The Monsoon and Its Variability
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Lecture – 29
El Nino Southern Oscillation (ENSO) Part 6

You recall that actually Southern Oscillation was discovered by Sir Gilbert Walker when he analysed worldwide datasets to try and find predictors for Indian rainfall.

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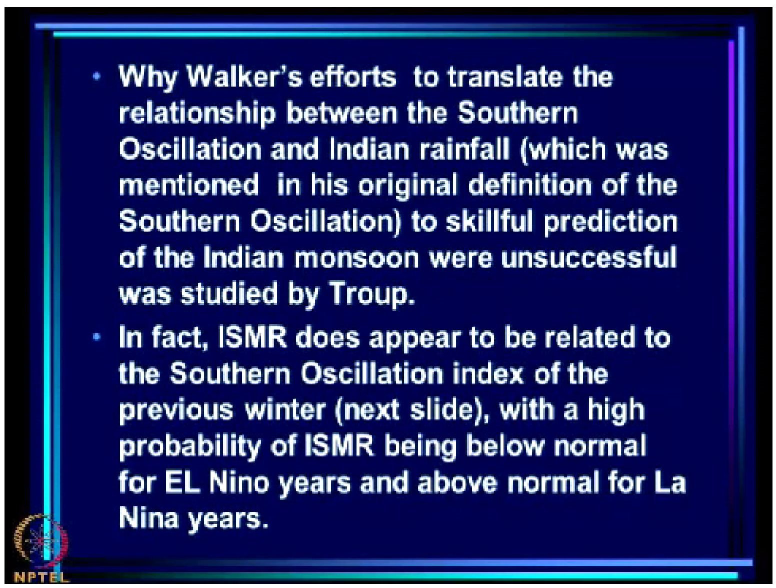

Now why Walker's efforts to translate the relationship between the Southern oscillation and Indian rainfall which was actually mentioned in his original definition of the Southern oscillation. Why his efforts to translate this relationship between Southern Oscillation and Indian rainfall to skilful prediction of the Indian monsoon were unsuccessful was studied by Troup. In fact, ISMR does appear to be reasonably well related to the Southern oscillation index of the previous winter with a high probability.

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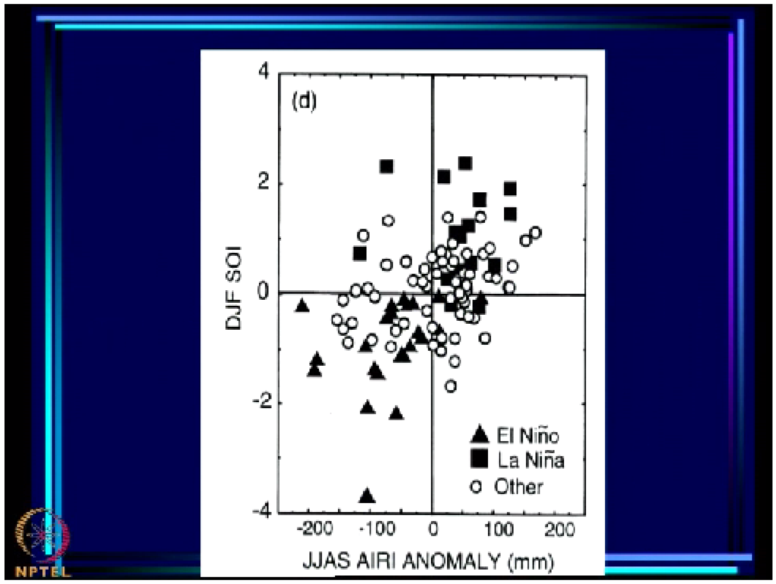

So you have here on the Y axis the previous winter SOI. On the x-axis is the JJAS the anomaly of the ISMR and what you see is that most of the El Nino years correspond to negative ISMR anomaly, most of the La Nina years correspond to positive rainfall anomaly. Of course, there are a few exceptions but by and large, there is high probability of El Ninos being associated with negative anomaly of ISMR and La Nina as assessed by the SOI in DJF are being associated with above normal rainfall.

So this is very clear that there is a high probability of ISMR being below normal for El Nino year and above normal for La Nina years.

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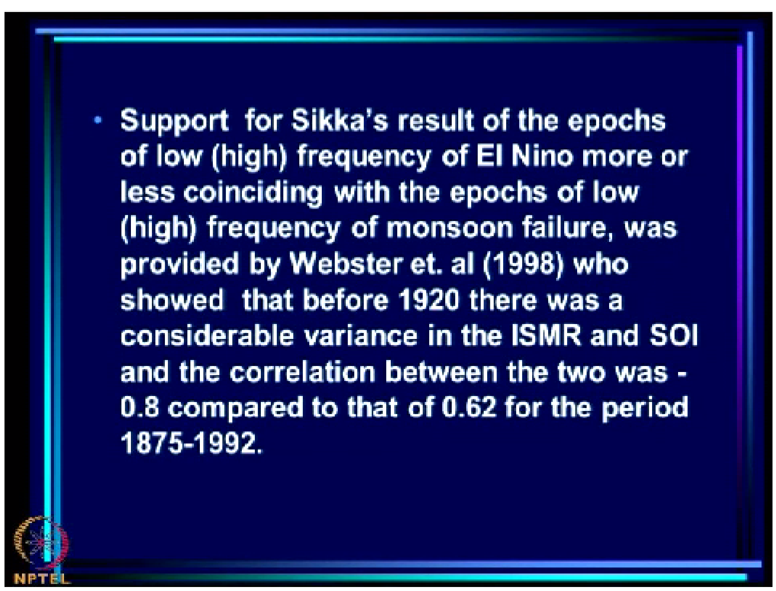

Now support for Sikka's result of the epochs of low and high frequency of El Nino, more or less coinciding with the epochs of low or high frequency of monsoon failure. Now this we are talking now of association and not prediction, was provided by Webster et. al. What Sikka did was only point out that you had this major change in the frequency of occurrence of these events from one epoch to another.

Now this support for this came from Webster who actually calculated the correlations and showed that before 1920, there was a considerable variance in the ISMR and SOI. This is because they were a high frequency of occurrence of droughts as well as El Ninos and the correlation between the 2 was-0.8 compared to 0.62 for the period 1875-1992. So one had a very high correlation in the epoch when there was a high frequency of these events occurring.

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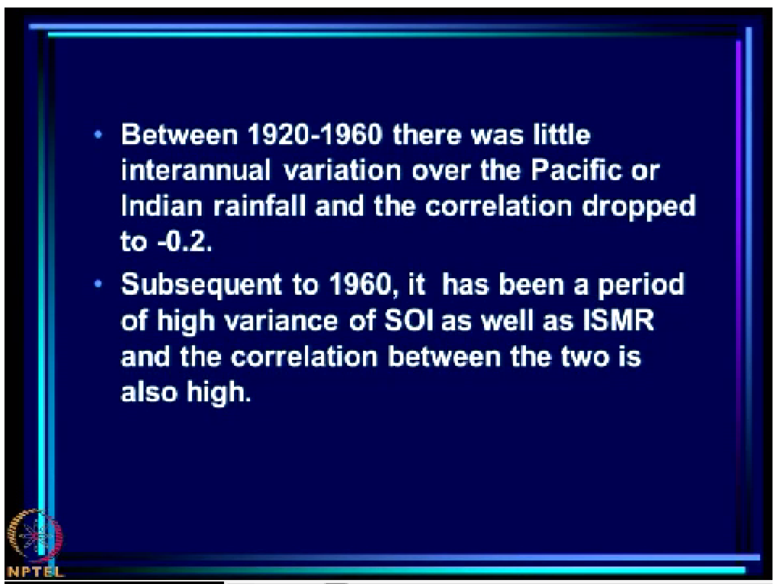

Between 1920 and 1916, there was little interannual variation over the Pacific or Indian rainfall and correlation dropped to -0.2. Subsequent to 1960, it has been a period of high variance of SOI as well as ISMR and the correlation between the 2 is also high.

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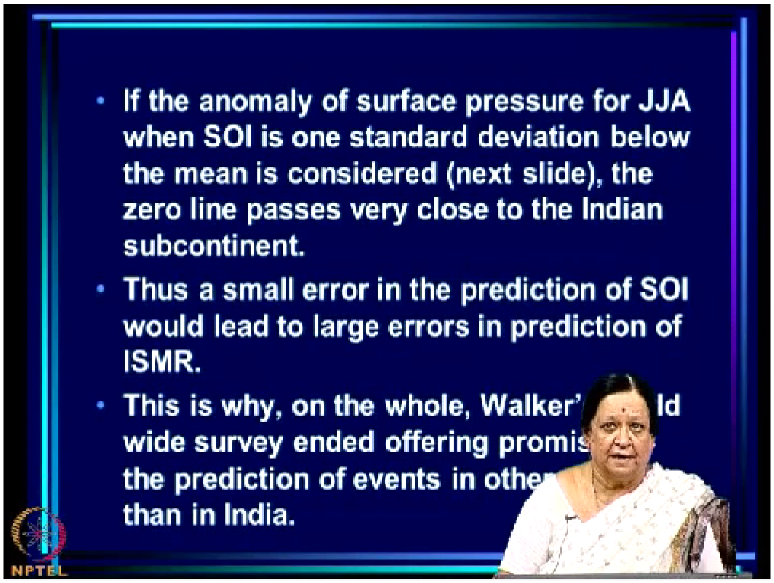

So the association is well-established, the one that Sikka had shown but now the question is, why is it that the SOI of the previous winter or previous why can it not be used as a predictor for the summer monsoon rainfall over India? Now if the anomaly of surface pressure for JJA when SOI is one standard deviation below the mean is considered, okay.

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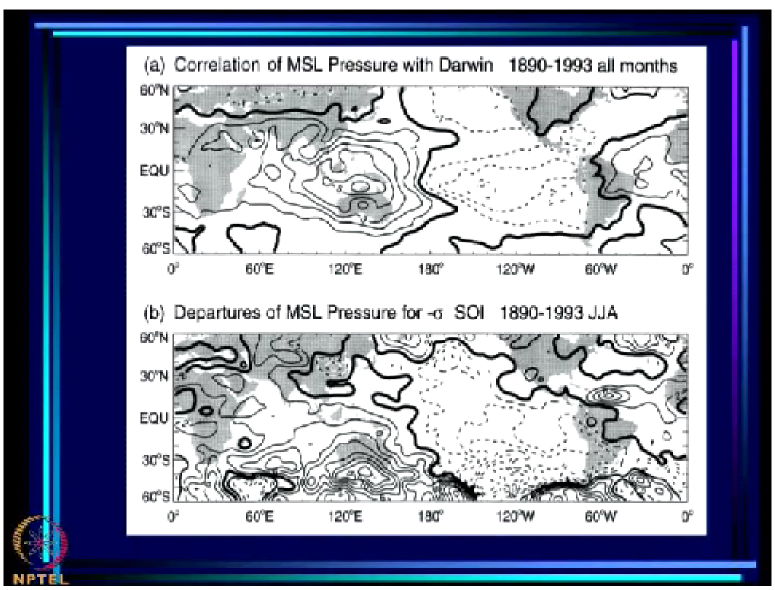

Now what you see here is correlation of the mean sea level pressure with Darwin. So this is simply the Southern Oscillation. You have positive correlations over this part, negative correlations over this part and this is in fact the Southern Oscillation. What you see here is departure of the mean sea level pressure, that is the surface pressure anomaly for minus sigma SOI, that is to say when the Southern Oscillation index is one standard deviation below the mean and what you see here is, this is India right here.

And what you see is that the 0 line which is drawn very dark here passes very close, in fact it goes over the Indian subcontinent, you know, it is to the west of Bangladesh. So it is passing right through here, so the node of this, you know, this is where the anomalies change sign across this. So these boundaries are very much on the Indian subcontinent. So small errors in the predicted value of Southern Oscillation index will lead to very large errors over Indian rainfall.

So as we have seen that the 0 line passes very close to the Indian subcontinent of the anomalies of surface pressure when Southern Oscillation is one standard deviation below the mean. So since the 0 line passes very close to the Indian subcontinent, small error in the prediction of SOI would lead to large errors in prediction of ISMR. This is why on the whole Walker's worldwide survey ended offering promise for the prediction of events in other regions than India. Other regions which are not so close to the node, close to the 0 line.

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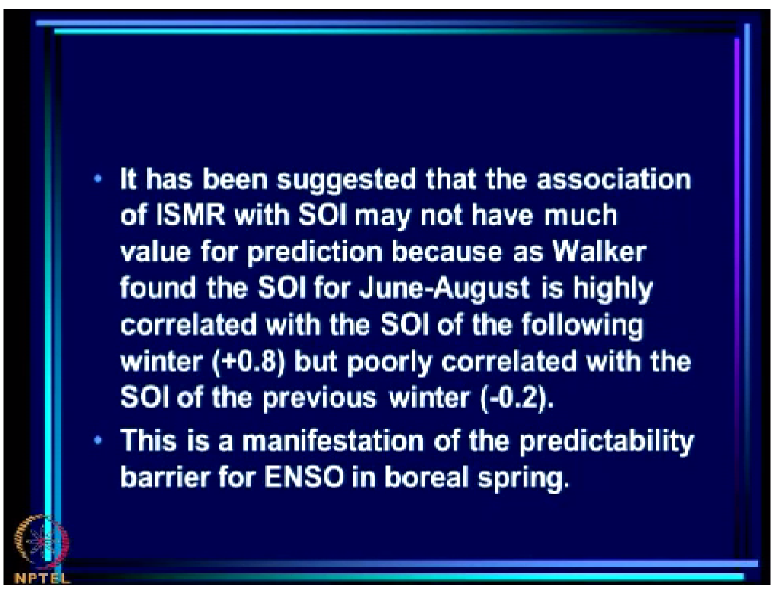

Now it has been suggested that the association of ISMR with SOI may not have much value for prediction because as Walker found the SOI for June to August is highly correlated with the SOI of the following winter, that is the season following the summer monsoon but poorly correlated with SOI of the previous winter. Following winter, the correlation is +0.8; previous winter, the correlation is only -0.2. So this is a manifestation of the so-called predictability barrier for ENSO in boreal spring.

It is believed that there is a predictability barrier that if you start integrating from before the spring, it is very difficult to generate predictions with reasonable skill for ENSO beyond the spring. So there is as it were a barrier in the boreal spring and this is one manifestation of this that the conditions of the previous winter are not highly correlated with what follows in summer across the Spring barrier.

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Thus, it appears that the Indian monsoon has connections with later than earlier events and in the words of Normand, the Indian monsoon stands out as an active and not a passive feature of world weather----more efficient as a broadcasting tool than an event to be forecast, okay.

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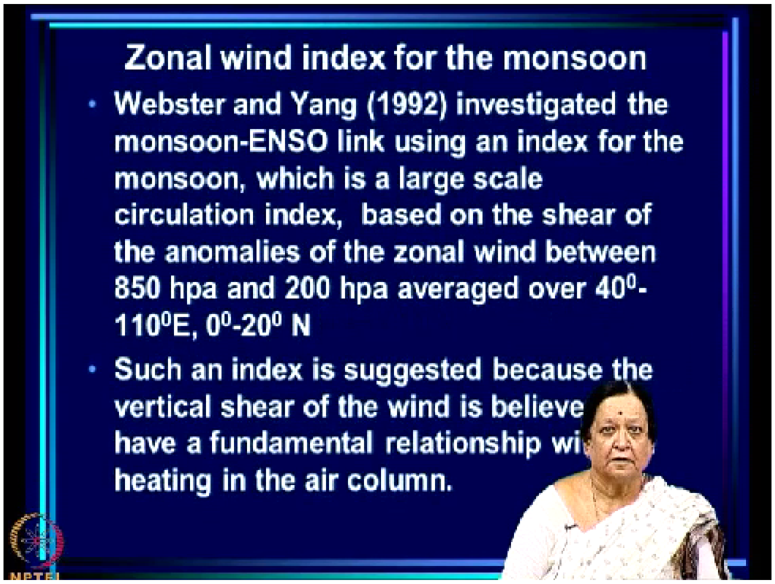

So having looked at Indian summer monsoon rainfall and not having found a sufficiently robust predictive relationship with ENSO, Webster decided that one should look at a larger scale than India and also then look at an index which is a circulation index rather than a rainfall index because rainfall is more difficult to get. Of course he could have chosen OLR but he chose to formulate an index for the monsoon which is the circulation index and it is based on shear of the wind at 850 and 200.

It is based on shear of the zonal component of the wind at 850 and 200 hpa over the following region.

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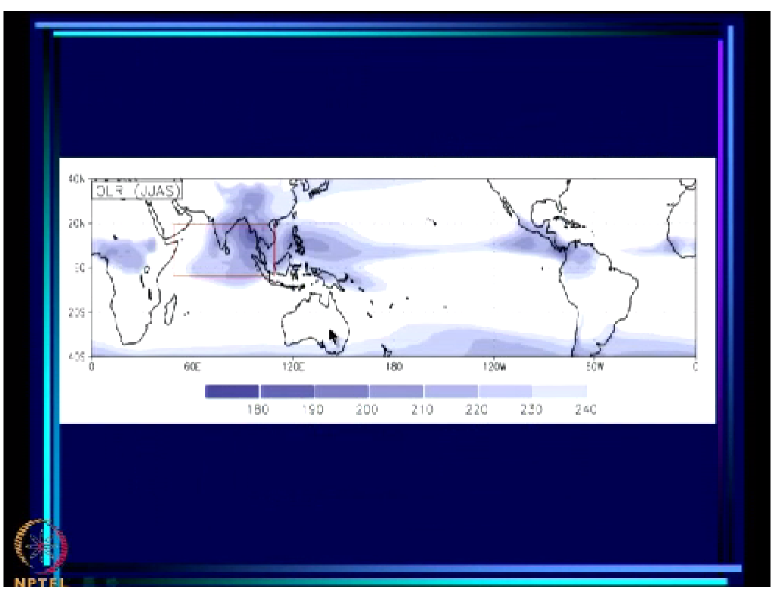

So he takes a huge region all the way from 40-110 and 0-20 north and over this region, what he is doing is actually seeing what is the zonal wind at 200 as an anomaly, that is to say zonal wind minus the mean wind, then he also looks at the zonal wind at 850 and subtracts the mean. So he has anomalies of the zonal wind at 850 and 200 and is the difference between the 2 anomalies that he defines as the monsoon index M.

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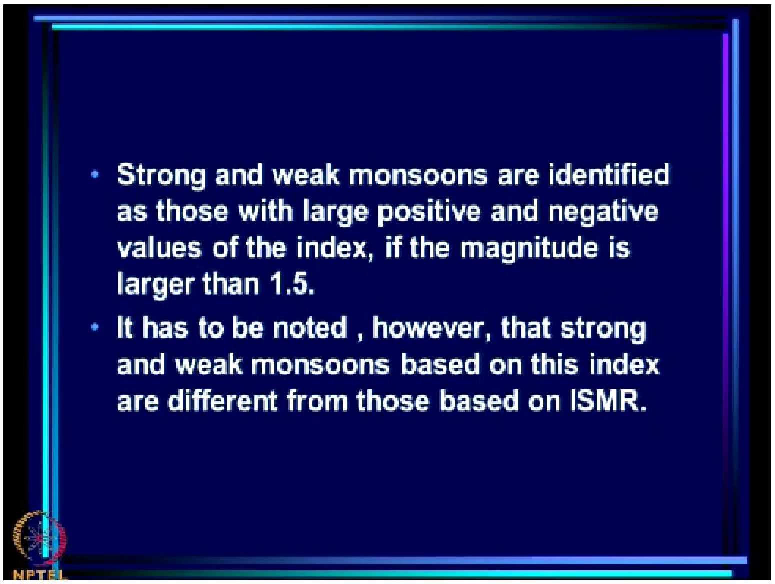

Now strong and weak monsoons are identified as those with large positive and negative values of the index if the magnitude is larger than 1.5. This threshold of strong and weak varies from place to place. For Australia, the threshold is somewhat different. It depends on the typical variation of this index over that region. Now one problem that is there with this index is, now first of all you may ask the question, why go to a wind index, why go specifically to an index which measures the shear of the wind between 850 which is 1.5 km to the upper troposphere which is a 200 HPA.

Now such an index is suggested because the vertical shear of the wind is believed to have a fundamental relationship with the heating in the air column, right and by rainfall, you know, we always use OLR as a proxy of rainfall and OLR in fact gives us a hint of the presence of deep clouds when the values are low and when you have deep clouds, the distinguishing attribute of that air with deep clouds is that there is heating in that air column because of the latent heat releasing the clouds.

So one can show that heating in the air column is related to the shear of the zonal wind and this is why Webster and Yang have chosen to use this as an index. Now the problem may not be with the index, it may be that the area over which they average it is far too large and is not coherent with the variations over the Indian region, the heat source over the Indian region. Be that as it may, it turns out that what we see as strong and weak monsoons from the Indian perspective.

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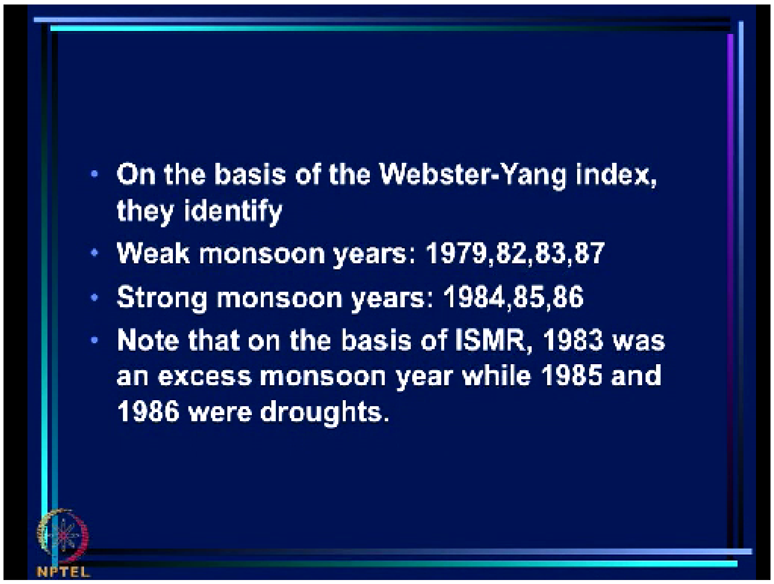

That is to say from ISMR, are different from strong and weak monsoons using the Webster-Yang index. So Webster-Yang index have identified weak monsoon years as 1979, 1982, 1983, 1987 and strong monsoon years as 1984, 1985 and 1986.

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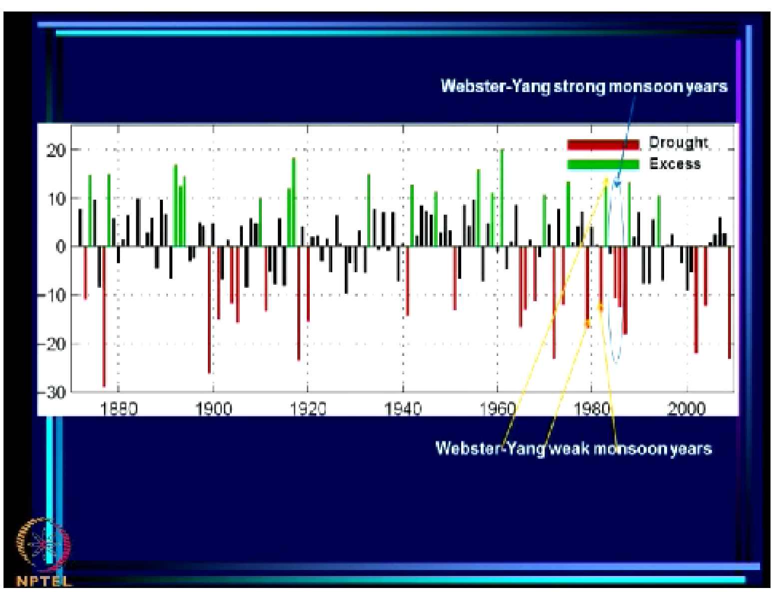

Now what we will find is the following: This is our good old diagram of the ISMR anomaly going all the way from 1875 and what I have marked here in yellow are the Webster-Yang weak monsoon years and these are the Webster-Yang strong monsoon years and you can see that among the strong years are 1985 and 1986, which are actually droughts and among the weak monsoon years, is actually this year here 1983 which is an excess rain year.

So among the weak monsoon, he counts 1983 which is an excess monsoon year and among the strong monsoon, he has 1985 and 1986, which are actually droughts of the Indian monsoon. So what is happening is, see 1979 was a drought, no problem; 1982 was a drought, 1987 was a drought but 1983 was an excess monsoon year which he gets as a weak monsoon. Now similarly 1984, no hassle. It was not particularly strong.

In fact, you can see that that this is 1985 and 1986, 1983 is here, 1984 was not at all strong. It was very close to normal. So there is very little matching between variation of his M index, Webster-Yang index and our Indian monsoon rainfall. So 1984 was normal, these 2 were droughts, he considers all these as strong monsoon years, then these 3, at least in the weak monsoon, there were 3 droughts but the 4th was an excess rainfall year.

So there is very little agreement between Webster-Yang strong and weak monsoons and strong and weak monsoons identified from ISMR, that is Indian rainfall.

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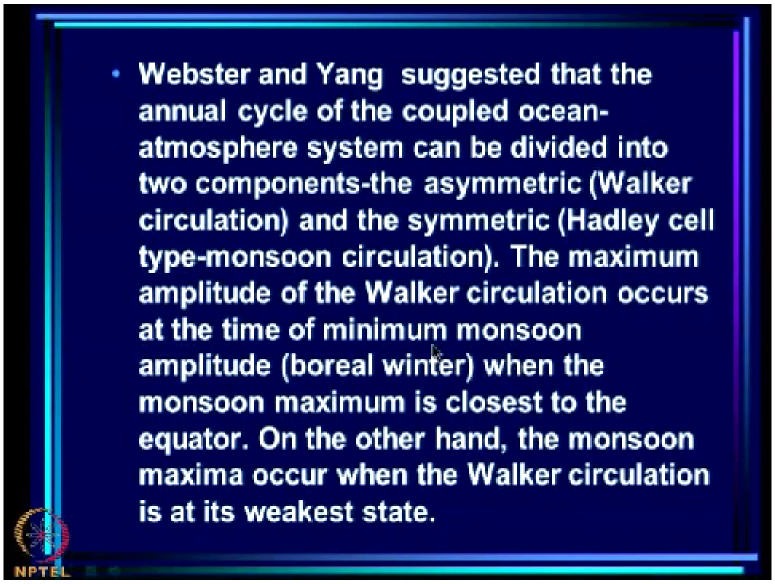

Now on the basis of this kind of classification, Webster and Yang have suggested how monsoon and ENSO could be interacting and they talk of selective interaction. They suggest-that the annual cycle of the coupled ocean-atmosphere system can be divided into 2 components, one is the asymmetric, that is to say east-west kind of circulation which is the Walker circulation and the other is the symmetric component which is the north-south component which is Hadley cell or monsoon type circulation.

So the maximum amplitude of the Walker circulation occurs at the time of minimum monsoon amplitude which is boreal winter, we have seen that. In boreal winter, in fact you do not see much of a Hadley cell over the Pacific and over the Indian Ocean also, the ITCZ is closest to the equator. So in fact, the maximum amplitude of the Walker circulation occurs at the time of minimum monsoon amplitude, boreal winter, when the monsoon maximum is closest to the equator.

On the other hand, the monsoon maxima occur when the Walker circulation is at its weakest state. We have seen that that in June, July, August, September, it is much more of a Hadley cell kind of circulation even over the Pacific.

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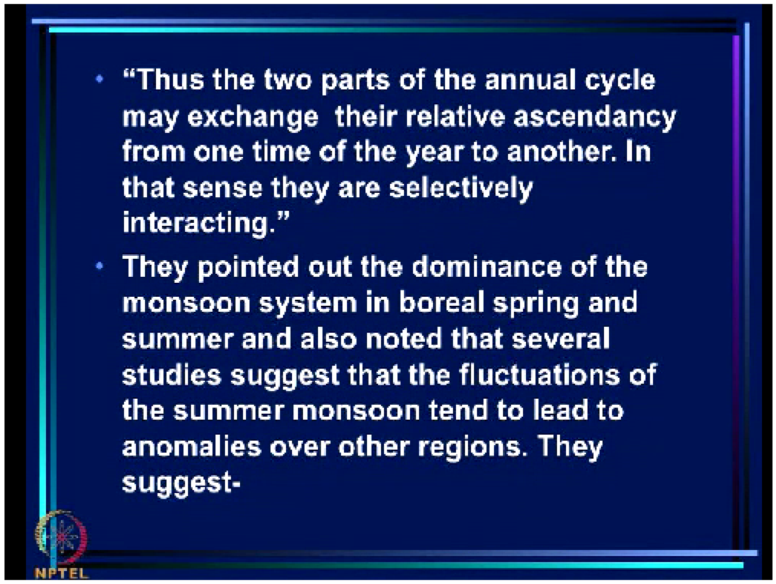

Thus the 2 parts of the annual cycle, one part is the symmetric part, the other part is asymmetric part may exchange their relative ascendancy from one type of the year to the other. In that sense, they are selectively interacting. So they point out the dominance of the monsoon system in boreal spring and summer, that is to say dominance over the asymmetric or the Walker circulation type, and also noted that several studies suggest that the fluctuation of the summer monsoon tend to lead to anomalies over other regions.

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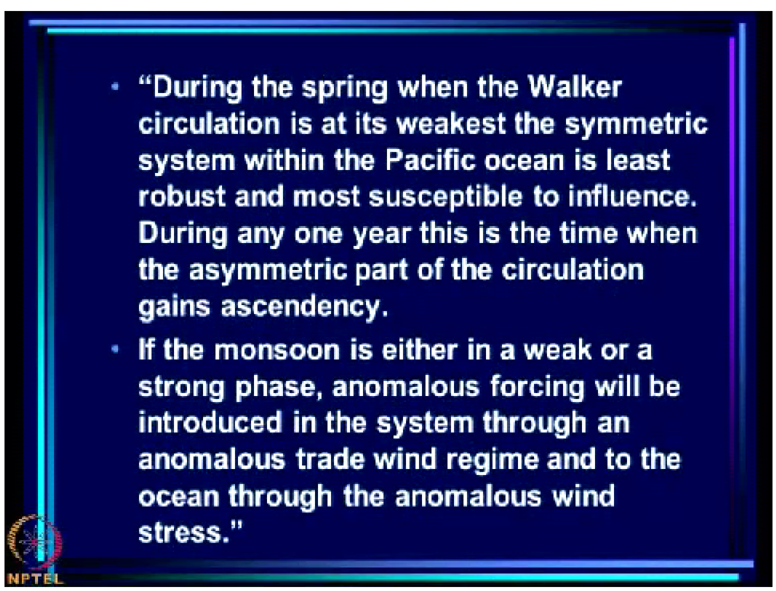

So this is the conclusion that Webster and Yang come to during the spring when the Walker circulation is at its weakest, the symmetric system within the Pacific Ocean is least robust and more susceptible to influence. During any one year, this is the time when the asymmetric part of the circulation gains ascendancy. If the monsoon is either in a weak or strong phase, anomalous forcing will be introduced in the system through an anomalous trade wind regime to the ocean through the anomalous wind.

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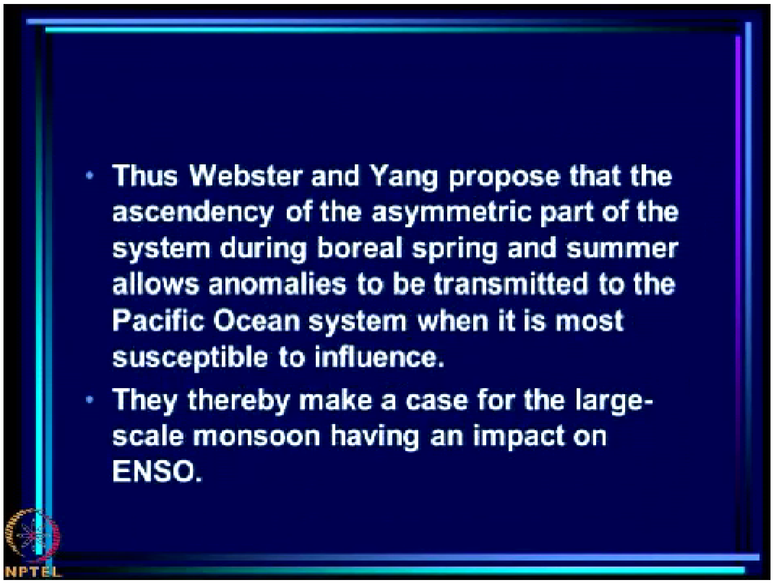

Thus Webster and Yang proposed that the ascendancy of the asymmetric part of the system during boreal spring and summer allows anomalies to be transmitted to the Pacific Ocean system when it is more susceptible to influence. They thereby make a case for the large-scale monsoon having an impact on ENSO. You know, this is the question that Sikka first raised if monsoon and ENSO are related, which is the cause and which is the effect, who is leading who and Webster and Yang seemed to favour the case for large-scale monsoons having an impact on ENSO.

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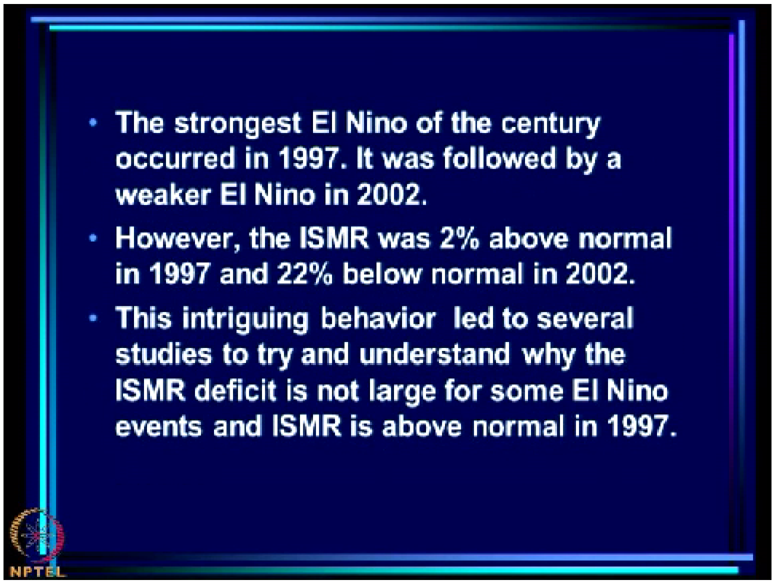

So this is the kind of thinking that is going on about what we can learn from ENSO for prediction of the monsoon and to what extent monsoon prediction will help in the prediction of ENSO itself and I guess one can summarise and say that still we have to do more work before any robust conclusions about this can be drawn and more work has to come from understanding the details of the interaction between the systems over the Indian Ocean and the Pacific Ocean, okay.

Now the strongest El Nino of the century occurred in 1997. What I am going to do now is to look at more studies of the monsoon-ENSO link, more recent studies of the monsoon-ENSO link and try and get an insight into what is happening, what is determining the variability of the monsoon. Now the strongest El Nino of the century occurred in 1997. It was followed by a weaker El Nino in 2002.

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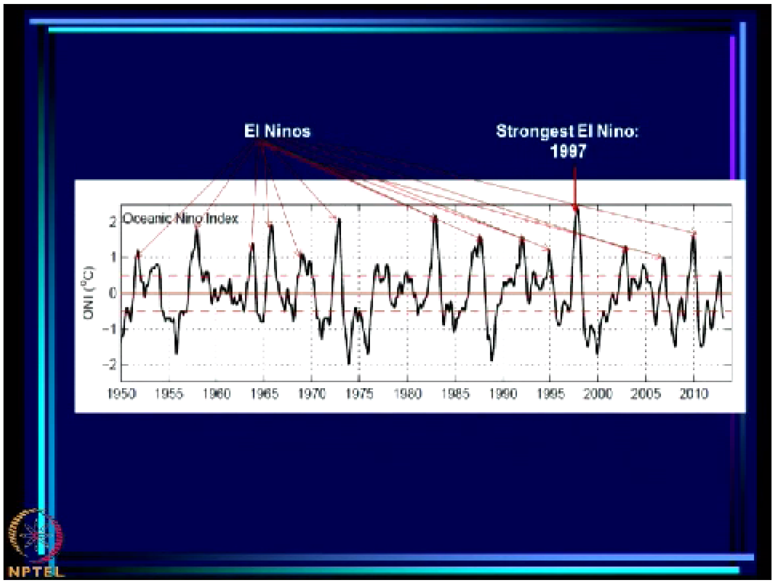

This is the ONI index that we have seen earlier. This is the strongest El Nino of the century in 1997 and after that, we got this in 2002, much weaker El Nino in 2002. You can see, it is amongst the weaker El Nino's from 1950 onwards and this was definitely the strongest El Nino in the plot, okay. But what was the impact on ISMR?

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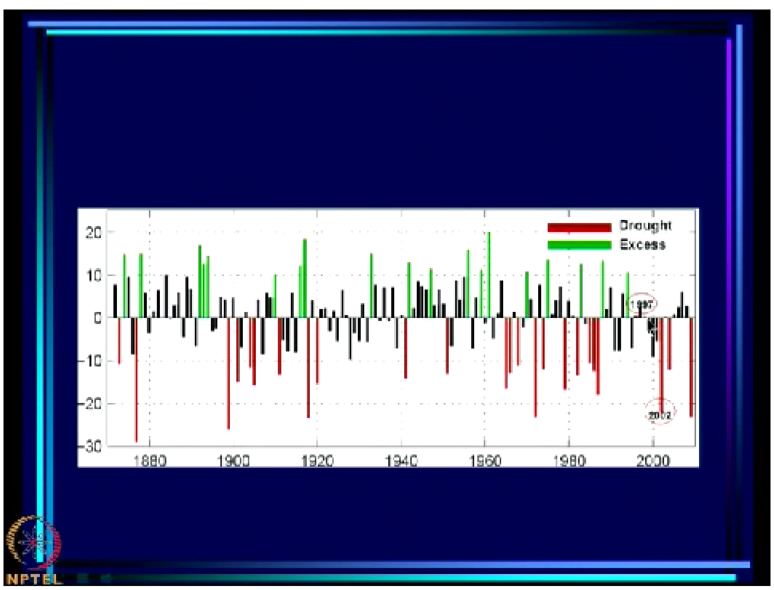

The Indian monsoon rainfall was actually, this is 1997. For 1997, Indian monsoon rainfall was slightly above normal, strongest El Nino now of the century and Indian monsoon rainfall is slightly above the normal, whereas for a relatively weak El Nino, 2002, we got a massive drought here, this is 2002. So this was a very intriguing kind of thing. So the ISMR was 2% above normal in 1997, the strongest El Nino and 22% below normal in 2002.

Now if one expects some kind of a link with the monsoon, certainly something had gone wrong with the link in these 2 years because in fact what happened was that there were small El Ninos even in the 1990s, here. See after 1988, we had a case here where we had a very good excess year in 1988 and another excess in 1994 but in between that there were small El Ninos that one does not see so much in the ONI, this is very very interesting, yes they were, they were, here they are.

There were small El Ninos that occurred after, this is 1988, La Nina is this one and after that you did have El Ninos here, but these El Ninos did not have much of an impact on the monsoon. You know the monsoon remained above normal in this period and furthermore in the strongest El Nino of the century, it again remained above normal. In fact, this lead to Krishnakumar and few others writing a paper in science which said that they believe that the link between monsoon and ENSO is actually weakened in this period.

And this is why when the ENSO of, El Nino of 2002 occurred, nobody expected this massive deficit. Because if you believe that the link between El Nino and Indian monsoon has weakened, then you expect the response to a much weaker El Nino to be much smaller than the response to the strong El Nino of 1997. But what happened here was, that you got a massive drought in 2002, okay.

Now the intriguing question is why does this happen, why are some El Nino events associated with droughts and deficits, large deficit and why are some El Nino event, however strong, not associated with deficit at all. So this is a very intriguing behaviour and this has led to several studies since 2002 to understand why the ISMR deficit is not large for some El Nino events and ISMR is actually above normal in 1997.

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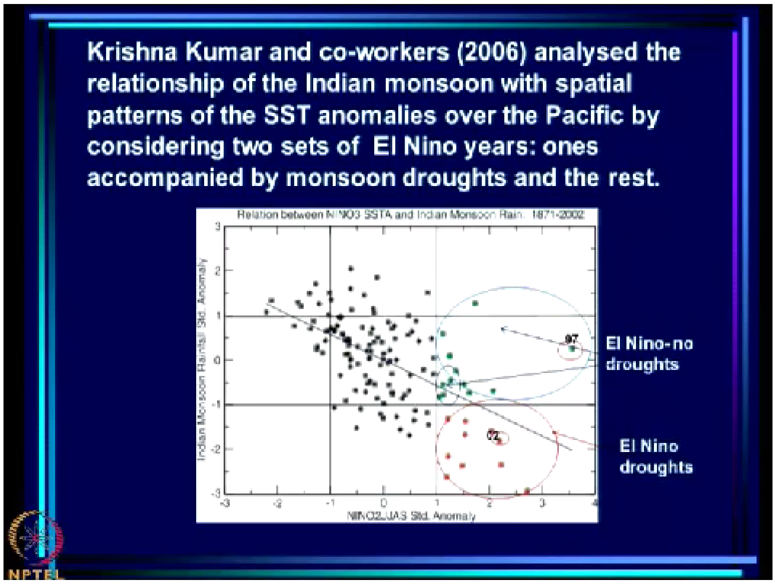

And one of these studies was by Krishna Kumar and co-workers in 2006 and they analysed the relationship of the Indian monsoon rainfall with spatial patterns of the SST anomalies over the Pacific by considering 2 sets of El Nino years, ones accompanied by monsoon droughts and the rest. So what you see here is, now they have chosen NINO 3 anomaly here, not Nino 3.4 but it does not matter, the results are rather similar and this is the rainfall here and what you see is that these are El Nino years and these are severe droughts.

All these are El Nino years here because this is Nino 3, SST anomaly being positive and these are La Nina years. They do not worry too much about La Nina. They are looking only at El Nino years and what do you find, this is the line -1 standard deviation. So this is where the deficit is of a larger magnitude than one standard deviation and these are the Indian droughts. So these are the droughts that occurred with El Nino. Now actually in all but few cases, you did have drought in…

"Professor - student conversation starts" (()) (22:50). That is right. **"Professor - student conversation ends"** In all, here. This is the 0 line here and you find that for several of the El Ninos, there was deficit but it was not a drought because the deficit width was not of a sufficient magnitude. Now the 0 line is here, you are getting some years with above normal rainfall which are El Nino years. In fact, there are 2 of them here but 1997 which is the strongest El Nino, was also above normal.

So there are a few years here which are above normal and one of them is in fact excess year and that must be 1983 because with Nino 3 that comes out as an El Nino year. So what they did is compare this set of years which are El Nino-droughts with this whole set of years which are El Nino-no droughts.

So in El Nino-no droughts they have included years which have deficit very close to -1 also as you can see, 3 or 4 of them about -0.9 standard deviation and have gone up to an excess year. So all these form the El Nino-no drought case and these are the El Nino-drought case. So these are the ones they consider as 2 classes and then asked the question what is the spatial pattern of SST corresponding to these years and what is corresponding to these years and how much do they vary.

One thing worrying about this approach is that these 2 things are separated by this -1 which is how we define the drought traditionally but you can see that some of these years are rather close together as far as ISMR is concerned and other of course are very distinct, like this excess year and these intense drought years. So the 2 classes are by no means distinct but this is how they have done it.

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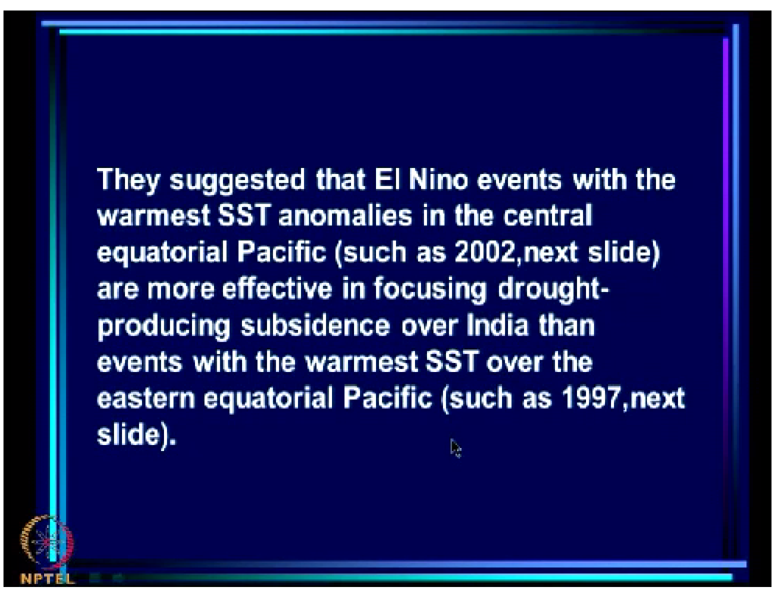

So they suggested that El Nino events with the warmest SST anomalies in the central equatorial

Pacific such as 2002, next slide, are more effective in focusing drought-producing subsidence over India than events with the warmest SST over the eastern equatorial Pacific such as 1997.

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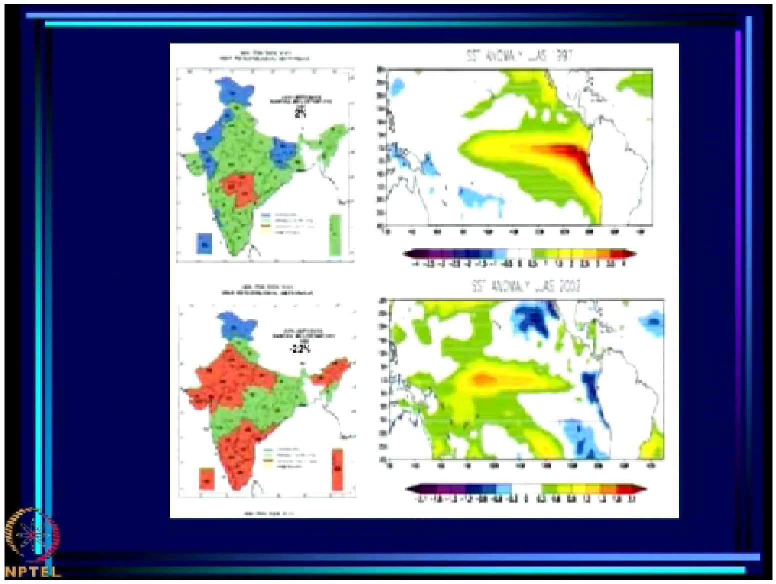

Now this is 2002, I am sorry, this in 1997 and this is 2002. You can see 1997 highest SST anomalies are in the eastern part of the coast of South America and Eastern Equatorial Pacific whereas in 2002, is primarily over Central Pacific. Now they claim that it is this difference that can be held responsible for the difference in Indian rainfall as you can see here the rainfall in 1997 is mostly green and blue. Blue is excess, green is normal.

Only one patch is red here which is deficit and so the overall rainfall all-India is +2%. Here almost entire region is red and something is normal. This is 2002 and this is a massive deficit of 22% in 2002. So Krishnakumar et al attribute these differences in all-India rainfall to these differences in SST patterns.

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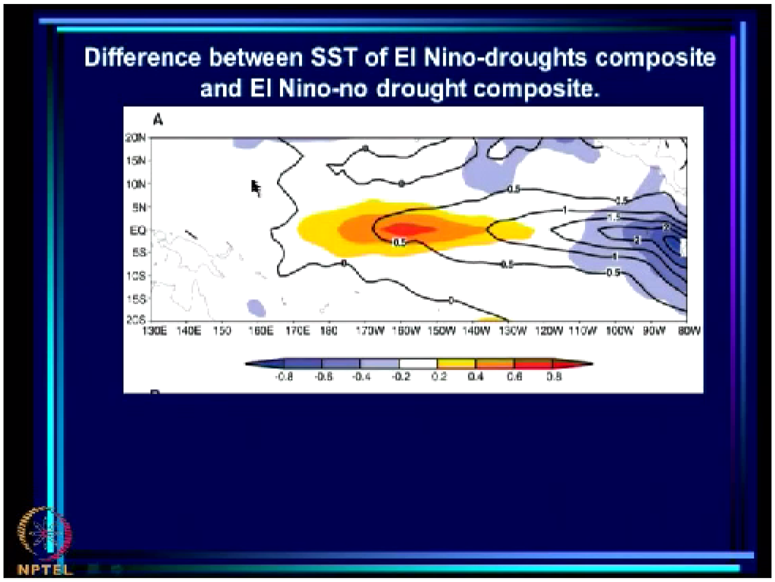

And so you say if we make composites of those 2 classes that you saw earlier, that is El Nino-droughts composite and El Nino-no drought composite and then make the difference between El Nino-droughts and El Nino-no drought, then what you find is that the drought case, the SST is much warmer over Central Pacific, remember this is a difference between the El Nino-drought and El Nino-no drought.

So given an El Nino, one is likely to get a drought rather than a no drought if SST anomalies are more positive over Central Pacific and are not so positive over East Pacific. This is their conclusion that Central Pacific is what determines whether you are going to get a drought or not. So these are the differences that you see that Central Pacific has to be much warmer than the East Pacific.

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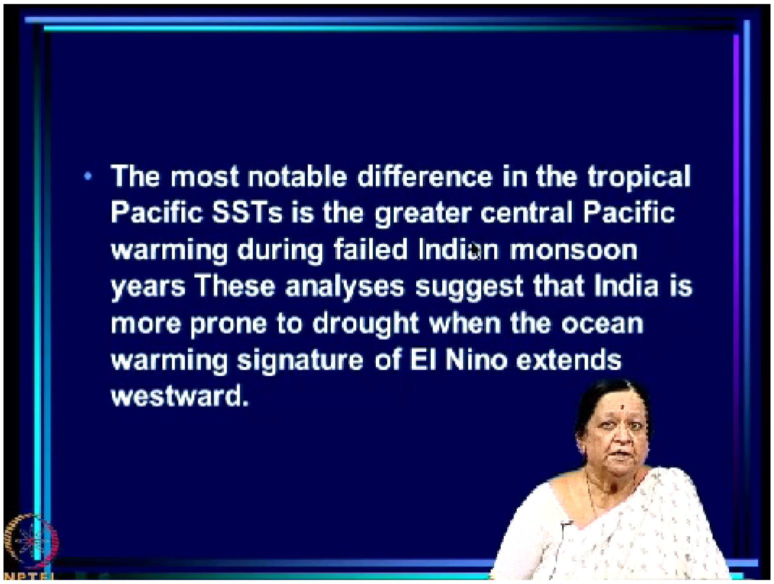

The most notable difference in the tropical Pacific SST is the greater Central Pacific warming during failed Indian monsoon years. These analyses suggest that India is more prone to drought when the ocean warming signature of El Nino extends westward. So what they are saying is that when you have a very large SST anomaly over the Central Pacific, then you are more likely to get a drought than an El Nino-no drought situation, okay.

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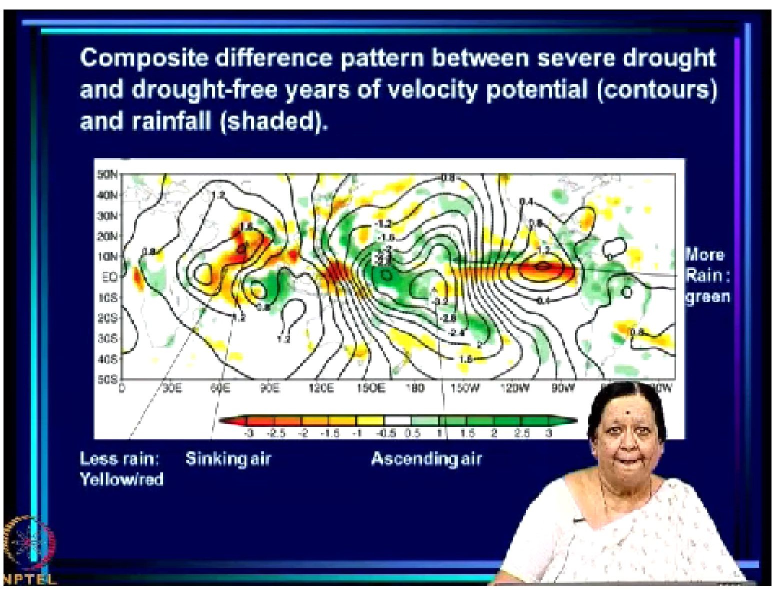

Now they have done composite difference pattern between severe drought and drought-free years of velocity potential and this is velocity potential at 200 millibar, these are contours and what it is saying is basically that air is ascending here, this is the Central Pacific and it is descending over the Indian region, okay. Notice also they have also shown the composites of the rainfall which is shaded and green means more rain and it is difficult to see perhaps.

But they are getting more rain exactly where the ITCZ is in the mean climatological pattern, between 5 to 10 north over this critical region and less rain in the equatorial region. This is an interesting part but you should also notice that drought case you are getting much more rain over the eastern part of the equatorial Indian Ocean and much less rain over the western part. So there is a big signature when you look at these differences over the equatorial Indian Ocean as well. We will in fact follow this in later part also.

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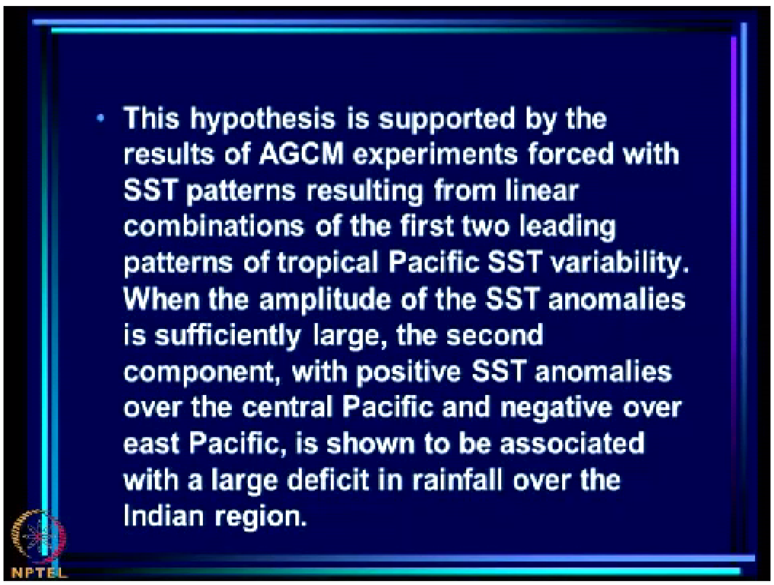

Now this hypothesis is supported by results of AGCM experiments forced with SST patterns resulting from linear combinations of the first 2 leading patterns of the tropical SST variability. So what are the leading patterns of the tropical SST variability.

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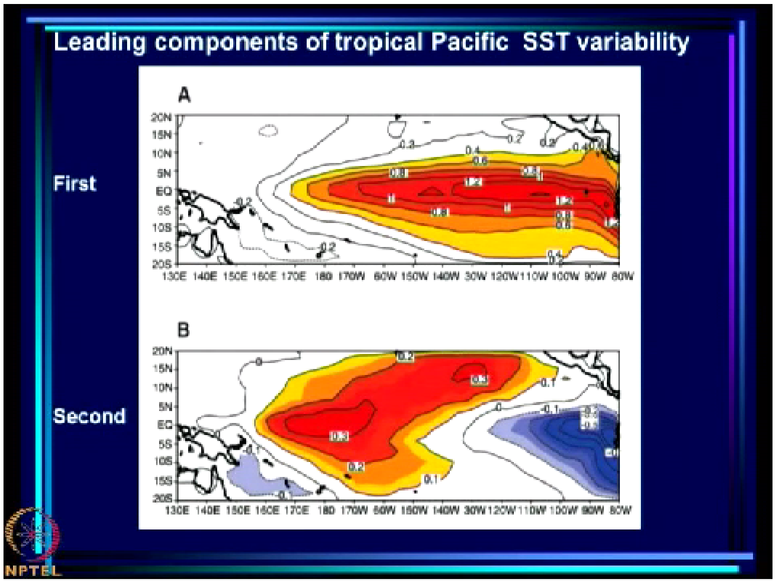

This is the first pattern. See there is a way, this is what we call empirical orthogonal function. If you want to understand the variability, say over tropical Pacific, it is possible to split it into spatial patterns such that the first pattern explains most of the variance, the second pattern, the second most and so on and so forth and these are all at right angles to one another. So the variability of the Pacific SST can be expressed in terms of these patterns.

So this is the leading patter and this is the second pattern. So the leading pattern has same sign everywhere. It is the entire equatorial tongue as well as the region of South America warming up. The second one has warming over the central part and cooling over this part, this is the second component and it is the combination of the 2 which will it explain quite a bit of the variance.

So when the amplitude of the SST anomalies are sufficiently large, the second component with positive SST anomalies over Central Pacific and negative over East Pacific is shown to be associated with a large deficit in rainfall over the Indian region. So by AGCM experiments with atmospheric general circulation model, they showed that this is associated with large deficit over India.

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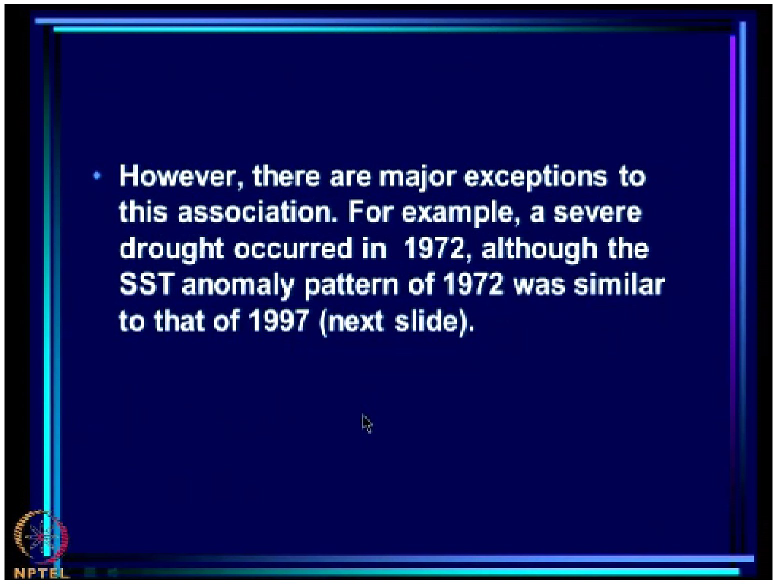

So it appeared that the case has been made that what matters is Central Pacific. However, there are major exceptions to this association. For example, a severe drought occurred in 1972, although the pattern was pretty much like the one in 1997.

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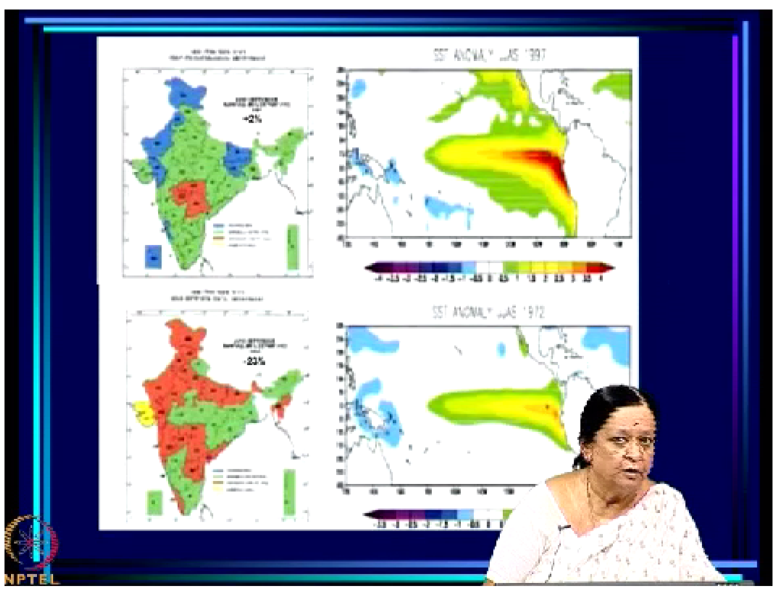

So this is 1997 that you saw before and this is 1972 and you can see again more SST, larger SST anomalies in the east than in Central Pacific pretty much the way it was in 1997 but whereas in 1997, it was 2% above normal; in 1972, ISMR was 23% below normal. It was one of the most severe droughts that we have had in the century. So it is not clear that one can actually except this explanation that they have given and jury is still out on this.

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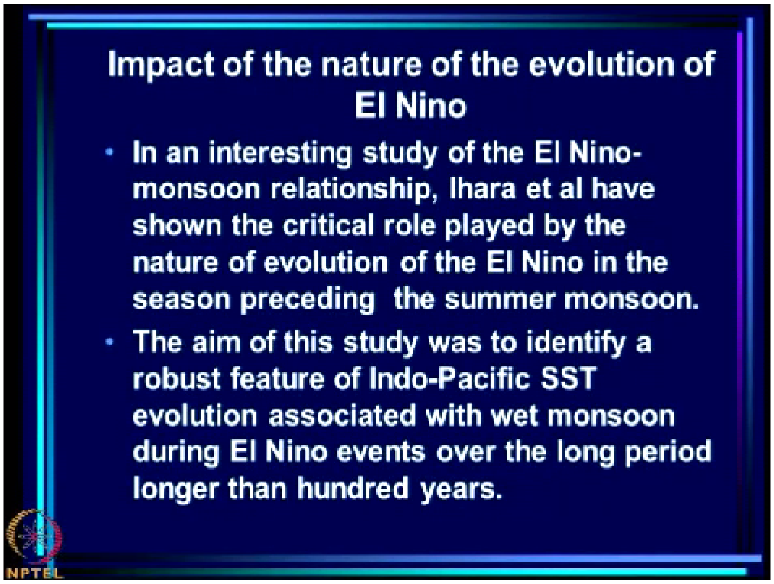

Now there is another interesting study which shows the impact of the nature of the evolution of El Nino. So what they are now saying is, not the spatial pattern associated with El Nino but also how that spatial pattern was achieved, how did the SST anomalies or SST evolved from previous winter through spring to the summer, in which monsoon rainfall occurs, that has an impact on how much deficit El Nino will create over the monsoon region.

So in an interesting study of El Nino-monsoon relationship, this is Ihara, Mark Cane and others have shown the critical role played by the nature of evolution of El Nino in the season preceding the summer monsoon. The aim of this study was to identify a robust feature of IndoPacific SST evolution associated with wet monsoon during El Nino events over the long period longer than 100 years.

So the great thing about this study is that they have used an enormously big dataset, a longtime series of sea surface temperature because amongst the authors are experts who have consolidated the data as well like Kaplan, okay.

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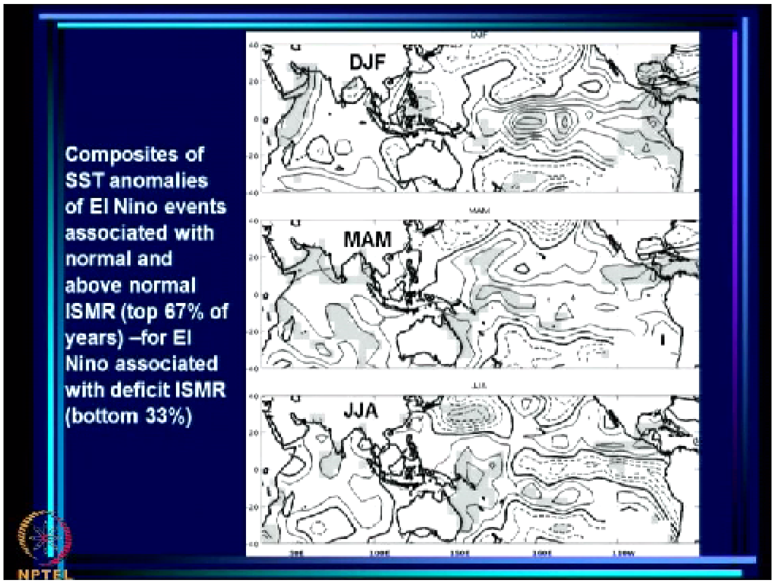

And this time they need not do what Krishna Kumar et al had done namely use a line of -1 standard deviation to define droughts and < -1 to be no droughts, rather what they have done in this is to use terciles, that is to say they use upper one-third, middle one-third and lower one-third to decide on the conditions. So there upper one-third would be excess rain, middle one-third would be normal and lower one-third would be droughts.

So this is how they have defined monsoon droughts. EL Nino, La Nina and so on have also been defined in the same way by looking at the Nina 3 index and the upper tercile defines El Nino, the middle one-third is the normal and the lower one-third, the colder part, is the La Nina. So what they have done now is made composites of SST anomalies of El Nino events associated with normal and above normal.

So now they are taking up two-third of the years and they ask the question, how many El Nino events had normal or above normal rainfall over India, that is the top 67% of the years as far as normal and above normal are concerned that is how they had defined and for El Nino associated with deficit which will be they defined deficit as the bottom one-third of the year. So they are now taking a difference between El Nino events associated with normal and above normal rainfall and El Nino events associated with droughts, okay.

And what they are finding is that the DJF here you see previous winter already warming has begun here in DJF which means that if early warming promotes the first type of years, that is to say not having a drought, then you have of course warming continuing in MAM and by June, July, August, you have warming largely restricted to the Central Pacific relative to the other class of course.

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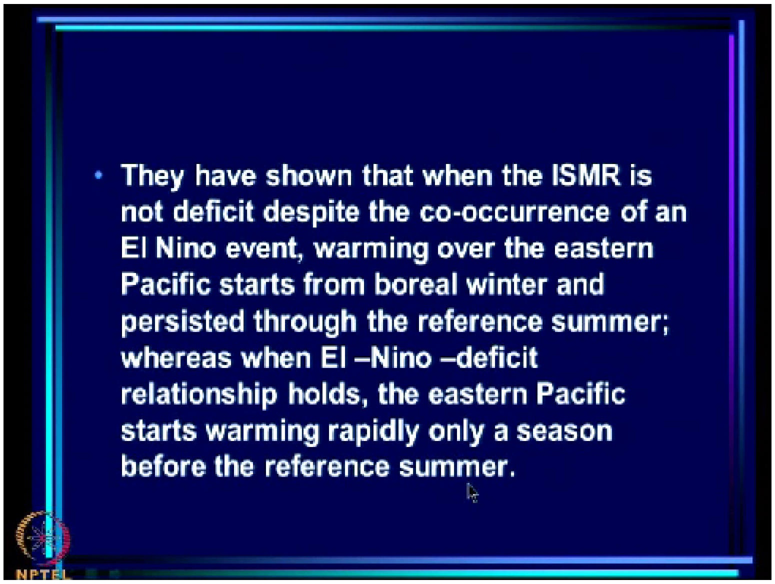

So they show that when the ISMR is not deficit, despite the co-occurrence of an El Nino event, warming over the eastern Pacific starts from boreal winter and persist through the reference summer, whereas El Nino deficit relationship holds, the eastern Pacific starts warming rapidly only a season before the reference summer. See this is the difference. So this is another very interesting idea that to understand the impact of El Nino, we should, on the monsoon.

It is important also to look at how the anomalies of SST or how the sea surface temperature over the Pacific evolves from the previous winter through spring to the summer in which the monsoon rain occurs. There are then many of these ideas floating around, the patterns at the mature phase of El Nino matter, how the El Nino has evolved, matter and so on and so forth and as I said jury is still out on what determines the impact of El Nino on the monsoon, okay.

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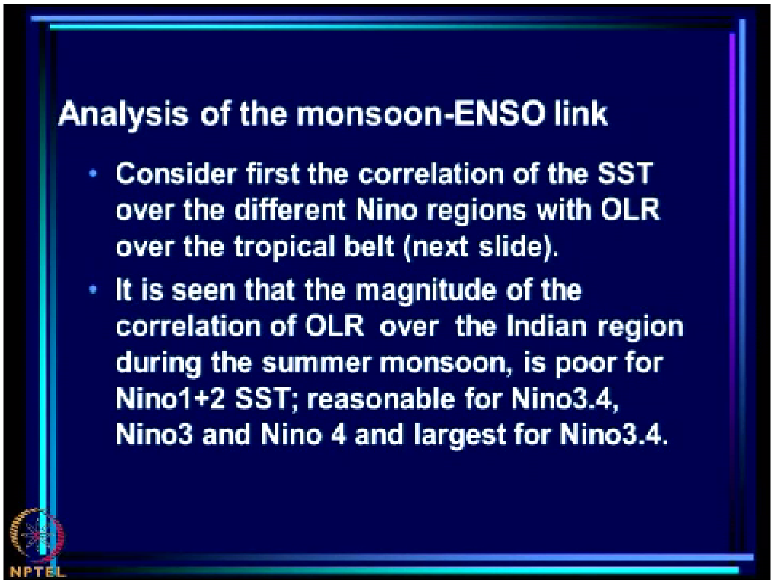

Now let us look at some data that is available and try and get some insight into the monsoon-ENSO link with all these studies taken as a background. So first thing we say is, what is the correlation of SST over the different Nino regions with OLR over the entire tropical belt, right. We want to see what is the influence of ENSO.

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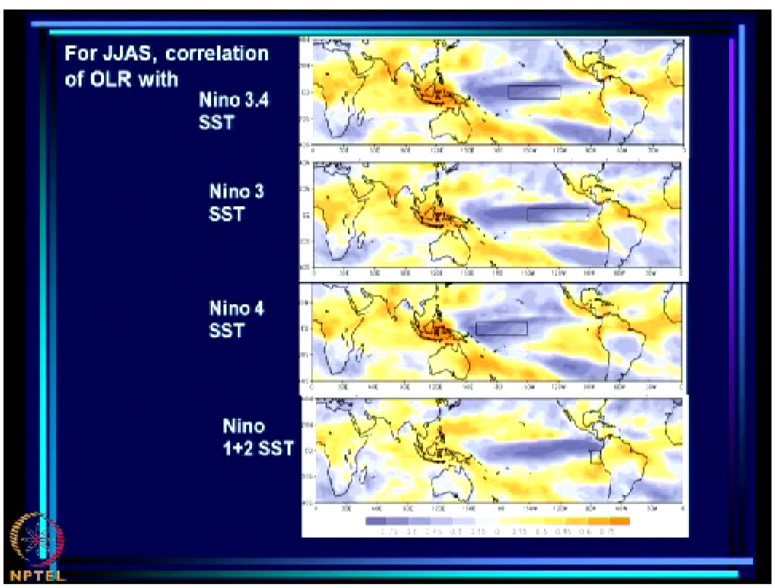

Now ENSO can be measured with many indices as you know Nino 3.4, Nino 3, Nino 4 and Nino 1+2, we have defined these earlier and what we do is we ask the question that you take any of these indices which are just the SST anomaly over the region that is marked and you ask the question how is the OLR everywhere related to the SST anomaly. Now the first thing you notice is irrespective of which Nino region you consider here over the equatorial region, that is to say

Nino 3.4, Nino 3, or Nino 4, you do get opposite sign suppression here.

In other words, if you have warming here, then you will get convection here and suppression of convection here. So there is a very large region over which convection gets suppressed. It is the African, Asian, as well as this west Pacific region and this is true of Nino 3 and also of Nino 3.4. Now if you look at Nino 1+2, then you find that when SST anomalies increase here, you get a belt which is more or less along the equator where you have flaring occurring.

And it is going almost all the way from west Pacific to east pacific zonal belt and north of it, you are getting suppression. So what has happened is that the ITCZ has come southward, this is what this suggests when you have intensification of convection here and suppression here. This means that there is a movement towards the equator of the ITCZ and in addition to that, of course you get the suppression that was mentioned. Notice that the highest suppression seems to occur with Nino 3.4 SST, okay.

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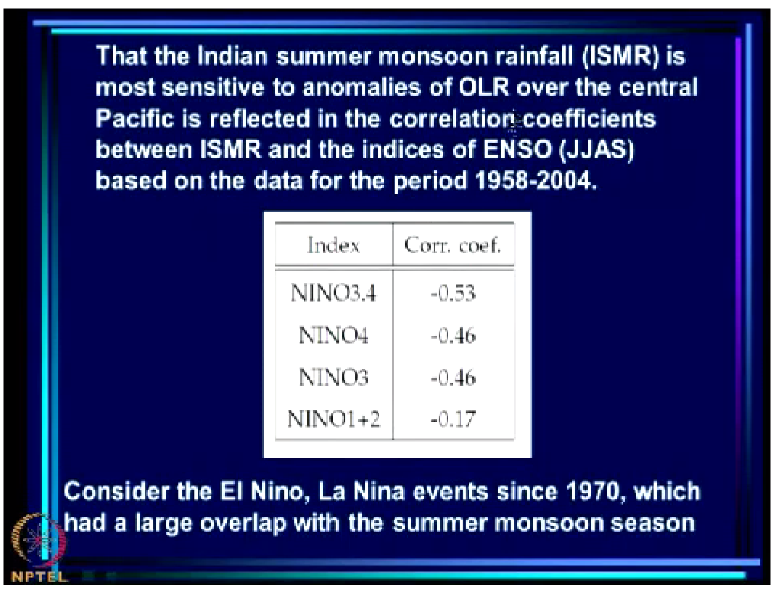

That the Indian summer monsoon rainfall is most sensitive to anomalies of OLR over the central Pacific is reflected in the correlation coefficient between ISMR and the indices of ENSO based on the period 1958-2004 and we have index Nino 3.4, correlation is -0.53. Nino 4, it is -0.46. Nino 3, -0.46. So comparable and Nino 1+2 is very small. So as we saw the correlation is good and comparable for Nino 3 and 4 and seems to be highest for this period for a Nino 3.4.

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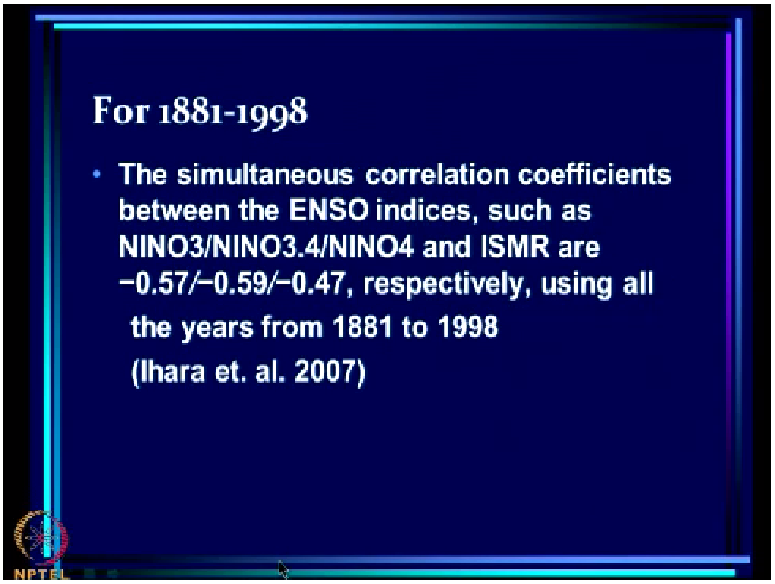

Now for 1981 to 1998, the simultaneous correlation coefficients between the ENSO indices such as Nino 3, Nino 3.4, Nino 4 and ISMR are-0.57,-0.59. So if you take a much longer period than we took there, then Nino 3.4 and Nino 4 correlations with ISMR seemed comparable but Nino 4 is somewhat smaller. So Nino 3 and Nino 3.4 are comparable but Nino 4 is somewhat smaller if we used all those years, okay.

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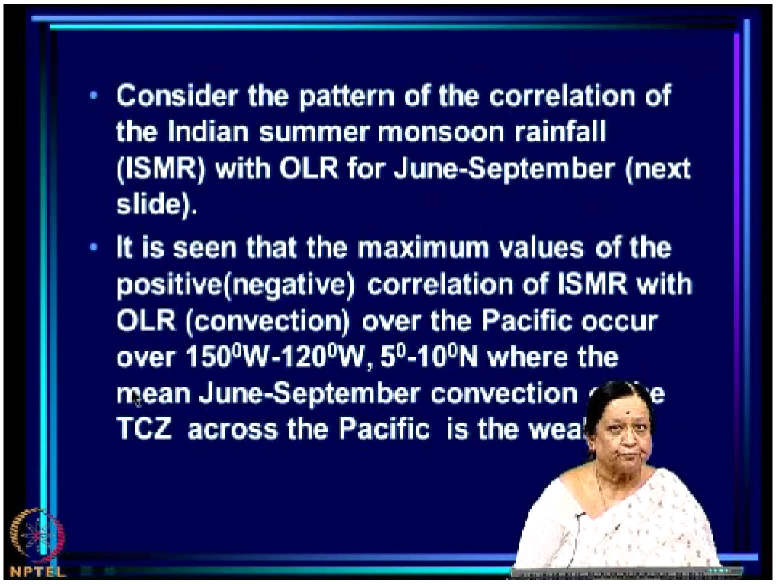

Now you consider the pattern of correlation of the Indian summer monsoon rainfall which is ISMR with OLR over the entire region.

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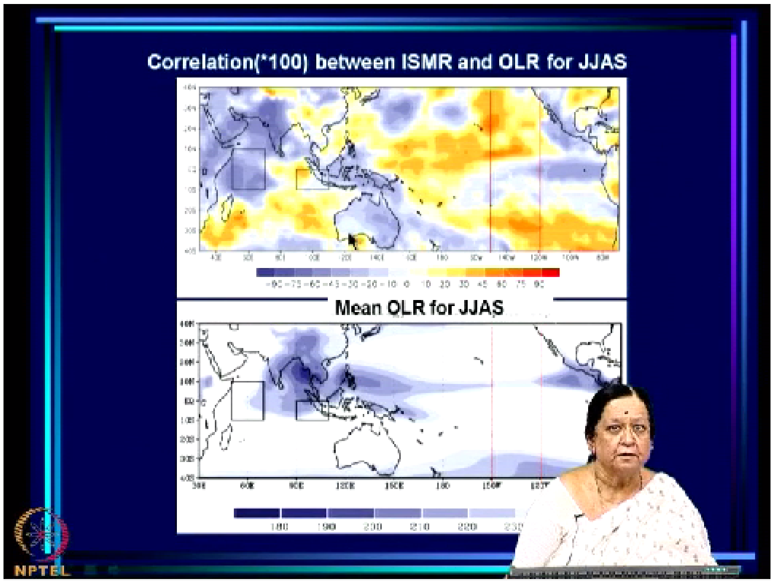

So this is the correlation of Indian summer monsoon with OLR and obviously you have a very large negative correlation with OLR here over the Indian region. Now let us go to the Pacific. This is the belt over which you get enhancement of convection over the Pacific and you find that the maximum magnitude of the correlation is occurring here.

And this is where, this is the mean OLR for JJAS, this is where you know you had this weak link between the ITCZ here and the ITCZ here. So maximum correlation of Indian monsoon rainfall occurs with this. You may also remember that we had maximum variation between El Nino and La Nina in this region itself. During El Nino, this link gets strengthened and during La Nina, there is hardly any convection here.

So it is this region which is very critical and the linking of the ITCZ and making the ITCZ strong right across the Pacific seems to have a negative impact on Indian monsoon rainfall. So it is very interesting that what turned out to be a difference between El Nino and La Nina composite, it is exactly that region OLR which is most highly correlated in terms of magnitude with Indian rainfall, okay.

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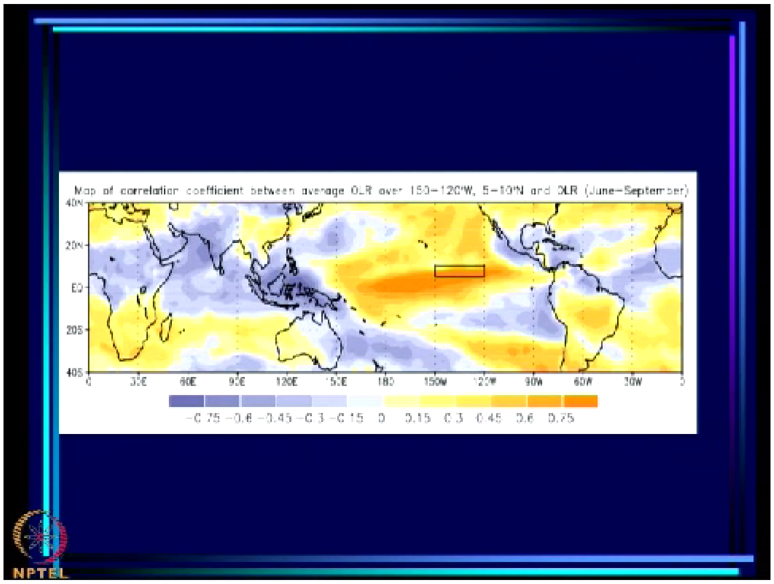

So this is the region to which Indian monsoon rainfall seems most sensitive. This is the convection over this region is highly correlated with Indian monsoon rainfall, of course negatively correlated but the magnitude of correlation is very high for this region here, okay. Now if we look at the OLR of this region with OLR everywhere, then you find that this region make part of the Pacific system.

There is a coherent variation across this part of the Pacific and opposite sign of variation over west Pacific and the Indian region. So this is the kind of correlation we get.

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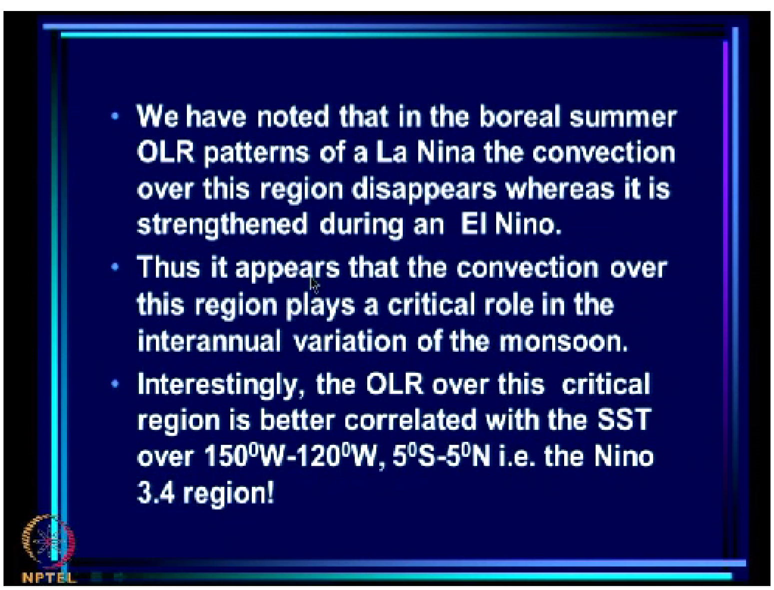

So we have noted that in the boreal summer OLR patterns of La Nina, the convection over this region disappears whereas it is strengthened during an El Nino. Thus it appears that the convection over the region plays a critical role in the interannual variation of the monsoon. Interestingly, the OLR over this critical region is better correlated with SST over the Nino 3.4.

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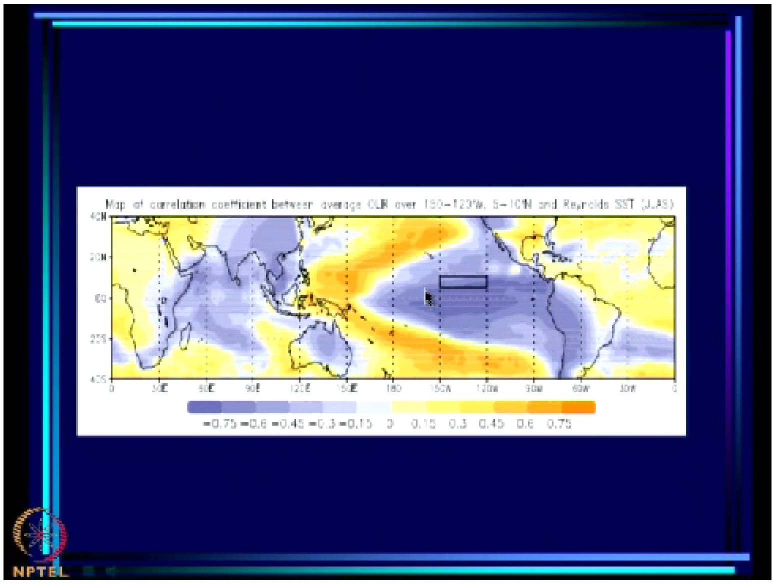

That is SST over the equatorial region to the south here, then with the SST over 150 west, 5 south to 5 north that is Nino 3.4 region. So this is very interesting that SST over the region to the south of it is what seems to be determining the OLR here. So that is why Nino 3.4 SST is so very important in this, okay.

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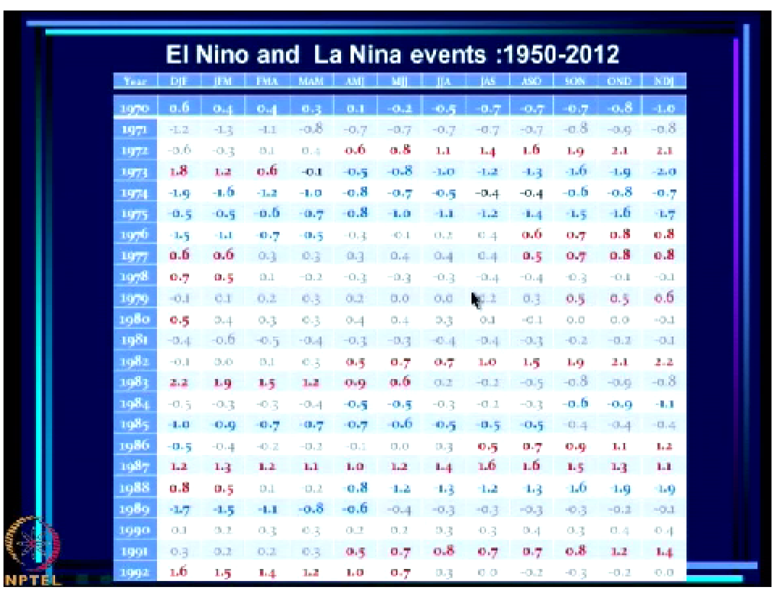

El Nino and La Nina events :1950-2012

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
1970	0.6	0.4	0.4	0.3	0.1	-0.2	-0.5	-0.7	-0.7	-0.7	-0.8	-1.0
1971	-1.2	-1.3	-1.1	-0.8	-0.7	-0.7	-0.7	-0.7	-0.7	-0.8	-0.9	-0.8
1972	-0.6	-0.3	0.1	0.4	0.6	0.8	1.1	1.4	1.6	1.9	2.1	2.1
1973	1.8	1.2	0.6	-0.1	-0.5	-0.8	-1.0	-1.2	-1.3	-1.6	-1.9	-2.0
1974	-1.9	-1.6	-1.2	-1.0	-0.8	-0.7	-0.5	-0.4	-0.4	-0.6	-0.8	-0.7
1975	-0.5	-0.5	-0.6	-0.7	-0.8	-1.0	-1.1	-1.2	-1.4	-1.5	-1.6	-1.7
1976	-1.5	-1.1	-0.7	-0.5	-0.3	-0.1	0.2	0.4	0.6	0.7	0.8	0.8
1977	0.6	0.6	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.7	0.8	0.8
1978	0.7	0.5	0.1	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.3	-0.1	-0.1
1979	-0.1	0.1	0.2	0.3	0.2	0.0	0.0	[illegible]	0.3	0.5	0.5	0.6
1980	0.5	0.4	0.3	0.3	0.4	0.4	0.3	0.1	-0.1	0.0	0.0	-0.1
1981	-0.4	-0.6	-0.5	-0.4	-0.3	-0.3	-0.4	-0.4	-0.3	-0.2	-0.2	-0.1
1982	-0.1	0.0	0.1	0.3	0.5	0.7	0.7	1.0	1.5	1.9	2.1	2.2
1983	2.2	1.9	1.5	1.2	0.9	0.6	0.2	-0.2	-0.5	-0.8	-0.9	-0.8
1984	-0.5	-0.3	-0.3	-0.4	-0.5	-0.5	-0.3	-0.2	-0.3	-0.6	-0.9	-1.1
1985	-1.0	-0.9	-0.7	-0.7	-0.7	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4
1986	-0.5	-0.4	-0.2	-0.2	-0.1	0.0	0.3	0.5	0.7	0.9	1.1	1.2
1987	1.2	1.3	1.2	1.1	1.0	1.2	1.4	1.6	1.6	1.5	1.3	1.1
1988	0.8	0.5	0.1	-0.2	-0.8	-1.2	-1.3	-1.2	-1.3	-1.6	-1.9	-1.9
1989	-1.7	-1.5	-1.1	-0.8	-0.6	-0.4	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1
1990	0.1	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.4	0.3	0.4	0.4
1991	0.3	0.2	0.2	0.3	0.5	0.7	0.8	0.7	0.7	0.8	1.2	1.4
1992	1.6	1.5	1.4	1.2	1.0	0.7	0.3	0.0	-0.2	-0.3	-0.2	0.0

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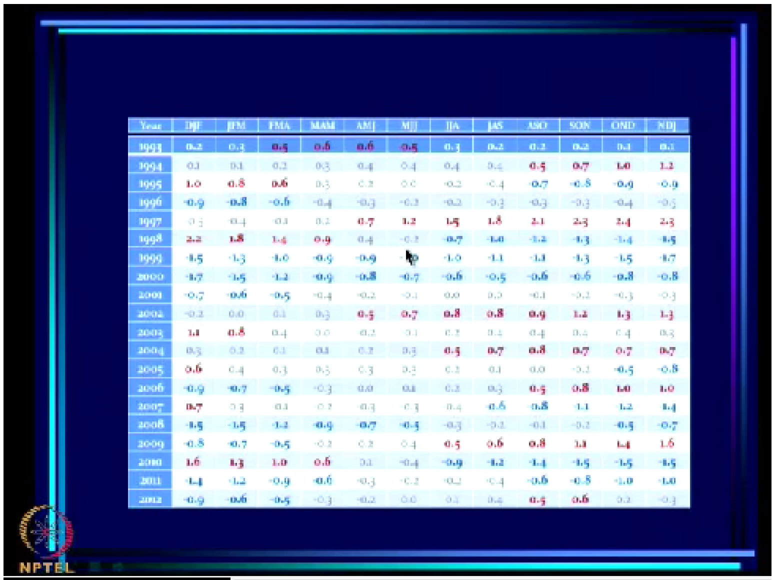

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
1993	0.2	0.3	0.5	0.6	0.6	0.5	0.3	0.2	0.2	0.2	0.1	0.1
1994	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.5	0.7	1.0	1.2
1995	1.0	0.8	0.6	0.3	0.2	0.0	-0.2	-0.4	-0.7	-0.8	-0.9	-0.9
1996	-0.9	-0.8	-0.6	-0.4	-0.3	-0.3	-0.2	-0.3	-0.3	-0.3	-0.4	-0.5
1997	-0.5	-0.4	-0.1	0.2	0.7	1.2	1.5	1.8	2.1	2.3	2.4	2.3
1998	2.2	1.8	1.4	0.9	0.4	-0.2	-0.7	-1.0	-1.2	-1.3	-1.4	-1.5
1999	-1.5	-1.3	-1.0	-0.9	-0.9	[illegible]	-1.0	-1.1	-1.1	-1.3	-1.5	-1.7
2000	-1.7	-1.5	-1.2	-0.9	-0.8	-0.7	-0.6	-0.5	-0.6	-0.6	-0.8	-0.8
2001	-0.7	-0.6	-0.5	-0.4	-0.2	-0.1	0.0	0.0	-0.1	-0.2	-0.3	-0.3
2002	-0.2	0.0	0.1	0.3	0.5	0.7	0.8	0.8	0.9	1.2	1.3	1.3
2003	1.1	0.8	0.4	0.0	-0.2	-0.1	0.2	0.2	0.4	0.4	0.4	0.3
2004	0.3	0.2	0.1	0.1	0.2	0.3	0.5	0.7	0.8	0.7	0.7	0.7
2005	0.6	0.4	0.3	0.3	0.3	0.3	0.2	0.1	0.0	-0.2	-0.5	-0.8
2006	-0.9	-0.7	-0.5	-0.3	0.0	0.1	0.2	0.3	0.5	0.8	1.0	1.0
2007	0.7	0.3	-0.1	-0.2	-0.3	-0.3	-0.4	-0.6	-0.8	-1.1	-1.2	-1.4
2008	-1.5	-1.5	-1.2	-0.9	-0.7	-0.5	-0.3	-0.2	-0.1	-0.2	-0.5	-0.7
2009	-0.8	-0.7	-0.5	-0.2	0.2	0.4	0.5	0.6	0.8	1.1	1.4	1.6
2010	1.6	1.3	1.0	0.6	0.1	-0.4	-0.9	-1.2	-1.4	-1.5	-1.5	-1.5
2011	-1.4	-1.2	-0.9	-0.6	-0.3	-0.2	-0.2	-0.4	-0.6	-0.8	-1.0	-1.0
2012	-0.9	-0.6	-0.5	-0.3	-0.2	0.0	0.1	0.4	0.5	0.6	0.2	-0.3

So now we look at El Nino, La Nina events to try and see what are the signatures in terms of Pacific as well as Indian region and I will not, this is simply the ONI index.

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And what I have done is from 1970, looked at those events which have at least 3 months satisfying the criteria of ONI > 0.5 during the summer monsoon season because our focus is the summer monsoon season. So these are the events from the 1970s and from 1980s, these are all in the satellite era. These are El Nino and La Nina read off from the ONI.

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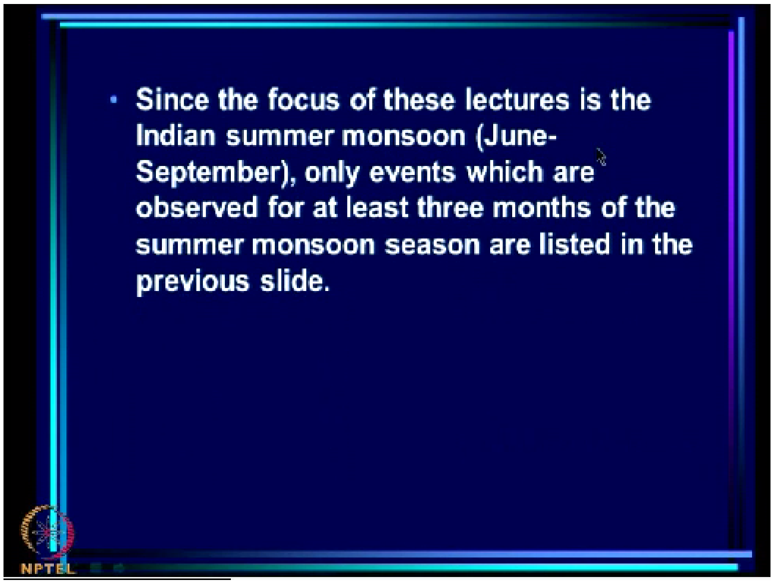

So since the focus of these lectures is the monsoon, June to September, only events which are observed for at least 3 months of the summer monsoon season are listed in the previous slide. So the first amongst them is 1982 of course, that is the first in the satellite era and I do not have any satellite data for 1972.

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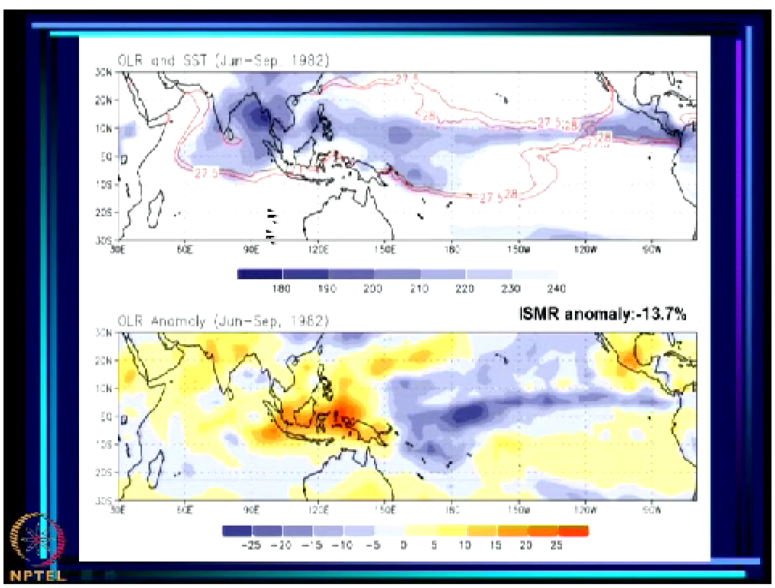

So if we look at 1982 then, what you see is in fact these are contours of SST and what you see is that the 28 degrees is now running right across in a coherent way and in this narrow critical region, the entire zone over 28 is actually low OLR region. Here only part of it is covered by low OLR but here, the entire one is covered and what you see here is the anomaly pattern here and you see that there is intense convection over here and suppression of convection all over here.

But notice in this case interestingly, the suppression of convection seems maximum over the equatorial latitudes, equatorial region here of west Pacific as well as Indian Ocean. This is very interesting. See where the suppression would be maximum within this longitudinal band varies from year to year.

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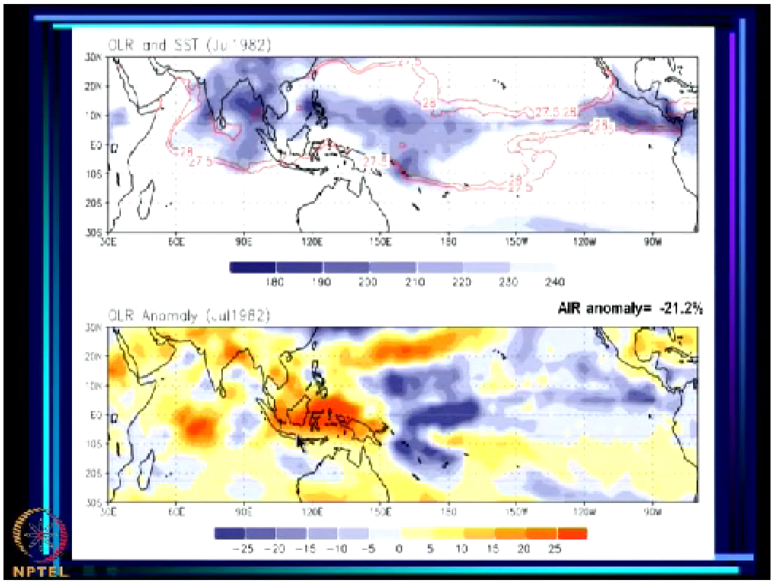

Now this is one of the months of the summer monsoon of 1982 and we find that actually there is intense convection here, this is the anomaly and this is the actual. This is July 1982 where we had a very large deficit in Indian monsoon rainfall, July 1982 deficit for all-India rainfall was -21% and what you see here is an enormous suppression of rain here, this part. Enhancement of rain over the eastern equatorial Indian Ocean and suppression over the western equatorial Indian Ocean, this is interesting.

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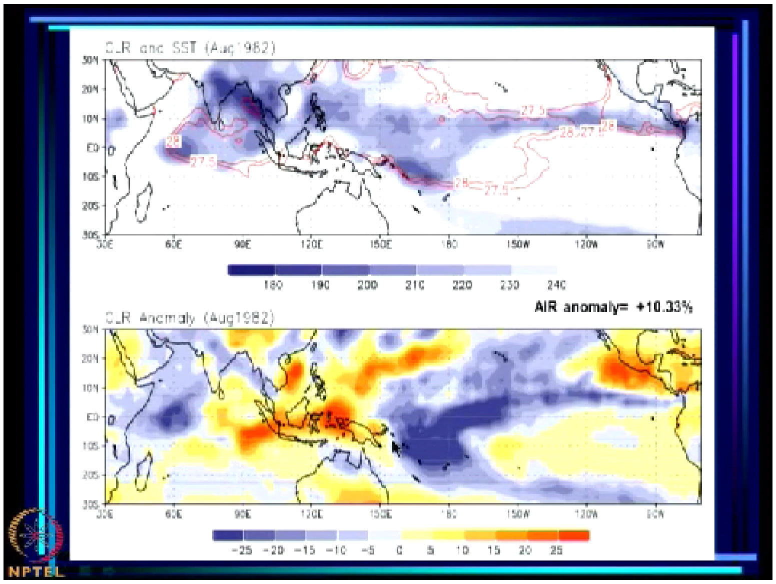

Now the next slide shows the next month and the next month, this is still the way it was, extremely intense convection over the Pacific but what has happened is that the suppression which was only up to here, now suppression of convection occurs also over EEIO, eastern equatorial Indian Ocean and there is enhancement of convection over western equatorial Indian Ocean. So there has been a big change over the Indian Ocean.

Here, it was orange here and blue here and instead of that it has just changed the colours. So you have enhancement of convection here, suppression of convection here and over the Pacific, there are not too many changes as you can see. You have this huge band of convection here and opposite here and pretty much a similar picture over here. So there has been and for August in fact, +10% is the anomaly over India and you can see that in the pattern here.

So it does appear that some changes in the Indian Ocean can lead to changes in this Indian rainfall.

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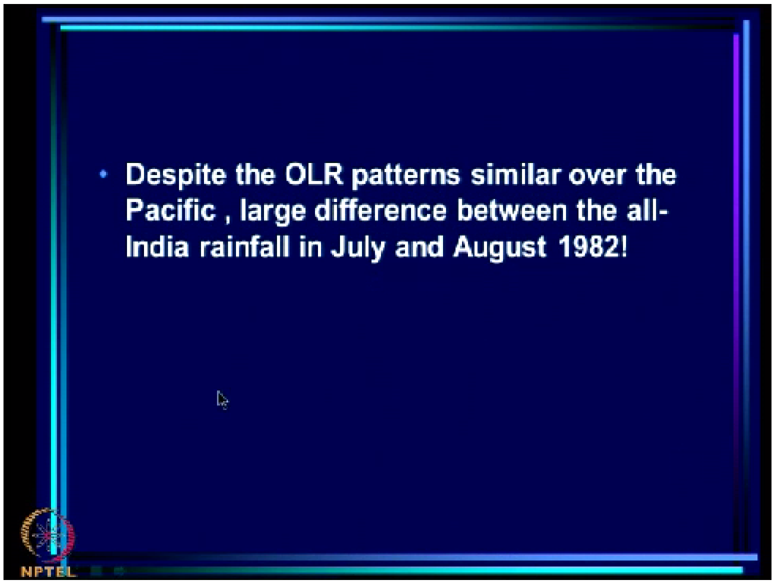

So we will come back to this. So despite the OLR patterns being similar over Pacific, there are very large differences between the all-India rainfall in July and August.

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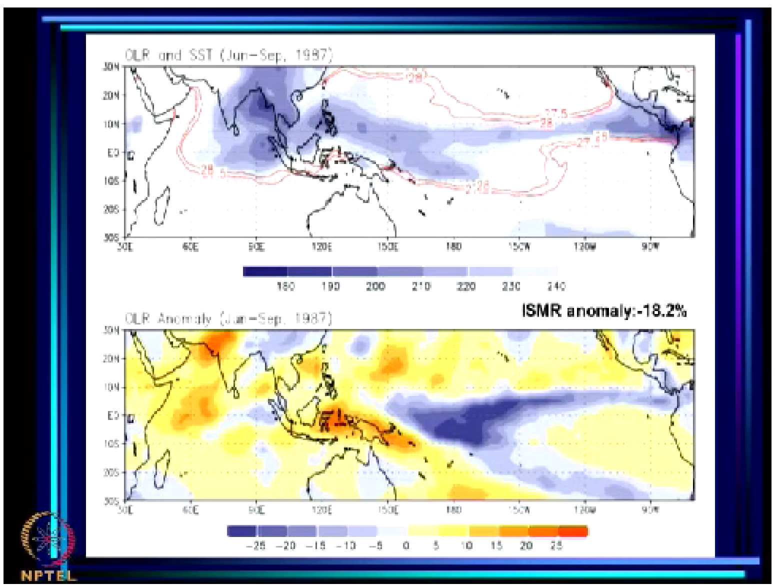

Now we come to 1987 and in 1987, this is June to September and there was a intensification over the Pacific as you expect for El Nino.

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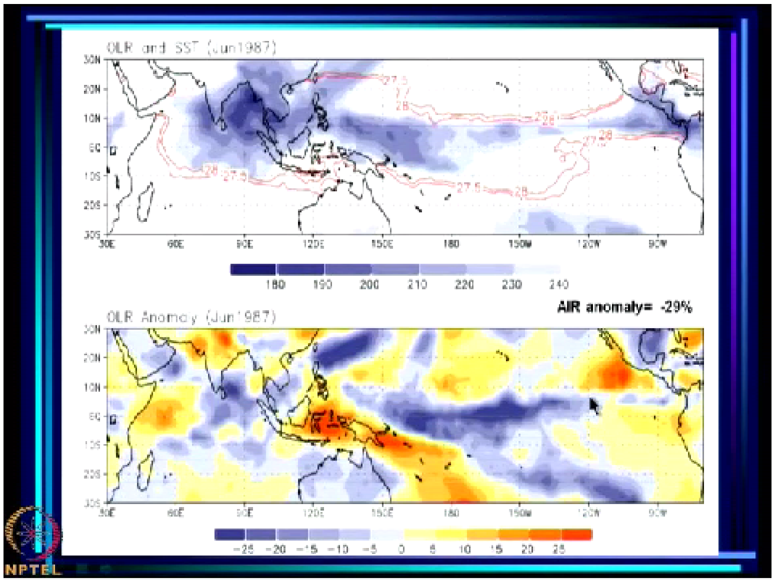

This is the case where we had intense drought, this was June 1987 when the anomaly was almost -30% and again we get blue here and yellow and orange here in addition to having this enhancement here.

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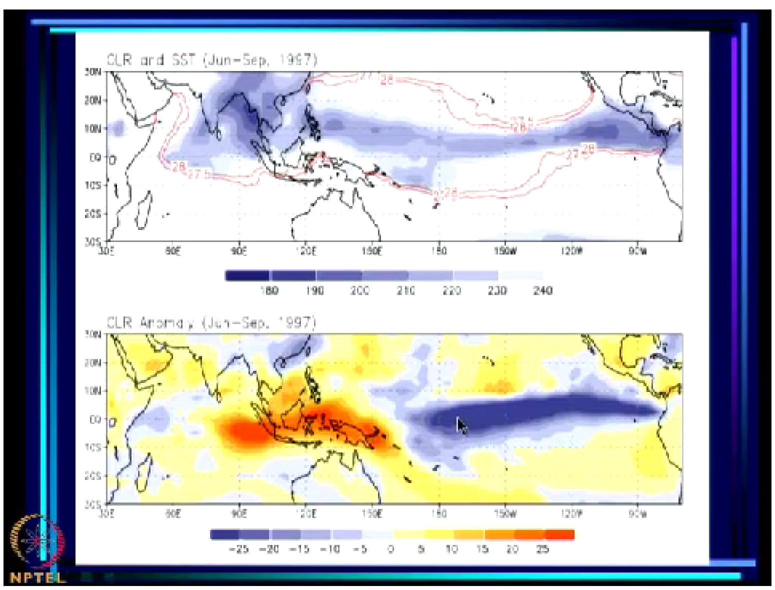

And this is a case of 1997 and you see this is the reverse of what you saw in 1987. You have enhancement and you have suppression of convection over this entire belt from central Indian Ocean, equatorial Indian Ocean, right up to west Pacific and you have enhancement of convection here and you have normal rain here.

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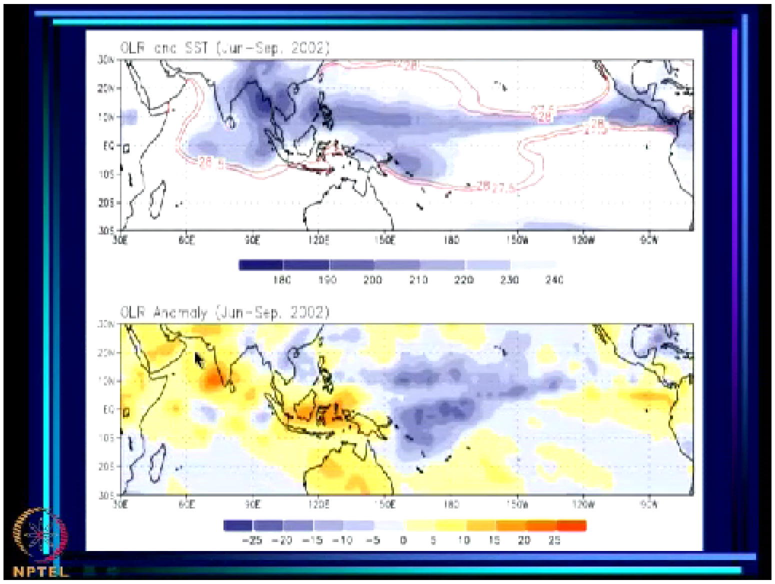

Now June to September 2002, I show these because we have mentioned those 2 cases. Here actually the Pacific convection is not as intense because after the El Nino was very much stronger in 1997 and so the intensity of convection over Pacific is not as much but you find that enormous suppression everywhere here of convection including over the Indian region.

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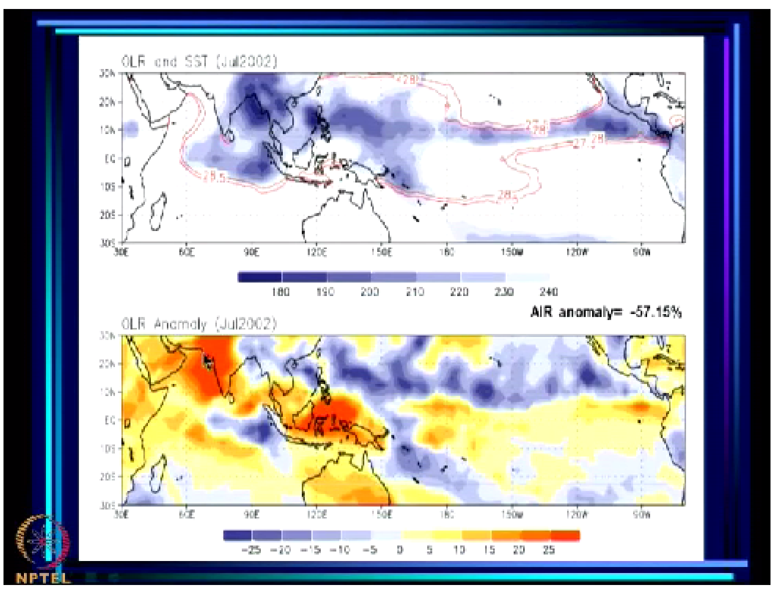

And if we compare some months, this in July 2002 in which case the drought was more than 50% deficit over India and in this case, you see a huge enhancement of convection over east and suppression over west. So you have enhancement of convection right across the Pacific as well as over the east equatorial Indian Ocean, contrast it with June 1997 where actually the anomaly was positive, 11% excess rain.

And what you get is that you have enhancement over west, suppression over east and of course, so there is a suppression over this large part of west Pacific and east equatorial Indian Ocean and enhancement here.

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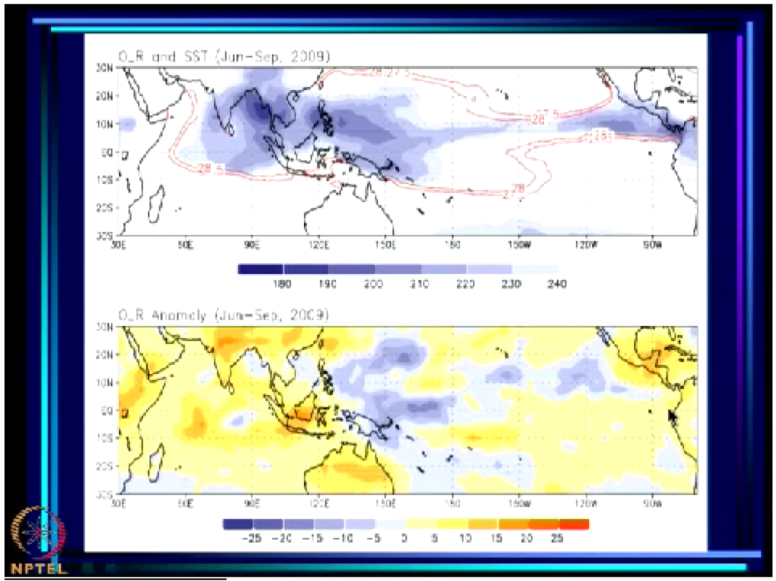

So 2009 again a drought and I will show you a case, again June 2009, where we had a very large deficit over Indian region and June 2009, you can see, El Nino was not that well developed but you do have this bad sign of having enhancement of convection here.

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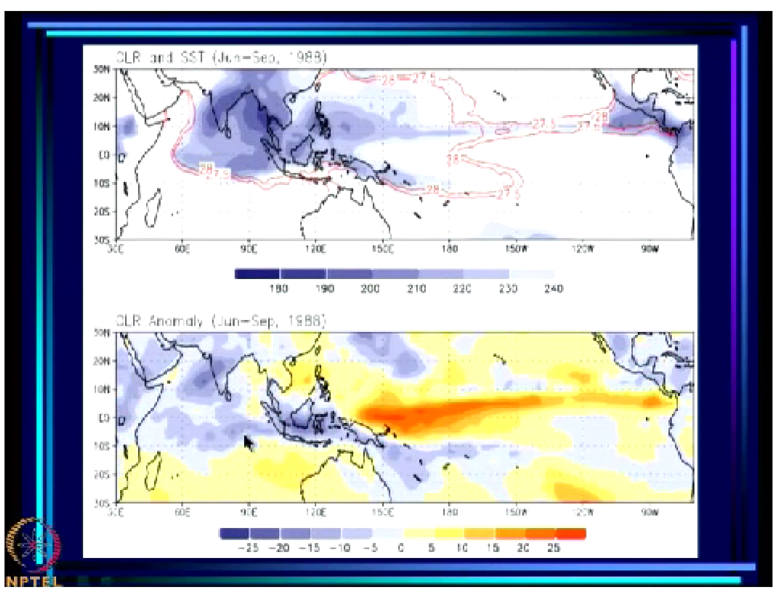

So one can see that every year is different, this is La Nina now. La Nina means suppression of convection here and enhancement of convection everywhere and the rainfall was good in 1988.

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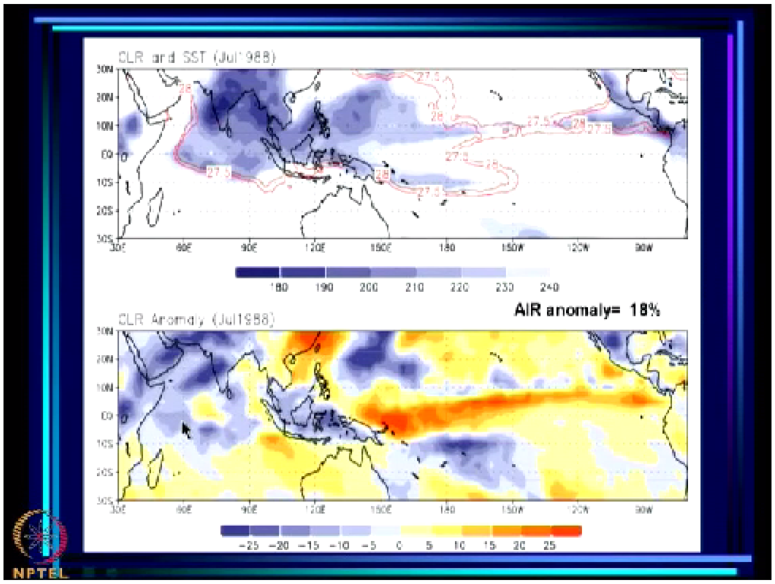

And this is a case in which we had 18% excess and then suppression of convection here and there is also suppression of convection over the East equatorial Indian Ocean.

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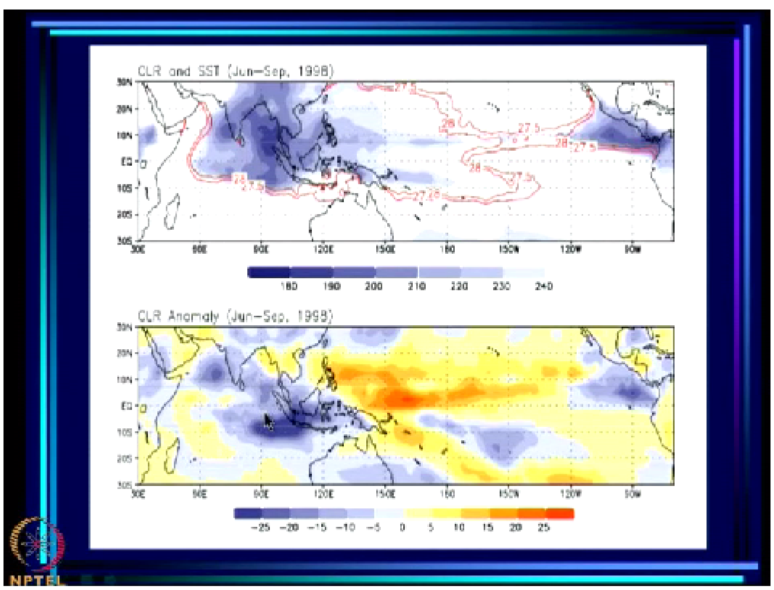

So it appears that it is a combination of conditions over the Pacific and the equatorial Indian Ocean that determine the fate of the monsoon and in the next set of lectures, just as we have focused on what happens over the Pacific here, we will look at what happens over the Indian Ocean and then with both these understanding, the coupled atmosphere Pacific Ocean system and understanding the coupled atmosphere Indian Ocean system under a belt.

We may be able to make more sense of the variation of the Indian monsoon. Thank you.

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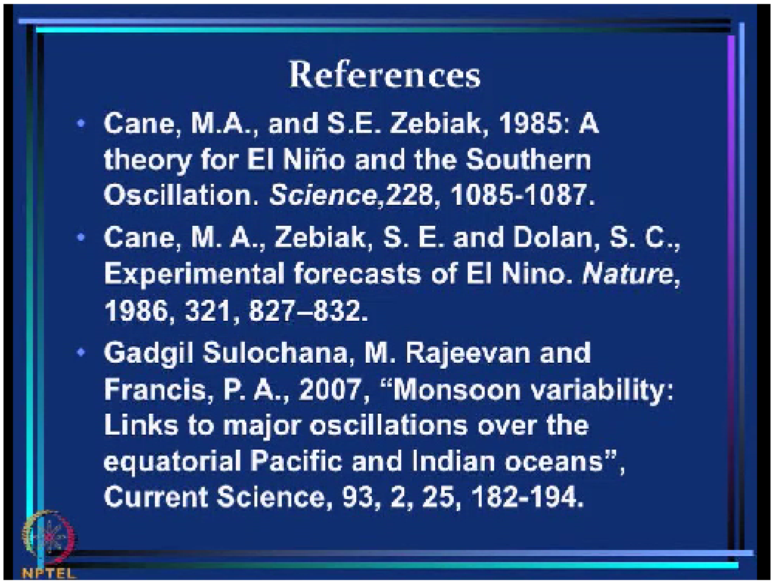

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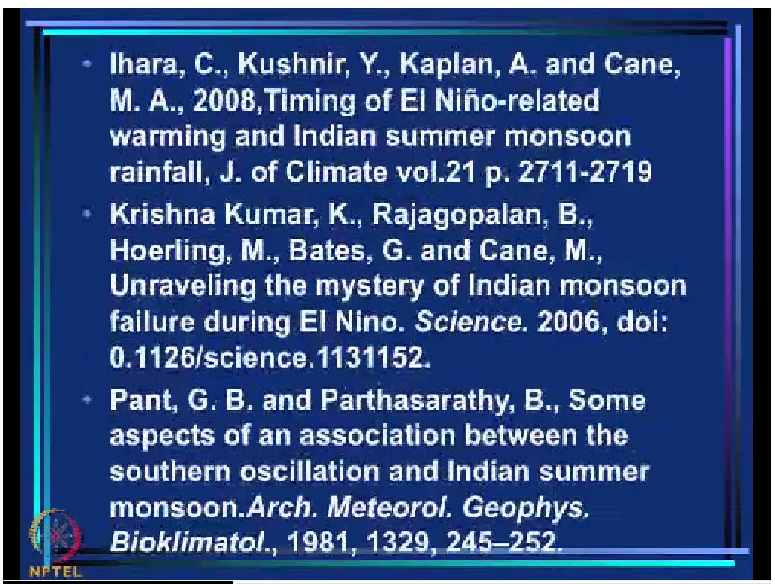

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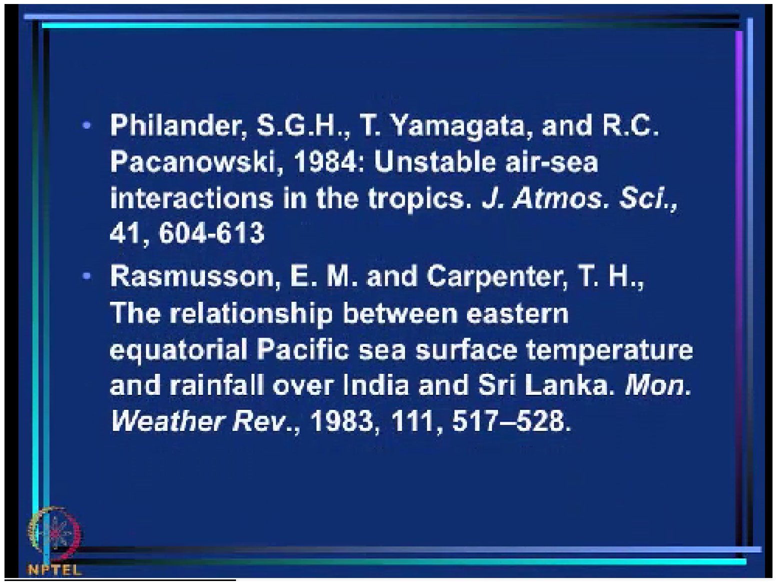

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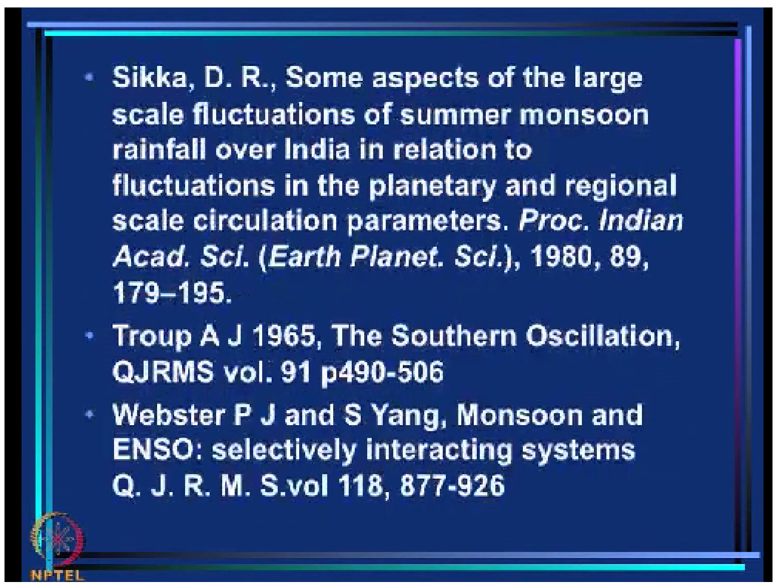

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