The Monsoon and Its Variability
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**Lecture - 27**
El Nino Southern Oscillation (ENSO) Part 4

So we continue our discussion about El Nino southern oscillation today.

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You know the El Nino southern oscillation cycle is an irregular oscillation with most of the variance concentrated in the 2 to 6-year frequency, but is also exhibits a pronounced biennial component, that is to say year to year variance. Now the characteristics of the 2 phases in terms of the sea-level pressure, SST and OLR are brought out in the composites for July to November in the next 2 slides.

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El Nino composite : July-November
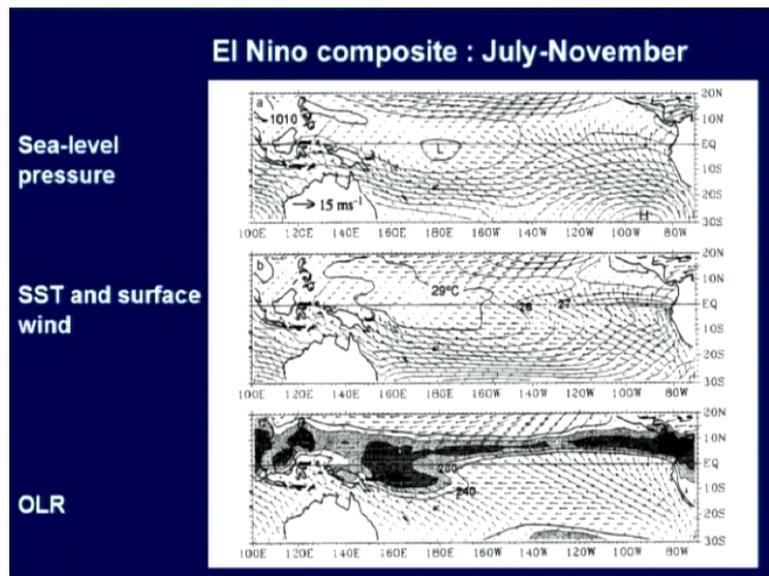
Now we are just trying to see what are the important features of the 2 phases. So this is an El Nino composite for July to November and what you see here is sea-level pressure for El Nino on top and this is of course the Pacific Ocean and then this is the sea surface temperature and this is the OLR. And what you see here is that there is a zonal band here of low OLR, that is to check deep convection right across the pacific during El Nino and it is quite intense.

This is where the outer curve is OLR of 240 and the shaded ones are 230 and below. So there is a reasonable amount of clouding in this band across, which joins the West Pacific high intense cloud zone with a reasonably intense clouding zone of America here. Now actually the sea surface temperature is also very warm during El Nino during El Nino and this is 29 degrees and 28 degrees stretching right across.

And the low pressure centre is around here, see this is the date-line right here, this is the date-line 180 and the lowest pressure is around the date-line in an El Nino composite, and otherwise of course you have the generally low pressure over west as compared to the east.

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La Nina composite: July-November
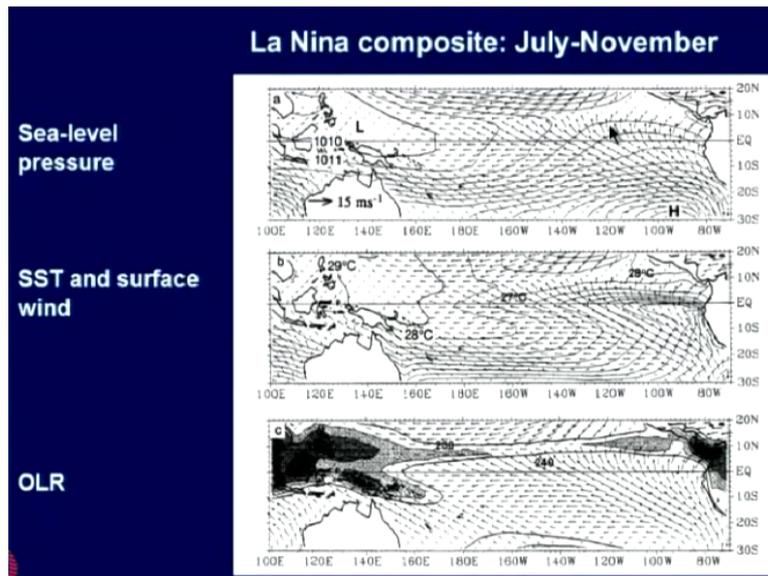
Now the La Nina composite has obviously different characteristics, the low pressure has moved away, remember it was near the date-line before, and most important difference is here in the OLR. If and/or 240, then you still see a zonal band, but you see that the convection is not at all intense here 230 does not occur here at all. So you have the West Pacific cloud zone, you have reasonably intense cloud zone here going up to the American coast.

But in between there is hardly any clouding here. So this is the major difference, remember for El Nino it was cloudy with reasonable intensity right across.

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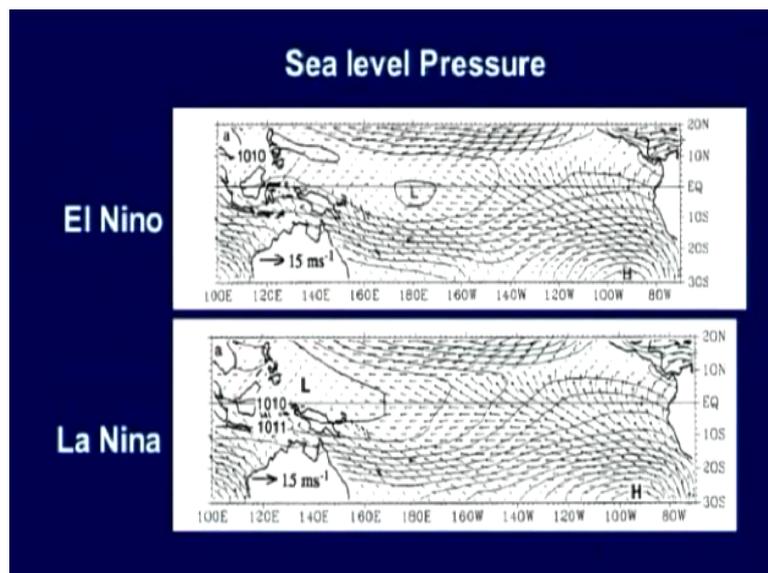
Sea level Pressure

So if you look at sea-level pressure those had all the features of the specific state. Now we compare sea-level pressure of El Nino with La Nina and what you see that La Nina the low

pressure is much more over the west pacific, in El Nino it has now shifted more to the central pacific here. So there is a major difference in the sea-level pressure pattern.

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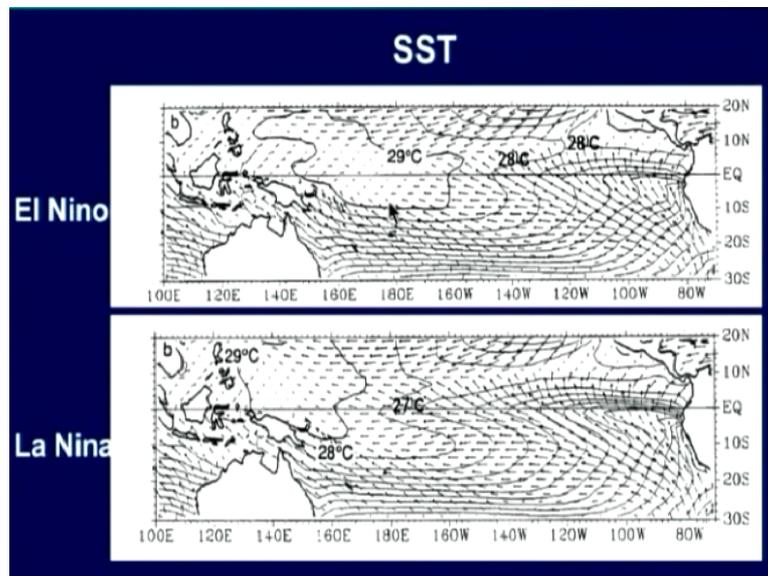
Now you see clearly the warm event that is El Nino here, see this entire region is about 29 degree centigrade, 28 degree centigrade contour is reaching right up to here and almost continuing here. That is to say this entire region here is above 28 for El Nino, above the threshold for convection which we talked about. So this entire band becomes favourable for convection in El Nino. Look at La Nina on the other hand.

La Nina has 28 degrees here that is to say the warm water is here and there is also warm water here. But in between, see this is 27 degrees, so in between it is < 28 and actually here parts of it are < 27, then it becomes 27 and 28 here. So this entire patch here is below the threshold for La Nina.

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OLR composites and mean for July-November
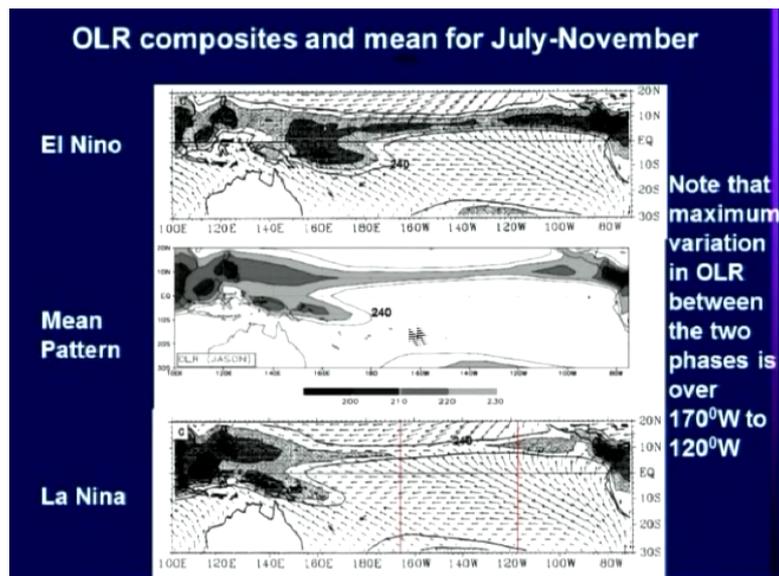
And naturally what you see is that for La Nina there is a gap in convection from here to here this is where the sea surface temperature was below the threshold. What I show here is the OLR pattern for El Nino, the mean pattern for July to November and La Nina OLR pattern. What you see is that there is a very major change which occurs between these longitudes here, these longitudes which are 170 west to 120 west.

You see that is hardly any convection in La Nina but you have intense convection here. So occurrence of convection in this band is a major distinguishing attribute of the El Nino, versus the La Nina. See over this region any where there is convection and it becomes more intense in La Nina. Over this region also any where there is convection, it becomes more intense during El Nino.

So but where there was hardly any convection in La Nina, this is 170 west to 120 west, now you are getting continuous band of reasonably intense convection. So this is a very critical region in which you see a major change in terms of the occurrence of the TCG for the El Nino and non occurrence of the TCG for La Nina.

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- Note that maximum variation in OLR between the two phases is over 170°W to 120°W.
- Over this longitudinal belt, SST is above 28°C around 5°N in the El Nino composite, whereas it is below 27°C in the La Nina composite.
- Thus a coherent region of low OLR across the Pacific in the El Nino composite is consistent with a coherent zone with SST above the threshold.

Now note that the maximum variation in OLR as mention between the 2 phases is over 170 west to 120 west. Over this longitudinal belt, the SST is above 28 degrees around 5 degrees north in the El Nino composite, whereas it is below 27 degrees in the La Nina composite. Thus a coherent region of low OLR across the pacific in the El Nino composite is consistent with a coherent zone of SST above the threshold.

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- The different phases of ENSO over the Pacific can be represented as shown in the following slides.

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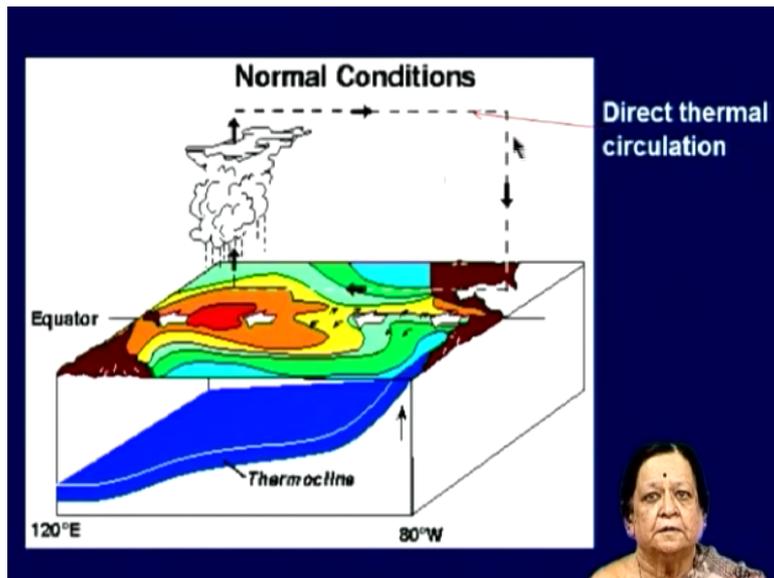
Now different phases, now we have looked at all the different attributes of the 2 phases, so now we will look at what they look like in terms of both atmosphere and ocean. These are normal conditions. During normal conditions you have convection primarily over the west pacific in the atmosphere and you have this is the direct thermal circulation, you have a descending zone here. Now this is the SST distribution.

SST is warm here and over the warm region there is arising end convection and then SST is very cold here along the coast of America and you have sinking here. Now this the thermocline shown in blue and you see that the thermocline is much, much deeper in the west than it is in the east. This is the famous tilt of the thermocline, that you see, these are normal conditions which are average over several years of what is seen over the Pacific and in the Pacific.

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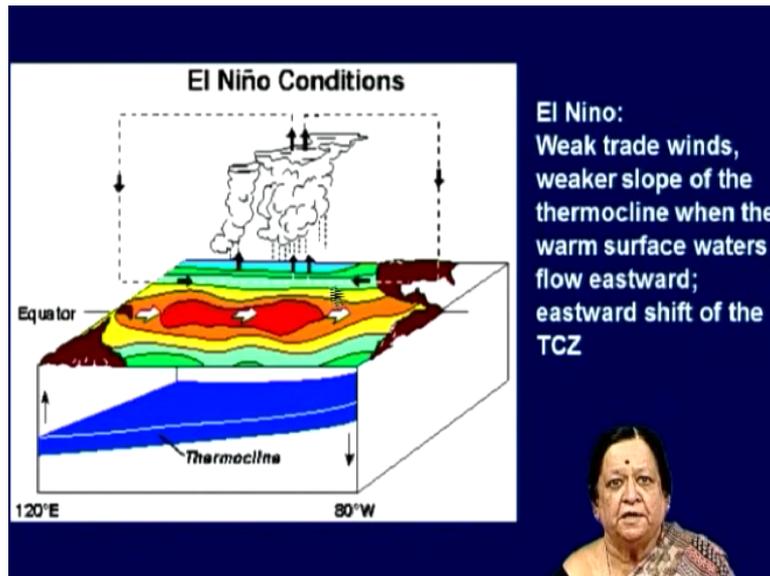
Then comes the El Nino conditions, what has happened is that the thermocline here has become deeper. You see in the normal conditions the thermocline was almost at the surface here at 80 degrees west. Now it has become deeper as you can see, so the slope of the thermocline has decreased that means there is more warm water here, you see here that the SST, warm SST is like a river going across here entire pacific.

And you get convection not only over west pacific but over central pacific as well. So in El Nino then because the convection has moved here what is the characteristic. You have weak trade winds, weaker slope of the thermocline which you have seen when the warm surface waters flow eastward, and eastward shift of the tropical convergent zone, whereas it was much more restricted to west pacific, now there is convection over central pacific as well.

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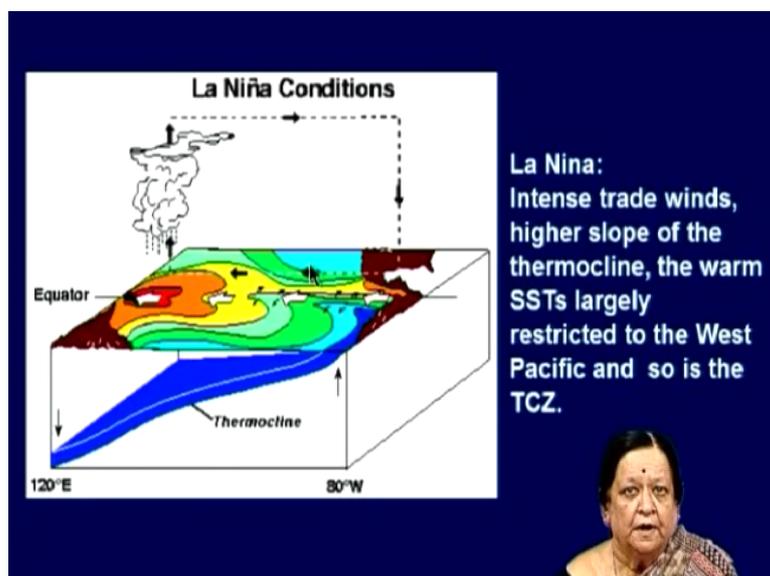
Now let us go to the La Nina it is the opposite or the cold phase you see. You have intense trade winds here, intense up welling here so the SST here is very cold, cold water here relative to here and higher slope of the thermocline than normal. So from normal El Nino has lower slope of the thermocline, it comes up to here and La Nina has higher slope of the thermocline.

Warm SSTs are largely confined to West Pacific as you can see and so is the TCZ the tropical convergent zone. So these are the 2 extreme phases of this couple ocean atmosphere system and you see how the 2 components, atmosphere and ocean go together in these 2 phases.

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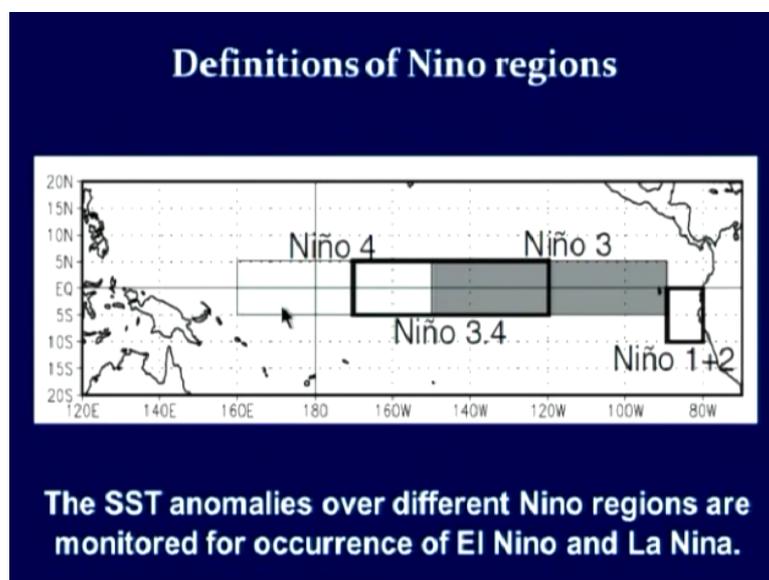
Now you have heard me use the word Nino 3 and Nino 3.4 before, let us define what these regions are. See these regions are supposed to be critical for El Nino and SST anomalies over these regions are used as indices for El Nino. So these regions are defined here, first you remember the original definition of El Nino in word SST anomalies of the coast of South America.

So Nino 1+2 is the region over which the SST anomalies decrease and that corresponded to the traditional or old definition of El Nino. Now we have seen that the cold tongue comes across the pacific as well and across the equatorial Pacific then there are 3 regions, Nino 3 which extends almost up to coast of America. It goes all the way from 90 west up to above 150 west. So this is the eastern part of the pacific going almost to South America, this is Nino 3.

Nino 4 is the adjoining region which covers the Central Pacific, so Nino 4 is much more Central Pacific and Nino 3 is East Pacific. Nino 4 as you can see goes from 150 west all the way to 150 east, so this is up to 160 east. So 160 east to 160 west actually is Nino 4, so this is just going across the Central Pacific so Nino 3 is East Pacific, Nino 1+2 is off the coast of South America and Nino 4 is Central Pacific here, 160 east to 160 west.

Now Nino 3.4 is in between, it has part of the East Pacific and it has part of the Central Pacific as well. But it starts east of the date-line, so it starts of 170 west and goes up to 120 west. This is Nino 3.4, all these 3 regions are from 5 degree south to 5 degree north. So SST anomalies over these regions are used as indices for the occurrence of El Nino and La Nina.

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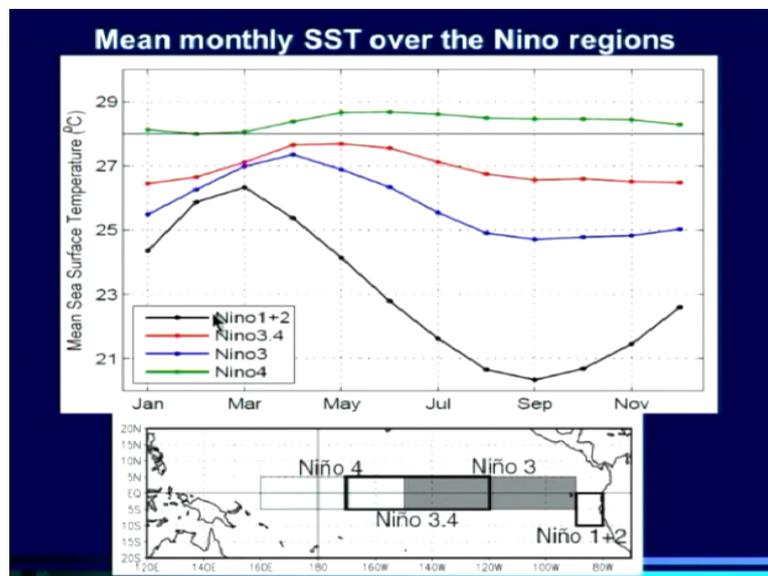
Now let us see how the sea surface temperature actually varies over these regions. So when we look at average SST for these different regions how does the sea surface temperature vary, now we are talking of the mean of course. So we have first Nino 1+2, you know that is the very cold part of the ocean, it attains its maximum which is actually around 26 or so in March.

But then decreases to a very low level here almost 20 degrees and then starts increasing after September. So it has a high in march, minimum in September and it is very cold, right. It is below 26 all the time. The next is Nino 3, which covers as you have seen. Nino 3 is here it is the eastern most part of equatorial Pacific and that has a maximum in April. It is actually not as cold as Nino 1+2, but is somewhat cold and it goes above 27 degrees from March onwards.

You can say March, April, May it is above 27 after that it decreases. So as you come towards the Central Pacific then this is Nino 3.4 and Nino 4, both of them get maximum SST in May. But you can see that Nino 3.4 is above 27 for a large part of the year all the way from March right up to July, it is above 27. So it is somewhat close to the threshold, but below the threshold of 28, this is Nino 3.4.

But Nino 4 the mean is all the time above the threshold. It is all the time above 28 this is a point to be born in mind. Now because I have included Nino 1+2 in this graph these look like a very gently varying.

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So in the next slide, we will see only the regions of the equatorial pacific. So as we have noted that while the mean SST of Nino 4 is 28 degree centigrade or above for all the months, the SST of Nino 1.2, which is of the South America is well below 28 in all the months. The mean SST of Nino 3 and Nino 3.4 is also below 28 degrees in all the month, but for Nino 3 it is above or close to 27 in March, April and in Nino 3.4 it is above 27 in March-July.

Thus positive anomalies of about 1 degree centigrade would imply SST above 28 degrees that is above the threshold for Nino 3 and Nino 3.4 in these periods where it is close to 27.

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**Mean monthly SST over the Nino3, Nino3.4 and Nino4 regions**
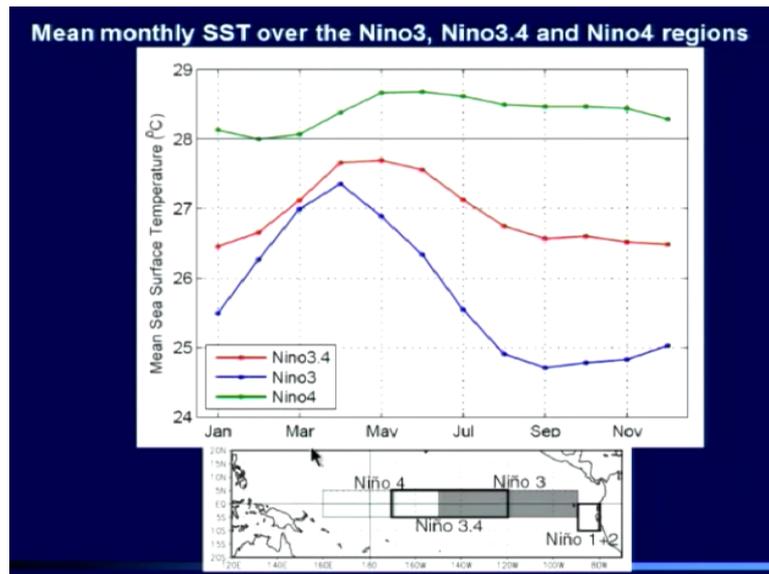
Now here we see the same graph but without Nino 1+2, and you can see better the variation of these other regions. You can see rather sharp peak for the Nino 3 region which is occurring here in April and so the Nino 3 region has much more variation with season. Nino 3.4 not too much variation and you can see that it is from March onwards for 4 months it is above 27 and even after that in August, it is not that far down from 27.

So 1 degree or more, slightly more than 1 degree would take it to 28, Nino 4 on the other hand is always above 28. Now let us relook at what we had seen before. OLR composites and mean for July to November, which is the mature phase of El Nino. What we see is we have already noted before that this was the region over which we saw maximum change between La Nina and OLR and we had marked it to be between 170 west and 120 west.

Now it so happens that this is precisely the longitudinal limits of Nino 3.4, so Nino 3.4 is on the equator between 5 south to 5 north and precisely between these longitude here, so in some sense Nino 3.4 captures better than the other Nino regions the OLR variation between the 2 phases.

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OLR composites and mean for July-November
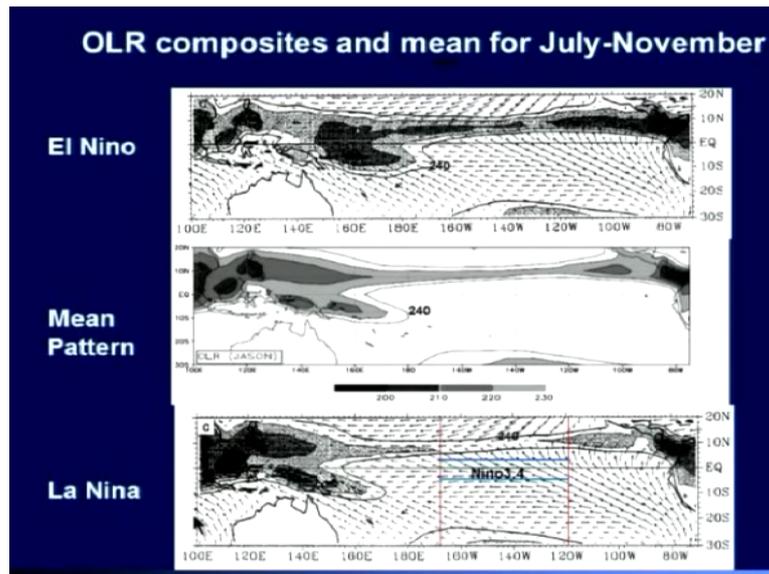
So Nino 3.4 seems a very appropriate index, so as I mention in fact the longitudes of Nino 3.4 are characterized by major differences in OLR between El Nino and La Nina, that is the last slide. Over these longitudes the SST changes between the cold phase, when the SST is well below the threshold and the warm phase when it is above 28 degrees are also significant. Not surprisingly, the NOAA official definitions of El Nino and La Nina are based on Nino 3.4 SST.

Now I may mention NOAA is the official agency of United States of America, National Oceanic and Atmospheric Administration, NOAA.

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Definitions of El Nino and La Nina

- El Nino and La Nina are defined by the Climate Prediction Centre, USA based on a threshold of +/- 0.5°C for the Oceanic Niño Index (ONI) which is defined as the three month running mean of Reynolds SST anomalies, based on centered 30-year base periods updated every five years in the Niño 3.4 region (5°N-5°S, 120°-170°W).

So how do they define El Nino and La Nina, they define El Nino and La Nina based on a threshold of +/- 0.5 degree centigrade for what they call an oceanic Nino index, which is

defined as the 3 month running mean of the Reynolds SST anomalies, based on a centered on 30-year base periods and so on and so forth. In the Nino 3.4 region which is 5 south to 5 north 120 to 170 west.

So Nino 3.4 region SST anomalies of which they use 3 month running means, that is what they think is based on, and if this 3 month running mean OLR is greater in magnitude than 0.5, you say it is either an El Nino if it is positive anomaly or a La Nina if it is negative anomaly.

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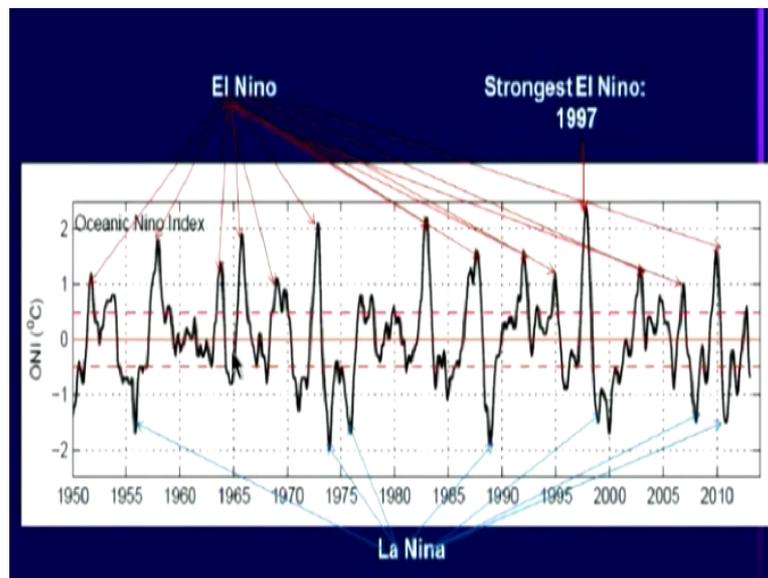
So this is the ONI index now, plotted for you, right from 1950 to 2011, and what you see here is these red lines are the 0.5 which are the threshold for the definition of El Nino and La Nina and you can see that when these anomalies are larger than 0.5, these are all El Ninos. All these are El Ninos, when you have the ONI becoming positive and larger than 0.5 and these are La Ninas here, you see when the index dips to below -0.5.

And you have a whole set of La Ninas here and a whole set of El Ninos here. Notice that the highest anomaly ever recorded is in 1997, this is the strongest El Nino.

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Teleconnections

- The ENSO phenomenon is not only of great interest in itself, it is also of great importance because it has teleconnections with the rainfall and temperature over a large part of the tropics as well as mid-latitudes.
- In fact, Bjerknes also emphasized the likely impact of the warm SSTs associated with the El Nino on the prevailing westerlies in the mid-latitudes.

So now we have the definitions of El Nino and La Nina under our belt, and we can now look at 1 more very important of ENSO. See ENSO phenomenon is not only of great interest in itself, but it is also of great importance because it has teleconnections with the rainfall and temperature over a large part of the tropics as well as mid-latitudes. So it is a phenomena that seems to have a impact on many, many regions in the tropics as well as mid-latitudes.

In fact, in those seminar papers of Bjerknes that I talked about in the last lecture, he also emphasized the likely impact of the warm SSTs associated with El Nino on the prevailing westerlies in the mid-latitudes and hence on the weather and climate on the mid-latitudes. So Bjerknes also emphasized the connection of these El Nino events with mid-latitudes.

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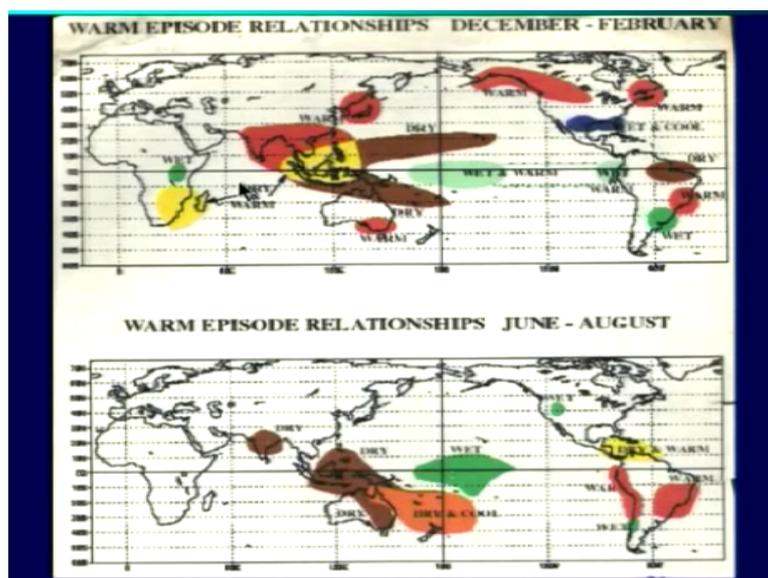
So this is how the influence can be depicted, first you see warm episode relationships between December and February, warm episode is El Nino and June to August is of greater interest to us that is when our monsoon occurs and what you see is dry patches here. So El Nino is associated with wet region over Central Pacific which we have seen and dry region over India. So you expected dry monsoon during El Nino, or a deficit monsoon during El Nino.

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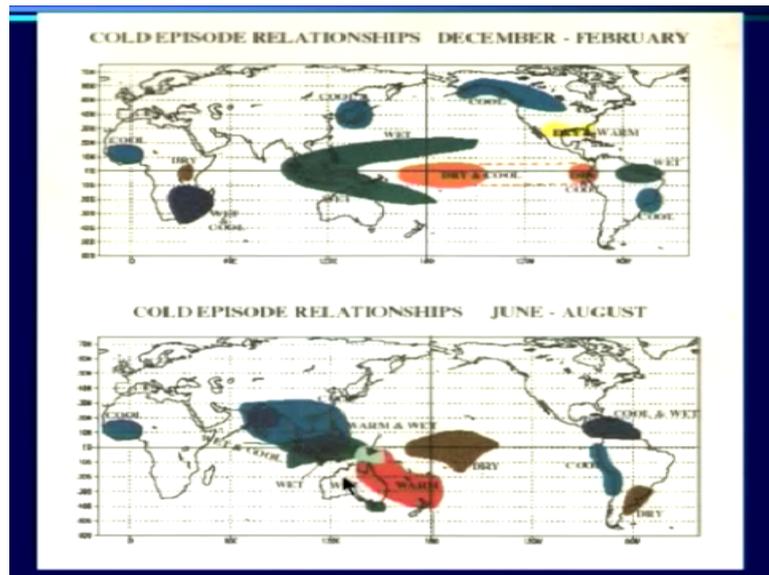
This is seen and if you see the cold relationship that is to say what happens when you have La Nina. When you have La Nina actually it is drier here over Central Pacific and it becomes rather wet over the entire Indian region + the adjoining part of the Asian region as well. So La Nina you more rain, and El Nino you get less rain.

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- It is seen that during the boreal summer, the Indian region has dry anomalies during El Nino and wet anomalies for La Nina. Thus it is clear that there is a link between the Indian summer monsoon rainfall and ENSO.
- Hence, even if one was primarily interested in the monsoon, it is important to try and understand ENSO and consider its predictions, which have improved enormously over the last decade.
- I shall discuss the monsoon-ENSO link in some detail in another lecture.

So during the boreal summer the Indian region has dry anomalies during El Nino and wet anomalies for La Nina. Thus, it is clear there is a link between the Indian summer monsoon rainfall and ENSO. Hence even if one was primarily interested in the monsoon, it is important to try and understand ENSO and consider its predictions, which by the way have improved enormously over the last decade. I will talk about the monsoon-ENSO link in some detail in another lecture.

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Now irrespective of which Nino index is used, ENSO has strong links with the OLR or rainfall of a large part of the tropics. This can be also clearly seen in the correlation of OLR over the global tropics with the different Nino indices for June to September.

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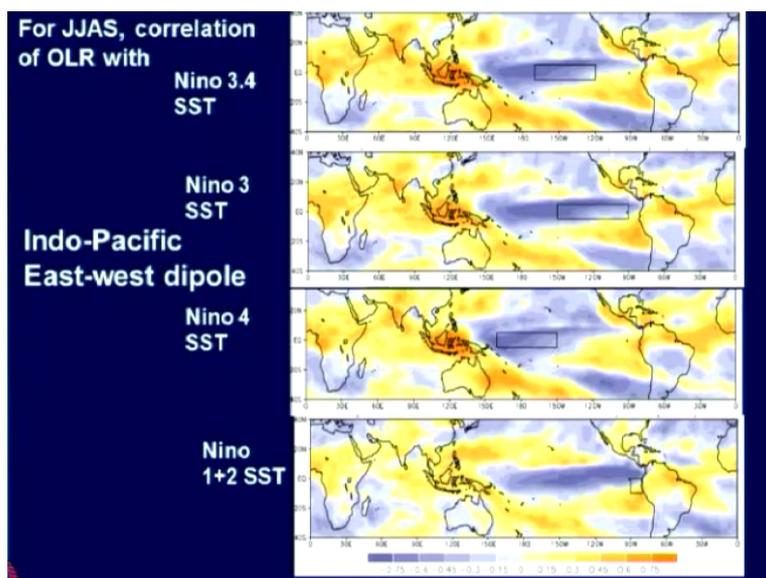
Now what you see here is correlation of Nino 3.4 SST with OLR everywhere. Obviously if it is warm, then you will get convection which means OLR will be negative, so the correlation is high and negative here. This is over the Central Pacific over this part, in fact the convection is high in an El Nino year corresponding to over a very large region here, and you get a suppression over a very large region here.

So it seems like an east-west dipole, with the entire Pacific in the northern hemisphere primarily convicting more except for parts of the West Pacific which seems to be convicting less, and from here onwards we have suppression of conviction here associated with the El Nino and opposite would be associated with a La Nina. This general pattern is there for all the indices.

But notice that Nino 3.4 seems to have a higher correlation with the Indian region, higher correlation in magnitude, than the other indices and here we have Nino 3 again very similar pattern to Nino 3.4, Nino 4 is also somewhat similar. Notice that all of them have negative correlation with the rainfall over this region just off the coast of South America, this is around 20 south or so.

But the more important 1 is this India pacific east west dipole if you wish. Now Nino 1+2 has the minimum correlation with Indian region and in magnitude of course. It also has a huge negative correlation all along here which is in the northern hemisphere. You know this is where the band was, the low OLR region was in the mean. So somehow it tends to suppress Nino 1+2 warming tends to suppress this entire Indo pacific region here, uniformly.

Whereas the other regions the ITCG over the pacific which occurs always in the northern hemisphere, you know 5 to 10 north, actually gets enhanced during El Nino, and this is seen with the other indices. But this index is somewhat different and this corresponds to looking at the way El Nino was originally defined by seeing SST anomalies of the coast of Peru and Ecuador.

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- We have noted that the distinguishing attribute of the warm and cold phases is the reversal in the signs of the SST anomalies (e.g. the figure below).

El Nino

Dec 1991

La Nina

Dec 1988
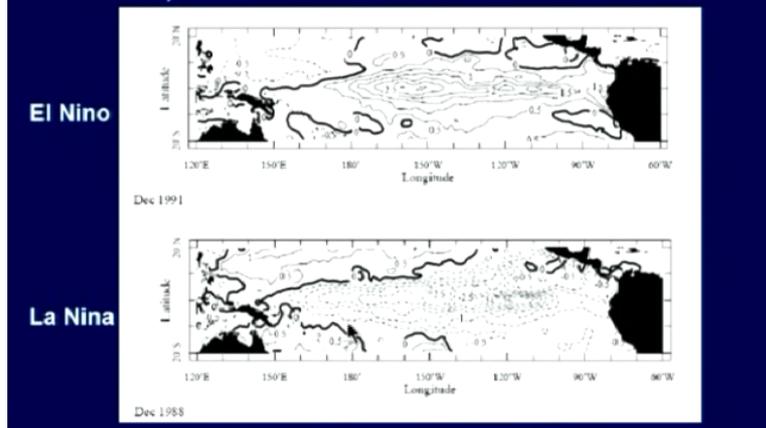
Now just as a point to make one should not think of El Nino and La Nina as always having mirror images of effects, of entirely opposite effects. See we have noted that in terms of anomalies the distinguishing attribute of the warm and cold phases is the reversal in the sign of the anomalies. So for El Nino you see throughout here actually the SST anomalies are positive, for La Nina throughout here the SST anomalies are actually negative.

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- It must be kept in mind, however, that in many ways, cold and warm phases are fundamentally different because the quantities that affect the remote atmosphere are not the SST anomalies, but rather the mean location of the regions of persistent precipitation. These depend on the SST (whether it is above the threshold) and its spatial gradients (which play a role in determining convergence).
- The SST anomalies can be the inverse of each other but the mean location of the heat source, which drives the response in the low and mid latitudes, is very different.

But it must be kept in mind, that in many ways cold and warm phases are fundamentally different, because the quantities that affect the remote atmosphere are not the SST anomalies. SST anomalies are our own creation it is saying how different SST is from the average, but what the atmosphere sees is the actual absolute SST. So it is not anomalies that affect the remote atmosphere, but rather the mean location of the regions of persistent precipitation.

So directly the teleconnections are with the regions of persistent precipitation, and we know what is that depend on. These regions are persistent precipitation depend on the SST, particularly if SST is below the threshold you would not to get any precipitation at all. So it depends on the region of persistent precipitation, and also on spatial gradients of SST, because as we have seen if SST is maintained above the threshold whether you have convection or not, whether you get convergence of low level air or not.

And that itself depends on spatial gradients of SST amongst other things, so if you have a very sharp maximum SST, then that would lead to convergence and if the SST is above the threshold that would lead to clouding, intense deep convection and precipitation. So what really matters for the atmosphere is the absolute values of SST and as we have seen in our El Nino.

La Nina composite the regions over which the SST is above the threshold vary considerably between the 2 phases and that is what is going to matter it is not anomalies although they can be inverse of the things, the precipitation regions how they vary cannot be thought of been inverse of 1 another. The SST anomalies can be inverse of each other, but the mean location of the heat source which drives the response of the low and the mid latitudes is very different.

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- In the warm phase of ENSO, persistent precipitation extends into the central Pacific while during the cold phases of ENSO it retreats to the far western Pacific.
- Because the rest of the world is forced by these regions of persistent precipitation and because these regions are in different locations for warm and cold phases of ENSO, there is no expectation that the global effects will be the negative of each other.

In the warm phase of ENSO, persistent precipitation extends into the Central Pacific while during the cold phases of ENSO, it retrieves to the far Western Pacific, we have seen this. Now because the rest of the world is forced by these regions of persistent precipitation and

because these regions are in different locations of warm and cold phases of ENSO, there is no expectation that the global effects will be the negative of each other.

See what is in world is a shift in the location of precipitation and also in its intensity, and these shifts will not lead to effects, which are positive and negative obviously.

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- After the ground breaking work of Bjerknes in the 60s, there has been a phenomenal progress in understanding the physics and modelling of ENSO since the 80s.
- Models of the coupled atmosphere-ocean system are now capable of generating predictions of ENSO with reasonable skill.

Now after the ground breaking work of Bjerknes, in the 60s there been a phenomenal progress in understanding the physics and modelling of ENSO since the 80s. Models of the coupled atmosphere ocean system are now capable of generating predictions of ENSO with reasonable skill.

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- Here, I discuss what is understood about the basic facets of ENSO and how this understanding was achieved, with the hope that some lessons can be learnt for studies of the monsoon.
- This discussion is primarily based on the excellent books by Philander and Sarachik and Cane, who have been major players in elucidation of the physics of ENSO and modelling the phenomenon .

Here I discussed what is understood about the basic facets of ENSO and how this understanding was achieved with the hope that some lessons can be learnt from studies of the monsoon which is really the focus of this lecture series. Now this discussion is primarily based on the excellent books by Philander and Sarachik and Cane, which I have referred to earlier.

And these people George Philander, Ed Sarachik and Mark Cane have been major players in the elucidation of the physics of ENSO and modelling of the phenomenon.

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The mean state of the tropical Pacific and the atmosphere above can be understood as follows:

- (i) The equatorial east Pacific is 4-10°C colder than the equatorial west Pacific. The east is cold because of equatorial upwelling, the raising of the thermocline exposing colder waters, and the transport of cold water from the South Pacific. All of these are dynamical features driven by the easterly trade winds.

Now so what is the understanding that has been gained about ENSO. We have mentioned this in several contexts before, but let me just quickly recapitulate the mean state of the tropical pacific and the atmosphere above can be understood as follows. The equatorial east pacific is 4-10 degrees colder than equatorial west pacific. The east is cold because of equatorial upwelling, the raising of the thermocline exposing colder waters and the transport of cold water from the South Pacific.

All of these are dynamical features drive by the easterly trade winds.

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So the atmospheric circulation is driven by the SST gradient, which leads to a low pressure over warm SSTs in the west and high pressure over cold SSTs in the east. Now over the equatorial regions, the surface wind is partly driven by the surface pressure gradients and has an easterly component. Obviously, because the pressure is low over the west and high over the east, the wind will go from east to west.

That is to say, it will have an easterly component. Now large-scale circulation in the tropics on time-scales of weeks or longer corresponds to direct thermal circulation. This is a very important thing to remember.

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Thus in the Zonal Walker circulation, air rises over the warm western tropical Pacific and sinks over cold eastern tropical Pacific. The moisture laden air carried westward by the trade winds converges over the warm West Pacific.

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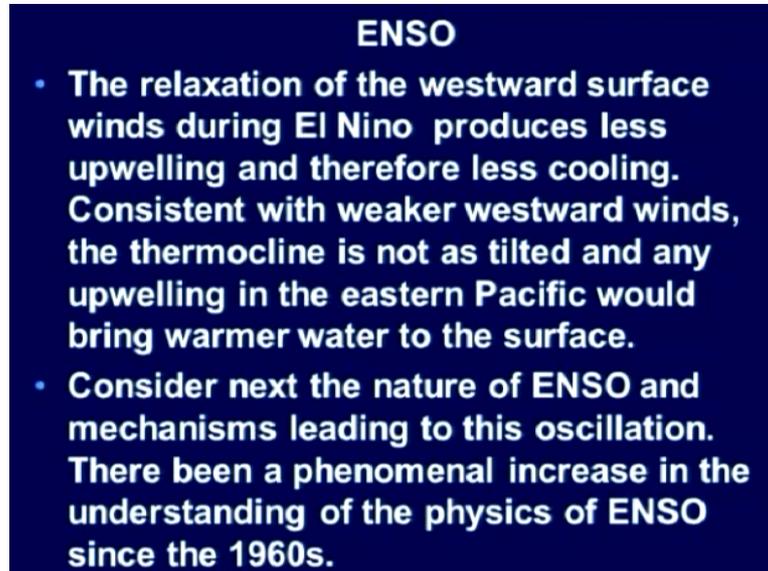
Now, ENSO. That was the mean state we were talking about. How does ENSO operate. The relaxation of the westward surface winds during El Nino produces less upwelling and therefore less cooling. Consistent with weaker westward winds, the thermocline is not as tilted and any upwelling in the eastern Pacific would bring warmer water to the surface, because the thermocline is now deeper.

Consider next the nature of ENSO and mechanisms leading to this oscillation. As I mentioned, there has been a phenomenal increase in the understanding of the physics of ENSO since the 60s.

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Elucidation of the nature of ENSO

- Until the 1960s there was relatively little data on ENSO and the El Nino was regarded as a departure from 'normal' conditions. It was believed that the phenomenon starts to develop at a certain time because of triggers that lead to its growth. The subsequent decay of the 'anomalous' atmospheric and oceanic conditions restores the normal state.

So elucidation of nature of ENSO, until the 1960s, there was relatively little data on ENSO and the El Nino was regarded as a departure from normal conditions. It was considered as an event that suddenly occurs. It was believed that the phenomena start to develop at a certain time because of triggers that lead to its growth. So when talked of an event, which was being triggered by certain factors.

The subsequent decay of anomalous atmospheric and oceanic conditions restores the normal state. So when thought of El Nino as an event, that is triggered, that develops, that grows, that dies and with the death, one gets back to, what we may call, the normal state. This was the perception based on the earlier data.

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- A lot more information was available about El Nino by the early 80s because of the recovery of earlier measurements made by commercial vessels over many decades as well as new data collected since the 60s.
- With an in-depth analysis of all data including data from ship tracks over critical regions for 1950- to 1973, Rasmusson and Carpenter (1982) elucidated the nature of the El Nino and its evolution.

Now a lot more information was available about El Nino by the early 80s, because of the recovery of earlier measurements made by commercial vessels over many decades as well as new data collected since the 60s. So a huge database became available in the 80s because of this and with an in-depth analysis of all data including data from ship tracks over critical regions for 1950 to 1973.
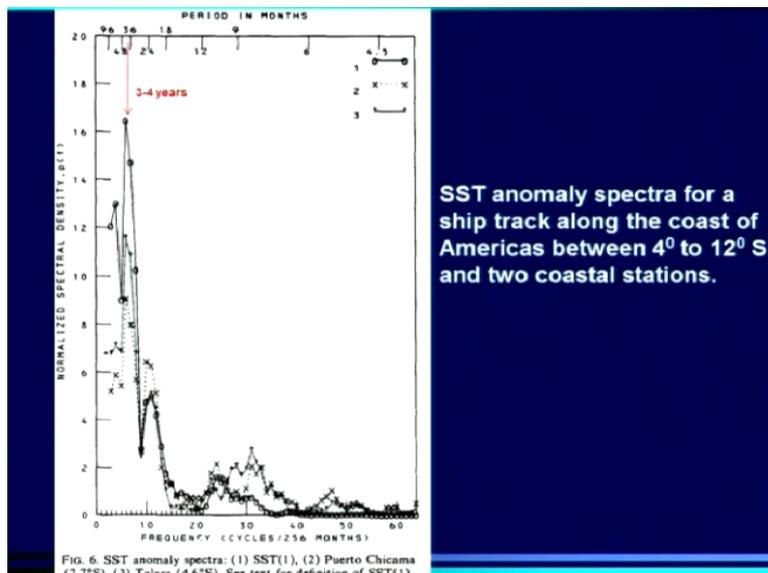
Rasmusson-Carpenter in paper, which is very famous now, elucidated the nature of El Nino and how it evolves.

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- There were seven El Ninos between 1950 and 1976. Spectrum analysis of SST clearly showed high amplitude between 2 to 7 years and a peak at a period of about 4 years (next slide).

So there were 7 El Ninos between 1950 and 1976 and spectrum analysis of the SST along the coast of South America now showed the following:

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SST anomaly spectra for a ship track along the coast of Americas between 4^0 to 12^0 S and two coastal stations.

FIG. 6. SST anomaly spectra: (1) SST(1), (2) Puerto Chicama (7.7°S), (3) Talara (4.6°S). See text for definition of SST(1).

What you see here is that there is a very clear peak now, this is the normalized spectral density on the y-axis and this the frequency on the x-axis and actually here the period is also shown in months and what you see here, this is 3 years that is 36 months and this is 48 months or 4 years. So the major peak is between 3-4 years. This is the major peak in the spectra. So they showed that these phenomena had a periodicity of about 3 to 4 years.
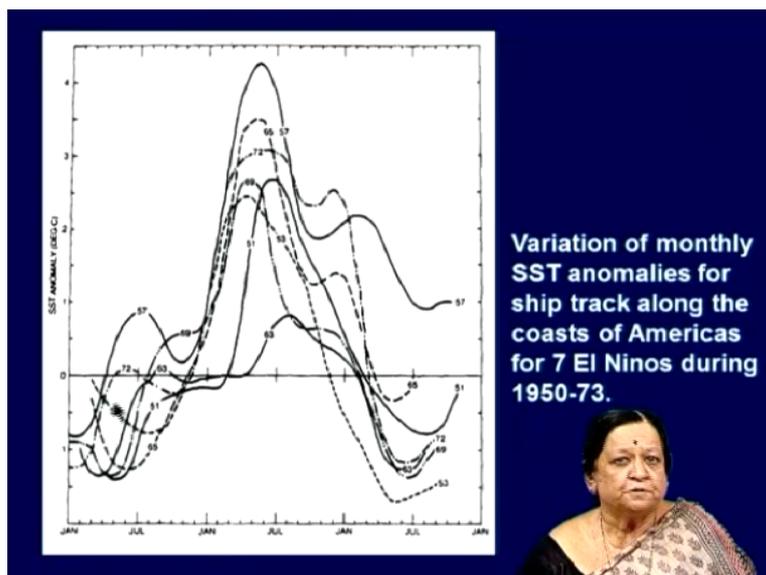
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Now they also elucidated the nature and evolution of a typical El Nino. They showed that although the amplitudes of the different El Ninos varied considerably, their phases are somewhat similar.

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You see these are all the El Ninos drawn and this is the SST anomaly here of the coast of South America and this is the month. So what you see is they all start developing around

here, around January of the El Nino year, then they reach a peak around here somewhere around June or so and then start decaying. So it is about an 18-month kind of period here. This is January and this is June.
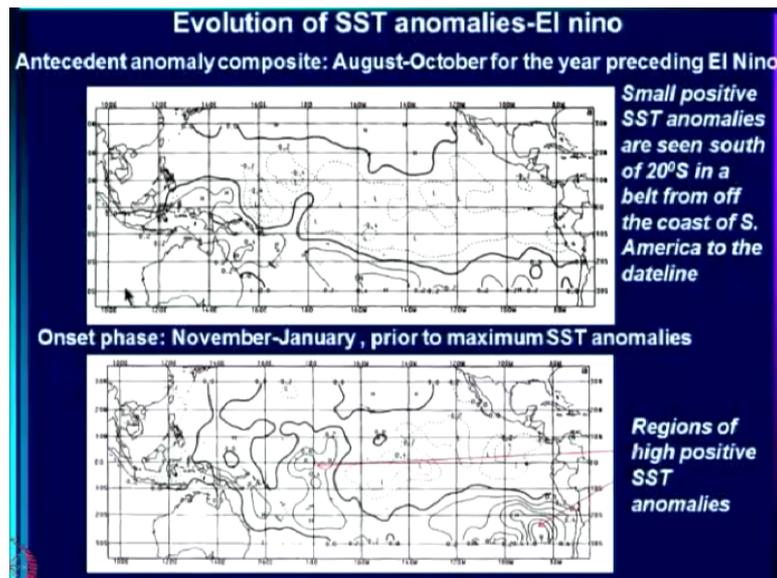
If you want to stop it here, this you can call as the El Nino year. When the anomalies are all positive, that is from around the beginning of the year to around the end of the year. So all profiles look somewhat similar and therefore one can make composites.

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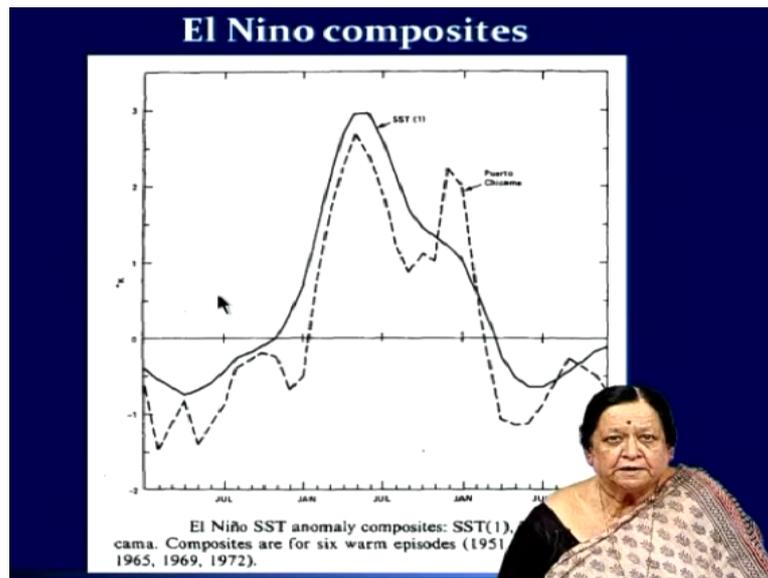
Because if they were totally out of phase, then the average makes no sense at all, composite makes no sense at all, but because by-en-law is there in phase, this is what you see is the composite SST anomaly along the ship track and this is for a specific station. So by-en-law, one can now think of a composite El Nino or an average El Nino if you wish, whose evolution we can look at by adding together all the information of 7 El Ninos that occurred.

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Evolution of SST anomalies-El nino

Antecedent anomaly composite: August-October for the year preceding El Nino

Small positive SST anomalies are seen south of 20^0S in a belt from off the coast of S. America to the dateline

Onset phase: November-January , prior to maximum SST anomalies
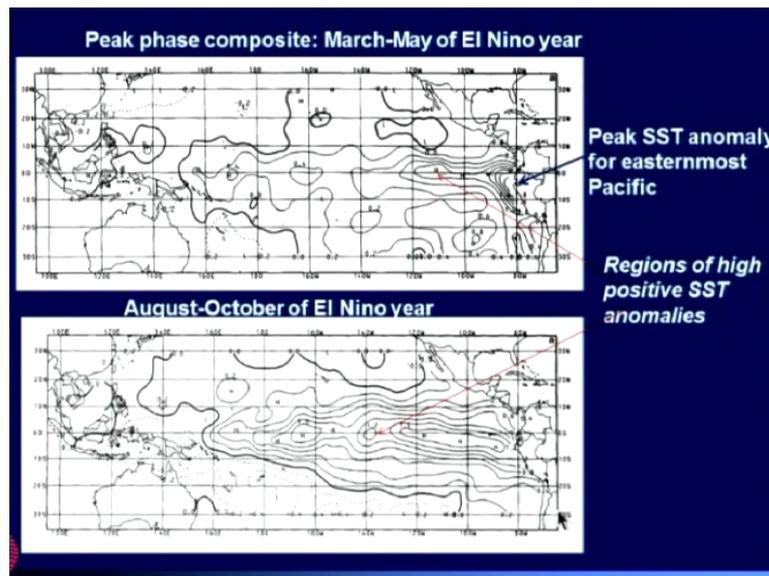
Regions of high positive SST anomalies

And that is what Rasmusson-Carpenter did. Now what they did was to show how this SST anomaly patterns evolve. So first they looked at the antecedent anomaly composite, August-October for the year preceding El Nino and what you see the anomalies are negative almost everywhere except here there is a small part here, which is positive. Now what happens then during November to January prior to SST anomaly.

This is the beginning of the El Nino event if you wish, what you see is rather large positive SST anomalies here, but notice interestingly there is also region of positive anomalies around the equatorial regions of the date-line, Central Pacific. So this is how things change from August-October to November to January. Now comes what Rasmusson-Carpenter called peak phase composite, because they insist on still defining El Nino by SST anomalies of the coast of South America.

And this is where the peak anomalies of the coast of South America occur. This is from March-May of the El Nino year. So this is what they call the peak phase composite and you notice that these SST anomalies have now actually spread to almost this part here. So if you went to the previous picture, then the SST anomalies were just here.

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Peak phase composite: March-May of El Nino year

Peak SST anomaly for easternmost Pacific

Regions of high positive SST anomalies

August-October of El Nino year

And in the next picture now you have peak SST anomalies, which are occurring here, but also positive anomalies have spread up to here and in the next picture, which is August-October of the El Nino, you have a very huge band warm SST anomalies. So you can see that it appears that anomalies have spread westward. Originally there were confined to this part of the equatorial pacific. Now they have spread westward to occupy a very large region of the Pacific.

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- In the peak phase composite of March – May of the El Nino year, strongest positive SST anomalies occur off the coast of S America (0^0-10^0S). The magnitude of the positive SST anomalies is high over a belt extending westward up to 120^0W.
- In August-October, the SST anomalies are higher than 1^0C over a belt from 180^0 E to the S. American coast.
- Thus there is a westward propagation of anomalies.

So in the peak phase composite of March-May of the El Nino year, strongest positive SST anomalies occur off the coast of South America. The magnitude of the positive SST anomalies is high over a belt extending westward up to 120 west. In August-October the SST anomalies are higher than 1 degree centigrade over a belt from 180 East right up to the South American coast. So there is a clear westward propagation of anomalies.
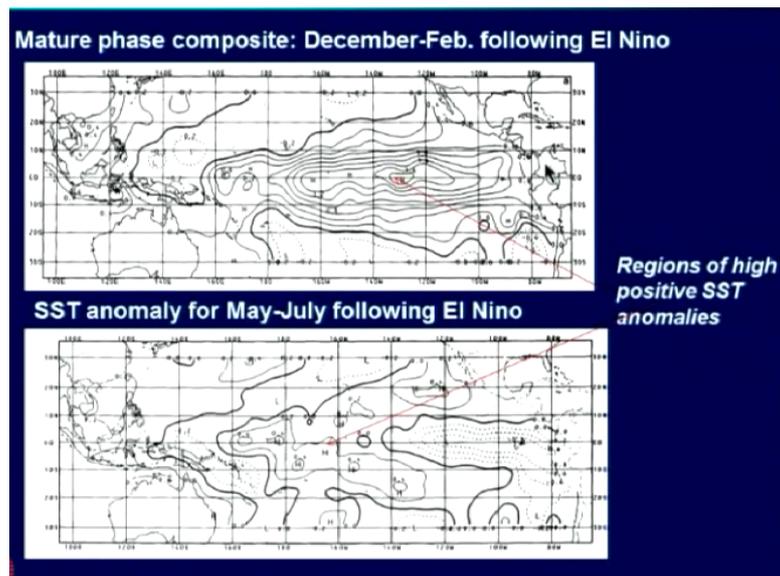
Now comes the mature phase and here we still have very high positive anomalies of SST. This is December to February following El Nino and after that this is SST anomaly from May to July following El Nino, now it has all become negative. So this is the end of the episode, if you wish.

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So in the mature phase, the largest SST anomalies are from 180 degrees to 100 degrees with anomalies larger than 1.2 degree centigrade over that critical region that we had seen 170 west to 120 west. So here the anomalies are very large over that critical region from 120 west to 170 west. See this is the belt here. This was the critical region which flared up during El Nino and which was suppressed during La Nina, you remember.

This is that Nino 3.4 longitude region and that is where the anomalies in the mature phase are very, very high. By May-July the following an El Nino year, negative SST anomalies over the equatorial belt east of 140 degree and positive anomalies over the central Pacific weaken.

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> • **Rasmusson and Carpenter suggested that the westward shift of the positive SST anomalies to the central Pacific coincides with the strengthening of westerly wind anomalies along the equator and a southward shift of the ITCZ over the West Pacific. This is also accompanied by a northeastward shift of the SPCZ.**

So Rasmusson and Carpenter suggested that the westward shift of the positive SST anomalies to the Central Pacific coincides with the strengthening of the westerly wind anomalies along the equator and a southward shift of the ITCZ over the West Pacific. This is also accompanied by northeastward shift of the SPCZ.

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> • **SST anomalies of the magnitude characteristic of the composite El Nino can have a major impact on the atmospheric convection and precipitation for regions over which they imply that the SST becomes higher than the threshold.**
> • **Positive SST anomalies over the eastern equatorial Pacific in March-May (next slide)can lead to the SST of that region exceeding the threshold.**

SST anomalies of the magnitude characteristic of the composite El Nino can have a major impact on the atmospheric convection and precipitation for regions over which they imply that the SST becomes higher than the threshold. Positive SST anomalies over the eastern

equatorial Pacific in March-May can also lead to some enhancement of convection over the region.

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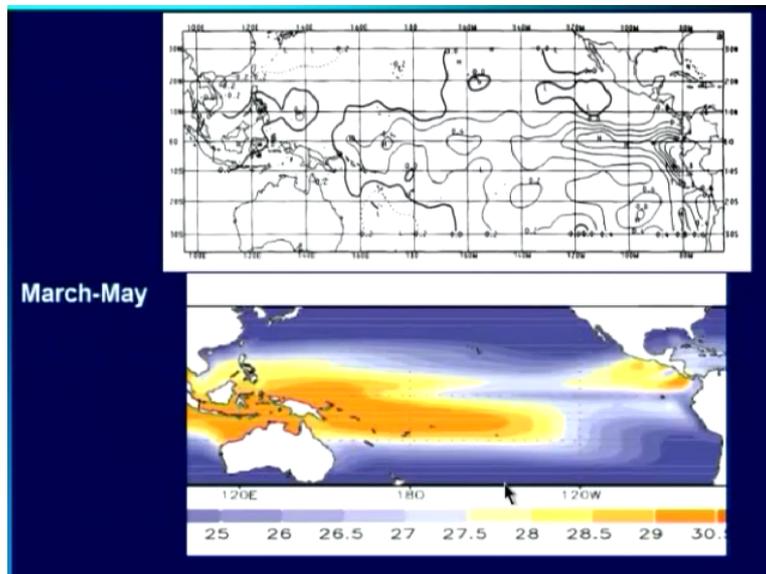
What you see here is the mean for the March-May. This is over 27.5 and you see that there are large SST anomalies here exceeding 0.5 and so on. So this can lead to intensification of this and can lead to part of this region going above the threshold in March-May. In August-October over 150 west to 120 west, the mean SST just above the threshold in a narrow band and OLR is not very low over this region.

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So now we are looking for mean of August-October and what you see here is a thin band here of OLR, not very intense and you can see that SST just above 28 in this thin band here. This is 27.5 just above 28 and if you look at the anomalies corresponding to El Nino, then you find

very large anomalies occur where actually there was relatively thin band which is above the threshold.

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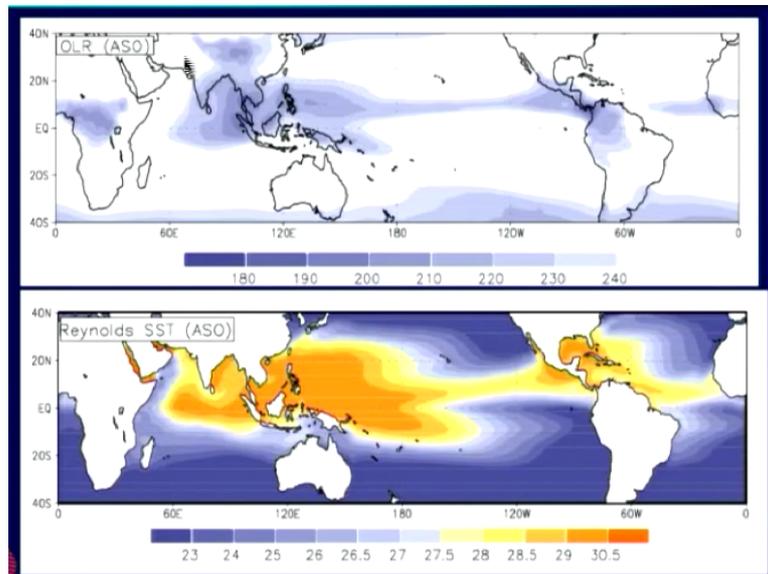
So the positive SST anomalies associated with an El Nino would lead to higher SSTs over this region and imply enhanced convection, which is what we saw in the composites that these kind of anomaly pattern makes this entire region highly warm and would therefore lead to enhanced convection over that region.

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- The most important result of the Rasmusson- Carpenter study was considered to be the westward propagation of the SST anomalies during the establishment of the composite El Nino. It suggested that monitoring the SST of the easternmost part could lead to anticipation of the anomalous conditions over the central Pacific.

So the most important result of the Rasmusson-Carpenter study was considered to be the westward propagation of the SST anomalies during the establishment of the composite El Nino. It suggested that monitoring the SST of the easternmost part could lead to anticipation

of the anomalous conditions over the Central Pacific. See we are always very happy to see propagations of this kind, which occur over a period of several months.

Because this means that if we see the event where the propagations begin, then we could anticipate what will happen in the region to which the event is propagating.

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- However, the year the Rasmusson and Carpenter paper was published, another El Nino occurred (1982-83) which did not behave like the composite El Nino in some aspects.
- This clearly showed that the phenomenon is more complex than the composite picture indicated.

However, the year the Rasmusson and Carpenter paper was published, which was in 1982, another El Nino occurred. This was the El Nino of 82 and 83, which did not behave like the composite El Nino in some aspects. This clearly showed that the phenomena is more complex than the composite picture had indicated, just when we thought that we know how a typical El Nino was, came and El Nino, which did not quite evolve in the way Rasmusson-Carpenter composited it.

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- The El Nino of 1982-83 was exceptional because of the large magnitude it attained and the unusual way in which it evolved. The warm SSTs propagated eastward from the central Pacific instead of the westward propagation seen in the composite.
- The OLR anomalies also propagated eastward from the central Pacific.

In what way was is exceptional. The El Nino of 82-83 was exceptional firstly because it was a very high amplitude, very large magnitude of SST, OLR anomalies and so on. Also it evolved in an unusual way. In fact, the warm SSTs propagated eastward from the Central Pacific instead of westward propagation seen in the composite and OLR anomalies also propagated eastward in the Central Pacific.

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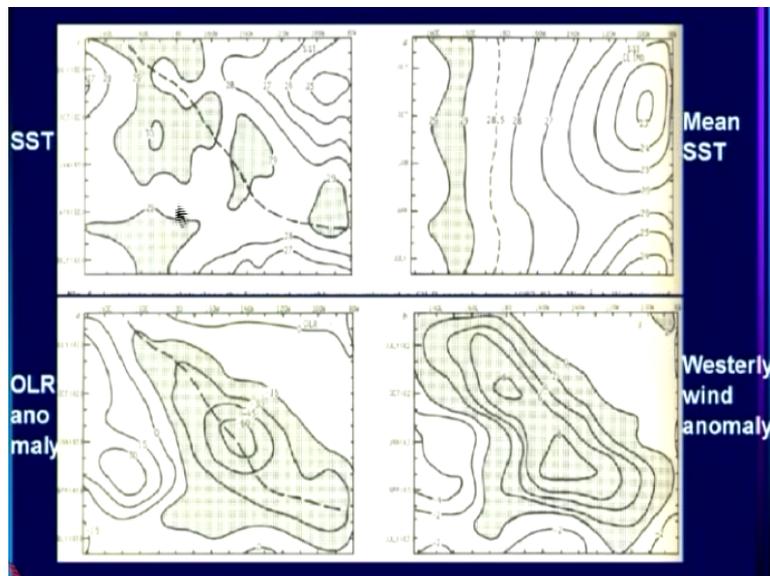
So this again is from a paper by Gill and Rasmusson. So Rasmusson also documented the El Nino, which departed from his classical picture of how El Nino evolved and what you see here is, see this is time and this is July 82 and time is increasing downwards. So this is July 83. So what you see is, this is warm. Warm water is actually moving westward with time. You see the longitudes are here moving eastward.

So it all began near the date-line here and this is 100 West. So this is the South American coast. So it begins here and moves eastward throughout. So you see warm water moving eastward and OLR anomaly moving the same way. And this is the mean sea surface temperature, which actually is simply decreasing, as you go towards the east and this is the westerly wind anomaly.

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So the evolution of the SST and OLR over the equatorial belt and OLR over 5-10 degree north where you know the ITCZ occurs in the mean pattern for 3 El Nino events, we look at in the next slides. Because this is a very interesting phenomena they showed that in 82-83, things began in the Central Pacific, not in East Pacific and then moves towards that. So what you see here is what meteorologist call a kind Hovmöller diagram and this is daily OLR now.

Most of the time, we have been looking at monthly OLR again, the shades the darker the shades, the lower the OLR the deeper the clouds. What you see here now time is going upwards in these graphs, not downward like in the earlier one. So this is January 82 and this goes all the way. This is January 83 and January 84. So this is for 3 years and here we are centered at the equator itself. So this is from 5 degree south to 5 degree north.

So this is OLR and this is weekly SST from Reynolds. So what you see here is initially you see that the SST for example is warm right from 40 degree east onwards. So this is the Indian Ocean and now this is the west pacific here and what you see here is that west pacific is warm, but as you go towards July 82, this warm SST region is moving towards the east and this is near the South American coast.

So you see a tongue of water moving westward. And just at the same time, this is the low OLR region. Low OLR region was more or less confined to the west of 160 degrees east that is to say to the West Pacific before July 82, but from July 82 it started moving eastward. So this is another way of looking at what we saw. This eastward propagation of both the warm water and the convection in the atmosphere was a characteristic of 82-83 El Nino.

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Note that during eastward propagation the low OLR region is over 5°S-5°N.
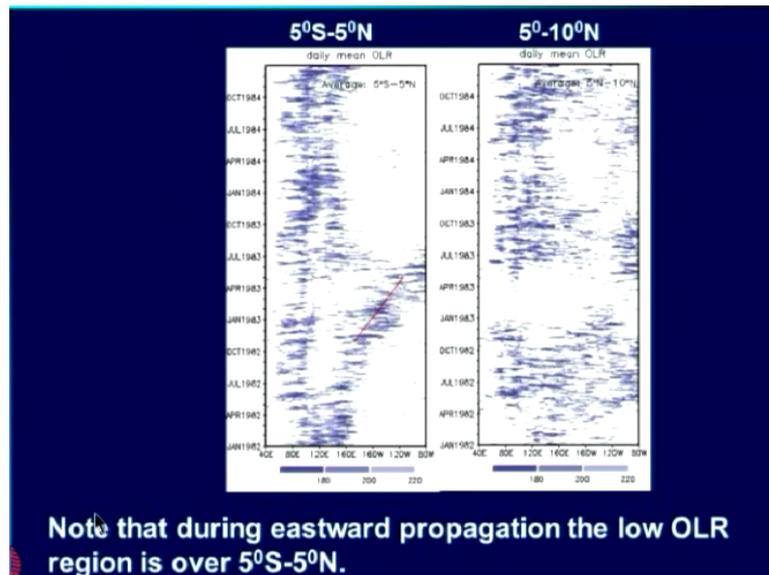
But remember the actual cloud band is between 5 and 10 north in the mean picture. So what you see here is this is the equatorial belt and this is the belt just to the north of it, 5-10 north. Again for the same period and what you see is this 5-10 north belt is actually active throughout here up to about January. It is active throughout this period, very much so up to July 82.

Now in this patch, from about October 82 to April 83, there is hardly any clouding over west pacific in the northern one, but you see it seems to have come to the equatorial region. So here in this part of the thing, you had clouding going all the way from 5-10 north over the entire region and over the equatorial region up to about 160. That is to say West Pacific was convecting over equatorial region as well as up to 10 degrees north.

And the rest of the region was mainly 5-10 north as we have seen. Now you see the movement here. See the eastward movement has occurred only in the equatorial band when there was no convection at all to the north. That is to say when the tropical convergent zone

move to the equatorial region, that is when the propagation has occurred. This is for 82-83 and similar situation you see for 97 El Nino as well.

Again you see things moving eastward here. This is the equatorial region. See the clouding has moved just when the sea surface temperature, warm water also moved or spread, if you wish and again you that actually the clouds disappeared from the northern part and were restricted to the equatorial belt and that is when the propagation occurred. This is very interesting because you remember in Bjerknes' argument.
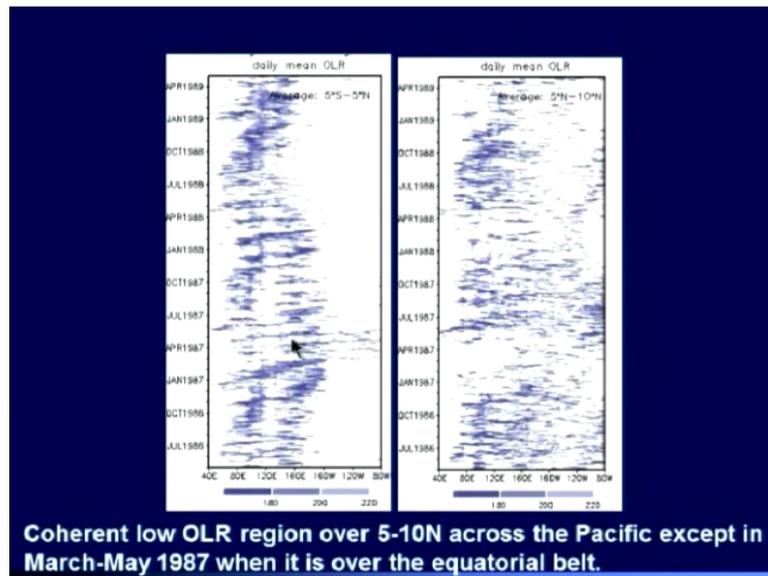
He had argued lucidly as to how because of the higher pressure in the West Pacific Ocean relative to the East Pacific, you have a current along the equator which goes from west to east. This is the equatorial undercurrent. Perhaps, what we are seeing is warm water being advected by the equatorial undercurrent here and because equatorial undercurrent is restricted to the equator, you do not see any advection of warm water or any convection propagation in the northern part.

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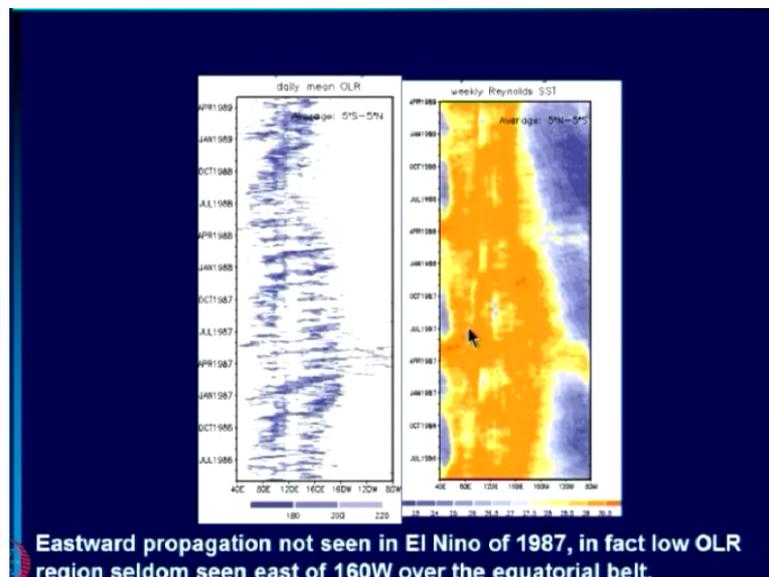
Now there are events like 87 in which there was no propagation of eastward at all. It may have been more classical Rasmusson-Carpenter kind of evolution.

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Coherent low OLR region over 5-10N across the Pacific except in March-May 1987 when it is over the equatorial belt.

So there is considerable variation in the way in which El Nino evolves from one event to another and I will consider the anomaly patterns of El Nino events in the satellite era in the later lecture. So in this lecture now, we have learnt what are the important attributes of El Nino, La Nina, we have learnt what the analysis of the data that became available by 80s has shown us, the periodicity of El Nino, La Nina and how it seems to evolve in a large number of cases.

But we have also seen how complex the phenomena is and as soon as one starts generalizing, saying that an El Nino evolves with propagation of anomalies from the east immediately, an exception occurred which told us that not all El Ninos behave in that way. So we will continue to look at El Nino and understanding gained on these very fascinating phenomena in the last 2 decades in the next lecture. Thank you.