergence contributed by easterly winds from here.

Now, once the winds become easterly here, the SST of EEIO drops even further because not only do we have up welling favourable winds parallel to Sumatra, we also have, like the Pacific, you know surface water being driven away from this region which will lead to equatorial upwelling as well. So, this is very analogous to Pacific, so if this process continues, then we can get triggering of an IOD event.

And remember that all this mechanism asks for some event, it could be of a synoptic scale event also, need not be of a larger scale in synoptic intra seasonal scale, some event which lead to suppression of the convection over EEIO is all that is required and then all these feedbacks will take place and we can go over to assist them in which this develops a cold anomaly of assistive along with the suppress convection.

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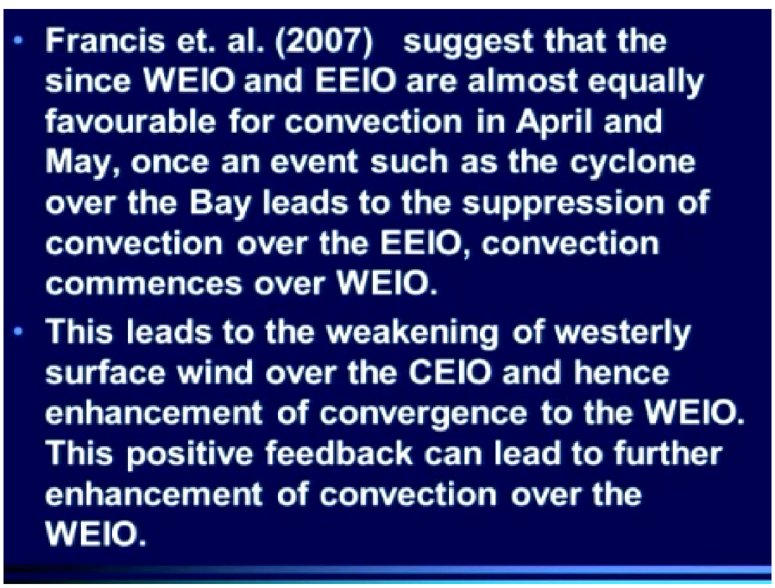

And if the process goes on, actually, SST can go below the threshold and once it goes below the threshold, there is no way the convection can revive here, no matter what and we get a IOD event. So, they suggest that since WEIO and EEIO are almost equally favourable for convection in April and May, once an event such as the cyclone over the Bay leads to the suppression of convection over EEIO, convection commences over WEIO.

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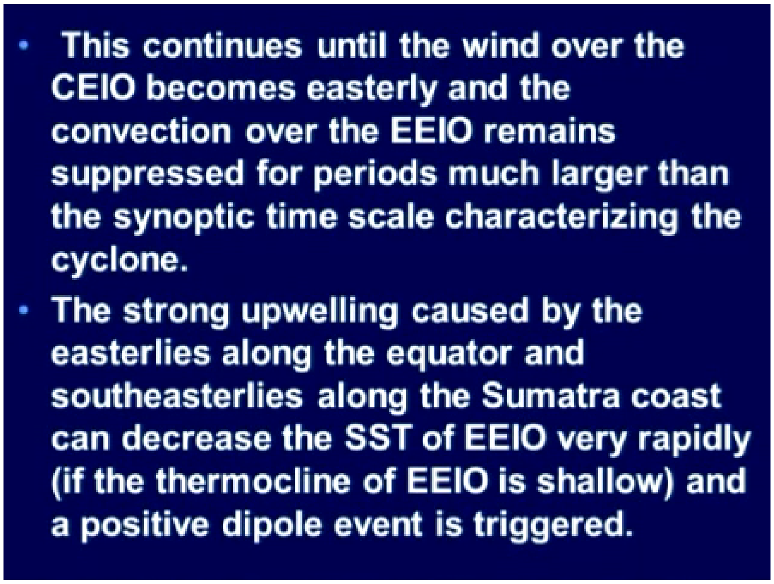

This lead to the weakening of westerly surface winds over CEIO and hence enhancement of convergence to the WEIO, this positive feedback can lead to further enhancement of convection over the WEIO. This is what we just explain. So, this continues until the wind over the CEIO becomes easterly and the convection over the EEIO remains suppressed for periods much larger than a synoptic time scale characterising the cyclone.

The strong upwelling caused by the easterlies along the equator and the south easterlies along the Sumatra coast can decrease the SST of EEIO very rapidly provided the thermocline is shallow and a positive dipole event is triggered, so we now have a story of how one could trigger positive IOD events and why is the positive IOD event of greater interest because a negative IOD event is intensification of climatology.

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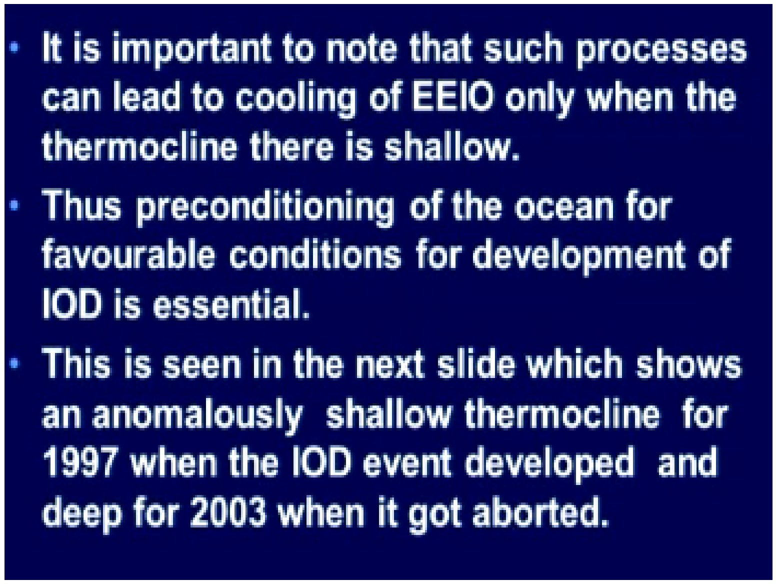

Whereas a positive IOD event involves reversal of the east west gradients of sea surface temperature and convection over the Indian Ocean. Now, it is important to note that all these processes of triggering can lead to cooling of EEIO only when the thermocline there is shallow okay, because if the thermocline is not shallow, the upwell water is not cold enough, so you do not get as much cooling as you would when the thermocline is shallow.

So, like the Pacific, this is a constraint that the thermocline has to be shallow for all these ocean dynamics mechanism to operate and lead to infect, an IOD event. Now, you know, we have seen in earlier lecture that the thermocline over the eastern part is deeper than the thermocline over western part in the equatorial Indian Ocean. Now, what leads to thermocline being shallow in April-May over the eastern part is something I do not have time to get into in this lecture series.

And you know this is what sets the stage for the possible development of IOD and kelvin waves and Rossby waves and so on play a very important role upwelling and down welling waves, play a very important role in the changes of the thermocline along the east west direction in the equatorial Indian Ocean. As I said I will not have time to go into it but let me just show you how important preconditioning for the ocean is. You remember that we had 2 cases; 97 and 2003.

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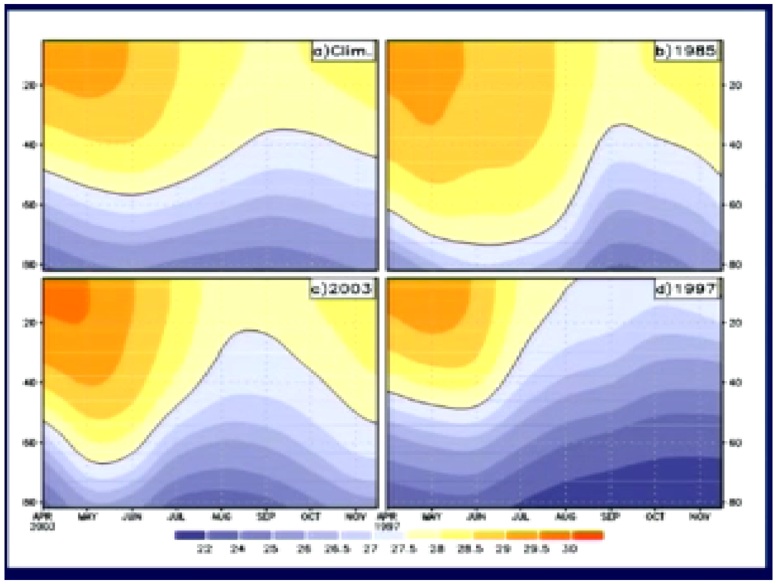

In fact, Francis et al have shown that the initial evolution of the OLR, SST and so on of EEIO were very similar in the 2 cases. That in the case of 97, we got a full-fledged IOD event developing with SST going below the threshold, but in the case of 2003, SST never went below the threshold and the event got aborted half way through the season and we can see here, how it happened.

This is in fact, the thermocline depths in 97 and 2003 as well as climatology, this is from soda data which is an analogue ocean; it is analogous in the ocean to the ncep reanalysis data which we have been using, see this is climatology now and these are the months here you can see; April to November, so this is only for EEIO, we begin with a very deep thermocline, this is climatology, we begin with a very deep and warm thermocline in April and slowly as we have seen SST cools.

And we have shallowing of the thermocline, so that it becomes rather shallow in September, October and then starts deepening again, so this is climatology, the mean of all the years. Now, what happen in 97 is here and it is a huge contrast. What happen in 97 is to begin with; you can see that it was shallower even in April and June onwards, you see it has become extremely shallow, so that the thermocline here has become very very shallow.

Now, remember these are the temperature contours, this is 30, this is 29.5, 29 and so on and so forth, so the warm water is over a much smaller region in 97 even to begin with and then this 27.5 which is a threshold, it actually surfaces around August, so after August, EEIO is colder than the threshold, so this is what is happening in 97 and you can see that initially itself, the ocean was preconditioned with less heat content and a shallower thermocline.

Look at the case of 2003, 2003 actually, the thermocline was shallower to begin with, all the processors have triggering and so on occurred in 2003 as well and a thermocline began to go shallow just like this, but the point is this it started from a much deeper level and it never really got to shallow, so that the water never became colder than the threshold and when for some reason, the west convection disappeared the east revived and IOD was aborted.

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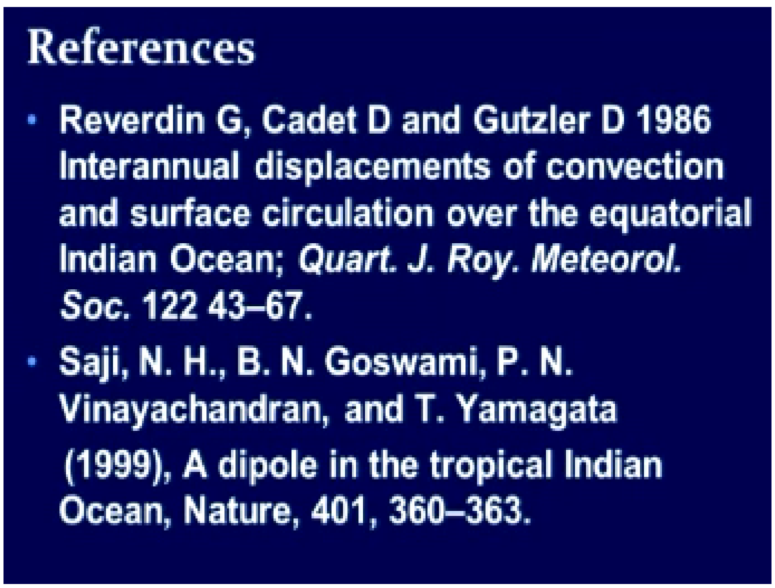

Now, I have mentioned at the end here, several of the important references, there are the; Reverdin, is the one who first described it.

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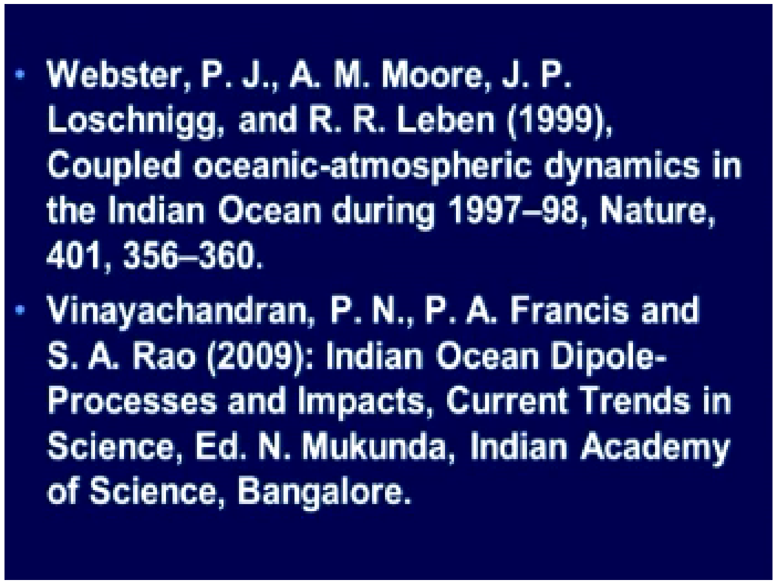

Saji et al and Webster et al, 99 the ones who first talked about the Indian Ocean dipole mode and Indian oceans zonal mode and there are nice review articles.

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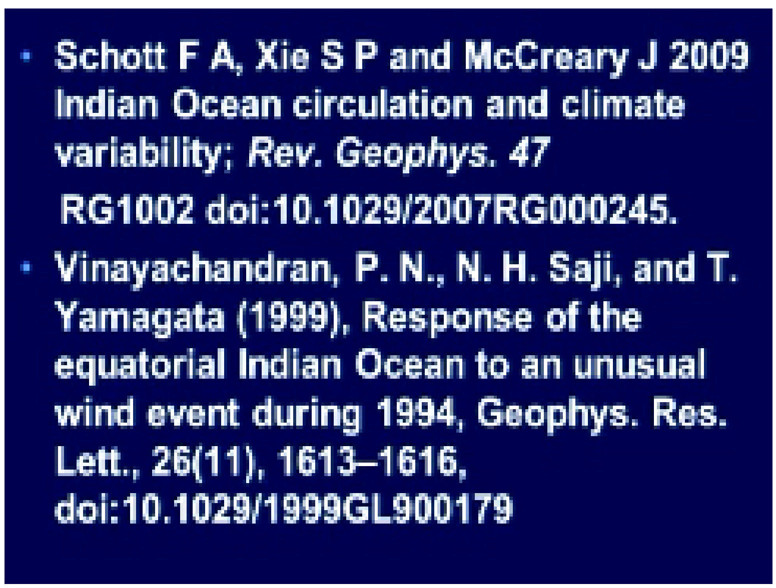

One by Vinayachandran et al, one by Schott et al and some critical papers like the one on 94 by Vinayachandran

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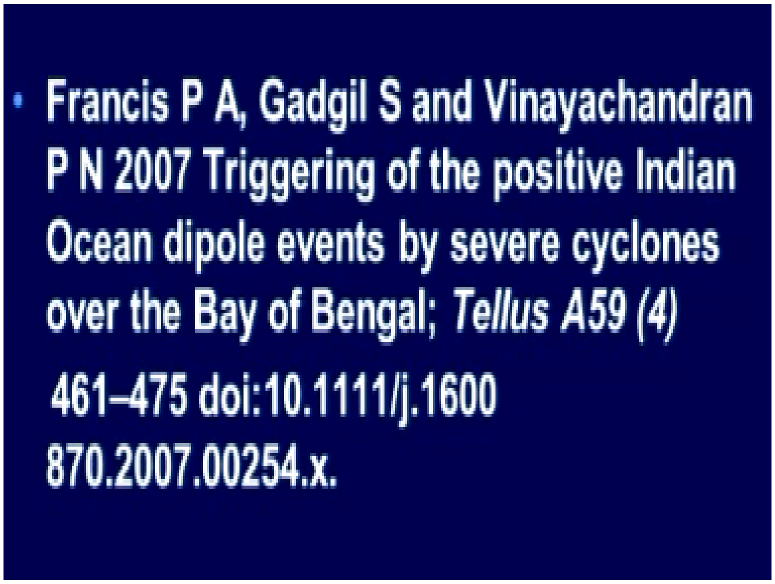

Then that the triggering papers that I mentioned at the end. So, with this, we come to the end of a discussion and IOD, it is a very hot topic and by no means I have been able to cover all the; all the issues involved but I think this should provide some guidance as to where to go from here. Thank you.