The Monsoon and Its Variability
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Lecture - 26
El Nino Southern Oscillation (ENSO)-Part 3

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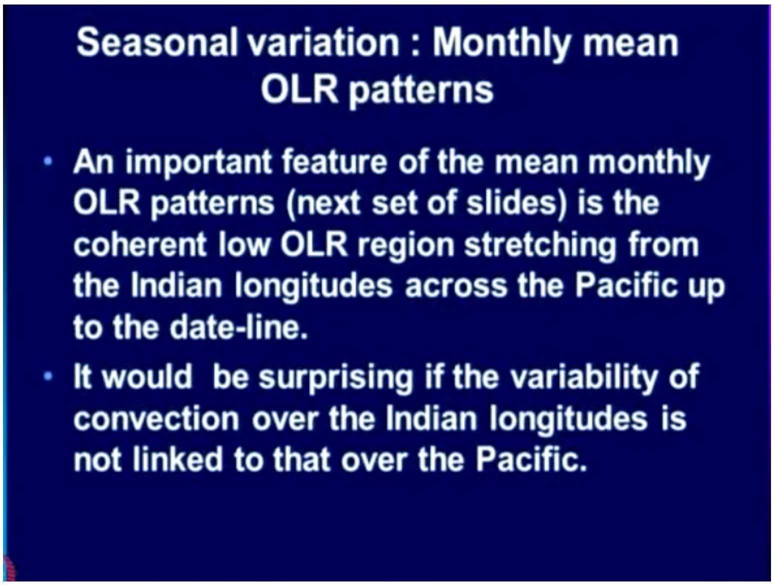

So in this lecture, I continue from where I left of in the last lecture, continue my discussion on the El Nino Southern Oscillation. Remember we were looking at seasonal variation of the tropical atmosphere over the Pacific and we already looked at the seasonal patterns. Now we begin with looking at mean monthly patterns and what we will see an important feature of the mean monthly OLR patterns which we will look at now is the coherent low OLR regions touching from the Indian longitude across the Pacific up to the date-line.

So month after month, you see this is a coherent low region, low OLR region, so it looks like what is happening over the Indian longitudes, is part of a large system of which the other part is over the Pacific. So it would be surprising if the variability of convection over Indian longitudes is not linked to that over the Pacific. In many of the ensource studies people focus just on the Pacific.

But we are interested in the monsoon so we have to focus on both and it is clear that understanding of the coupling over both the oceans is going to be important.

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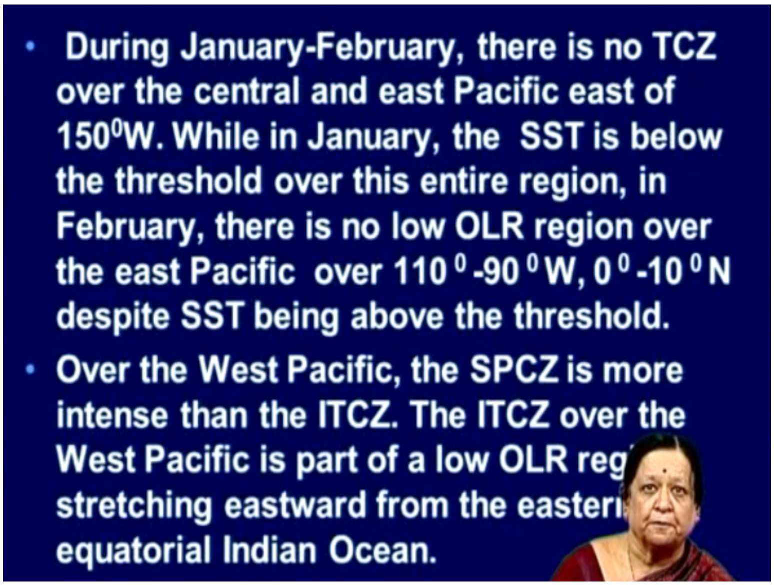

Now during January – February, as we saw in the seasonal pattern there is no TCZ over the Central and east Pacific, east of 150 west.

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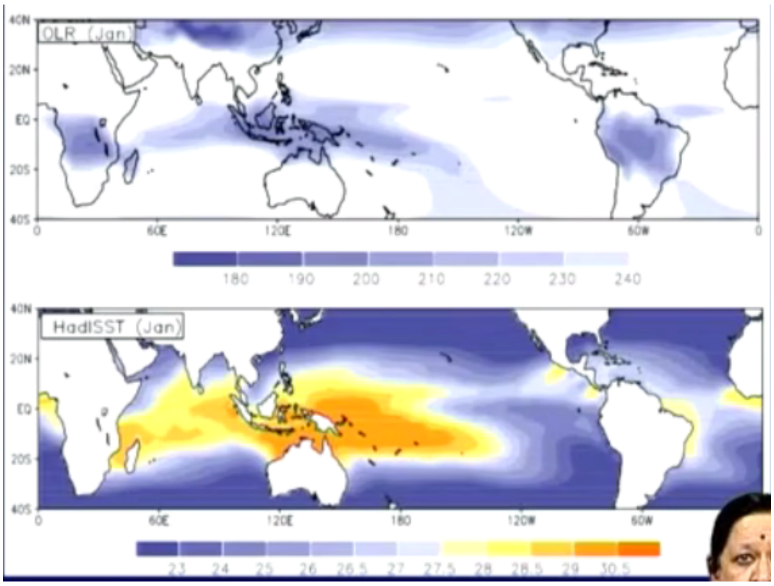

So this is January and you see there is no region of low OLR at all over the east Pacific, here there is no OLR region and you also see that sea surface temperature is below the threshold except for small patches here, very small patches here, so it is not a surprise.

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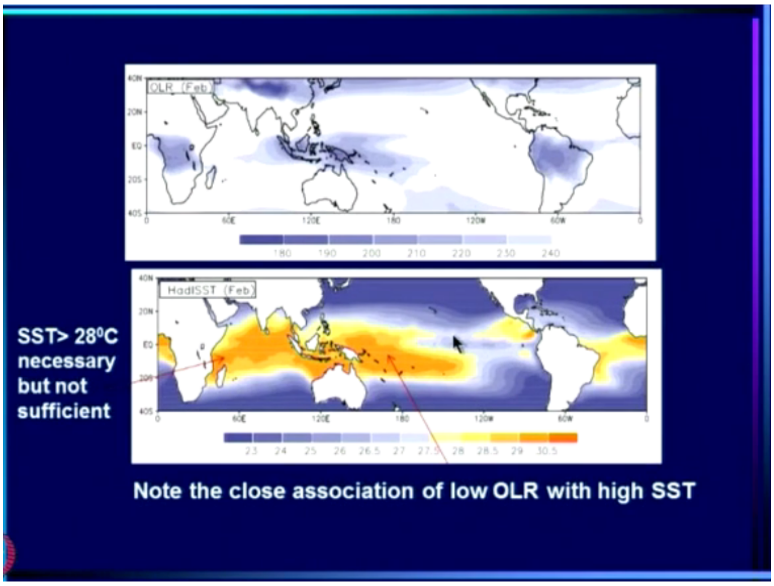

February also the same story, only thing is by February, this patch of warm sea SST higher than threshold has increased in extent as well as intensity. So while in January the SST is below the threshold over the entire region. In February there is no low OLR region over the east Pacific even though the SST is above the threshold, we saw that.

Over the west Pacific, the SPCZ is more intense than ITCZ and the ITCZ over west Pacific is part of a low OLR region which is stretching from the eastern Indian Ocean. So you see west Pacific ITCZ is here and you see the ITCZ is more intense than the SPCZ already. And there is of course no convection here and February despite the ocean being warm there is no convection over the east Pacific.

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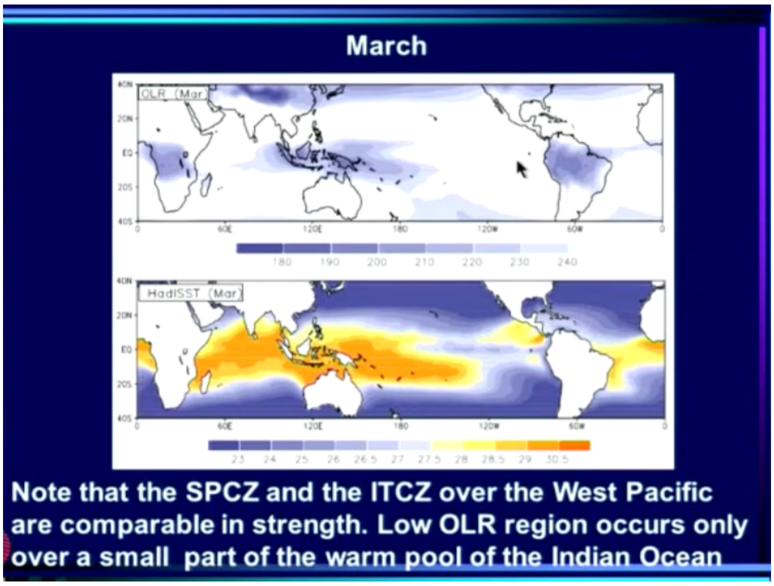

Now what happens in March? Now this region is becoming even warmer and still of course there is no low OLR region over central and east Pacific. But this remains a coherent zone right from the Indian Ocean, one goes to the ITCZ and the other is of course the SPCZ.

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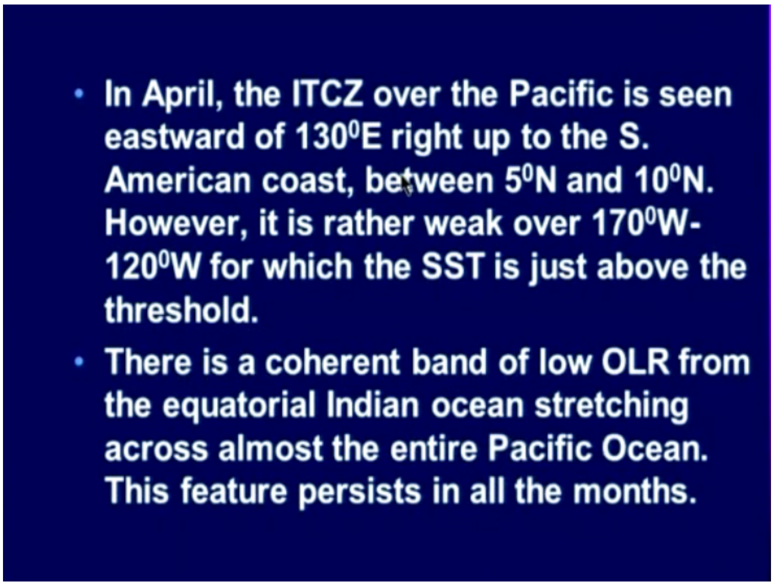

In April, the ITCZ over the Pacific is seen eastward of 130 east right up to the South American coast, so this is the first month in which we see a zonal band here. See a zonal band of low OLR is stretching right across the Pacific here and this is the first month in which we see it.

Remember it was not there in January February March where convection ended more or less over western central Pacific this was the limit and now you see the warm SSTs have become even warmer and the region of warm SSTs here has extended very much more, in fact this the warmest this part guess.

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In May, there is a coherent band of low OLR from 60 east over the equatorial Indian Ocean, stretching eastward

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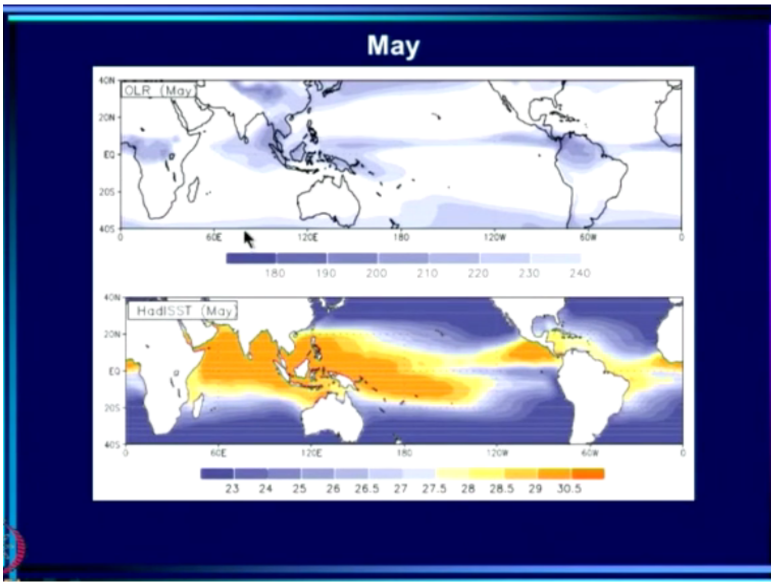

You see this, now what is happened is in April you did have a band which was coherent across this way, but it did not extend so far westward over the Indian Ocean. Now we are seeing a band right from 60 degrees east which is going right across the Pacific. In April, in between this was somewhat weaker, but now the Pacific ITCZ here has strengthened and the ITCZ is definitely stronger than the SPCZ.

So in May already the situation has changed and you see a very coherent band across ITCZ stronger and even here there is a region of low cloud, you also see that it has become even warmer here of the coast of America but remember this is all north of the equator this is not on the equator. On the equator the cold tongue persists.

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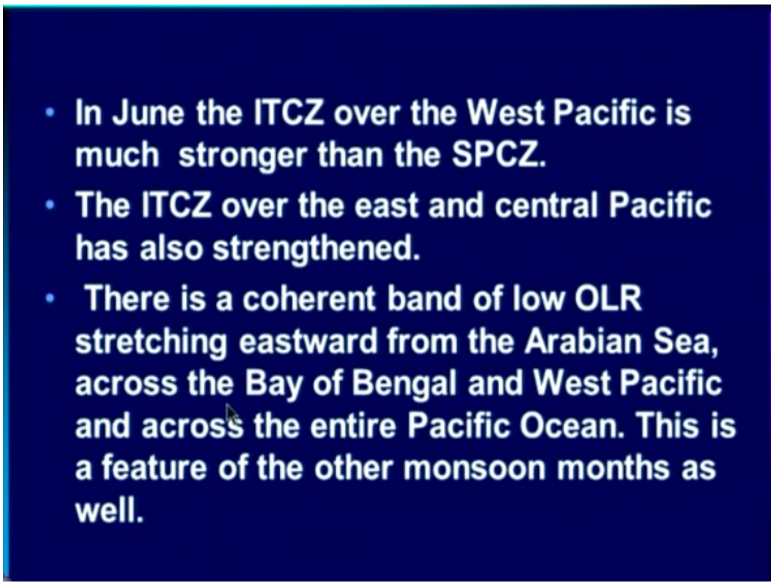

Now in June the west Pacific is much stronger than, the ITCZ over west Pacific is stronger than SPCZ which was true in May as well.

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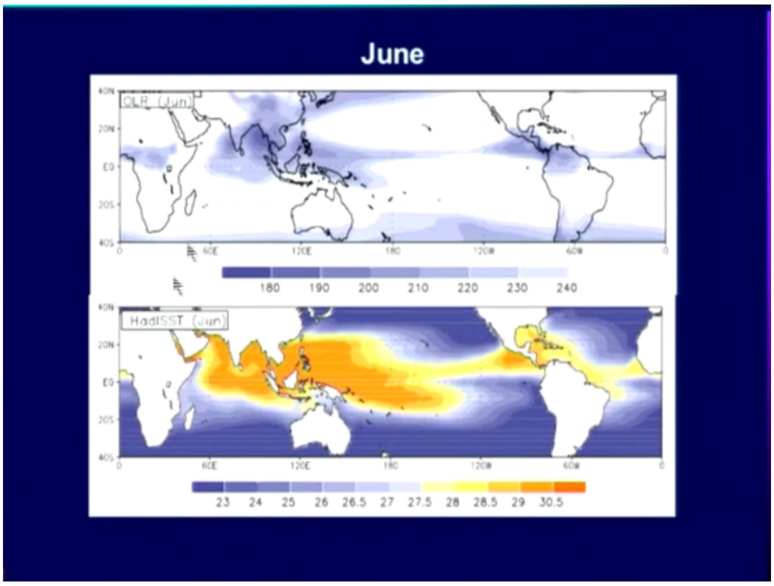

And this entire thing has strengthened more you see this has a stronger, this part has strengthened more and you see now a very coherent band of warm SSTs right across the Pacific in June.

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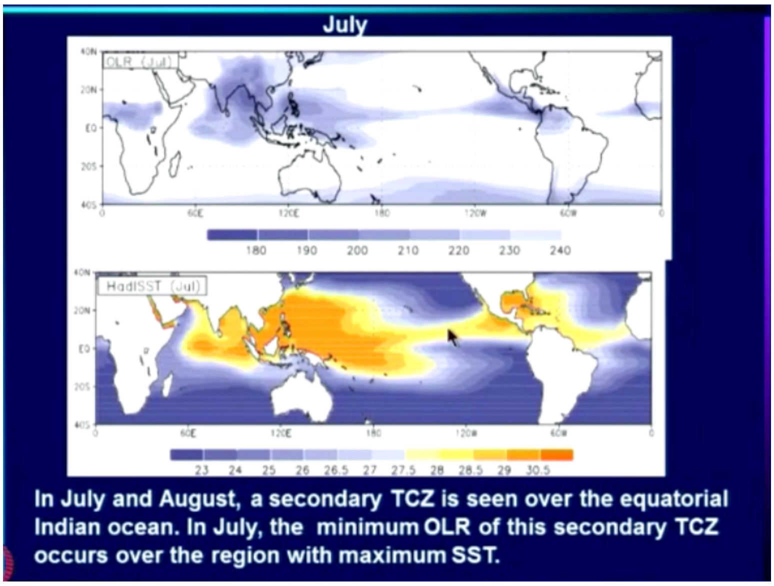

Now in July and August, a secondary TCZ is seen over the Indian Ocean, this is an interesting phenomenon. Of course in July, now the ITCZ over the west Pacific is very much dominating the SPCZ and we have a coherent band here. But what, by July the onset of monsoon has already occurred, so you have most of the clouding and low OLR over the Indian land mass and the Bay of Bengal.

But there is a secondary ITCZ, secondary TCZ rather which is actually just along the warm SSTs here you see. This is the Indian Ocean tropical convergent zone which we have looked at before.

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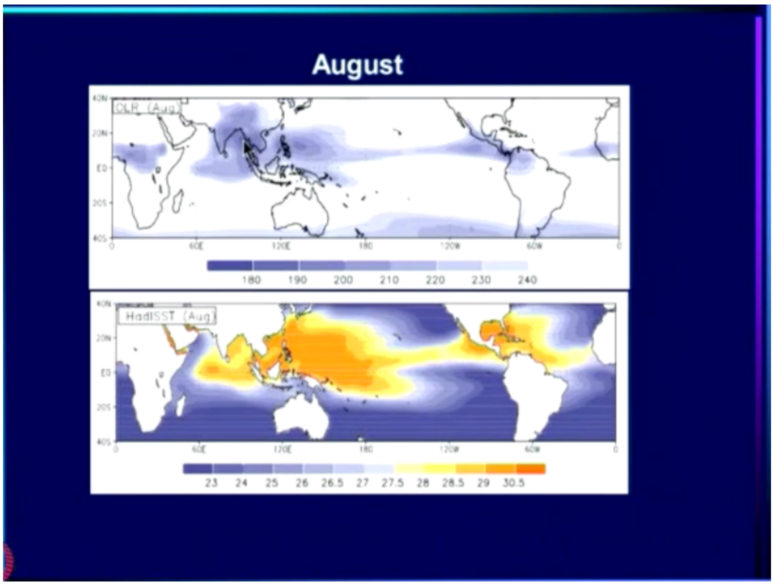

Now, August again the story is similar except this seems to become a more intense and we have a secondary band here and a secondary maximum in SST also over the equatorial Indian

Ocean. You see that this is one is still persisting but not as warm and not as large and extend as in May, you see. In May this was much larger; May you also see another phenomenon which was there also in April a huge band of very warm water here over the Indian Ocean but the clouding is restricted to a very small part of that.

You notice that we mention that SST being above the threshold is the necessary condition but not a sufficient one. This is the very nice demonstration of the lack of sufficiency. Obviously, in April although the ocean is warm, the dynamics is not favourable. So now this is the situation in July and August, the peak monsoon months.

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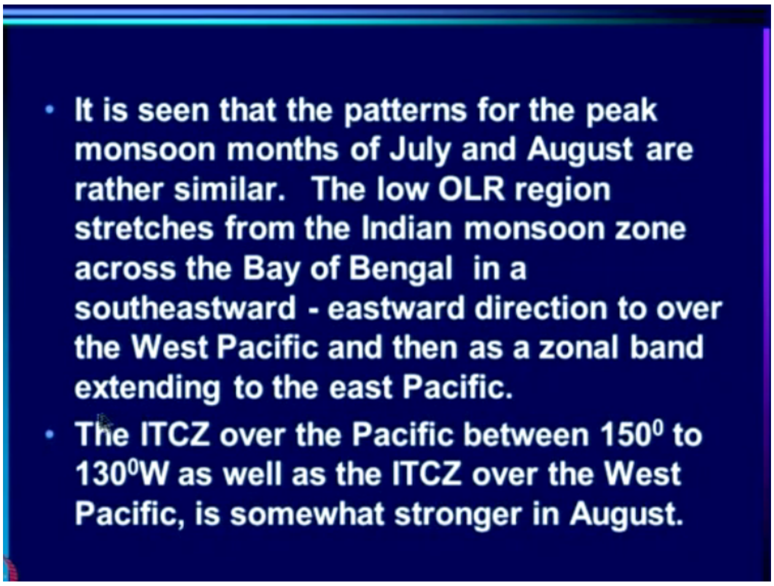

And we have seen that the patterns for the peak monsoon months are rather similar, low OLR region stretches from the Indian monsoon zone across the Bay in a southeastward-eastward direction to over Pacific and then as a zonal band So what is happening is, see here because of the monsoon the TCZ has moved much northward, here it has remained south of 20 north, so the band is going in this direction here and then zonal here.

The ITCZ over the Pacific between 150 and 130 west as well as the ITCZ over west Pacific is somewhat stronger in August. So in August you have very well formed ITCZ right across here and here also it is much stronger where it was somewhat weaker before.

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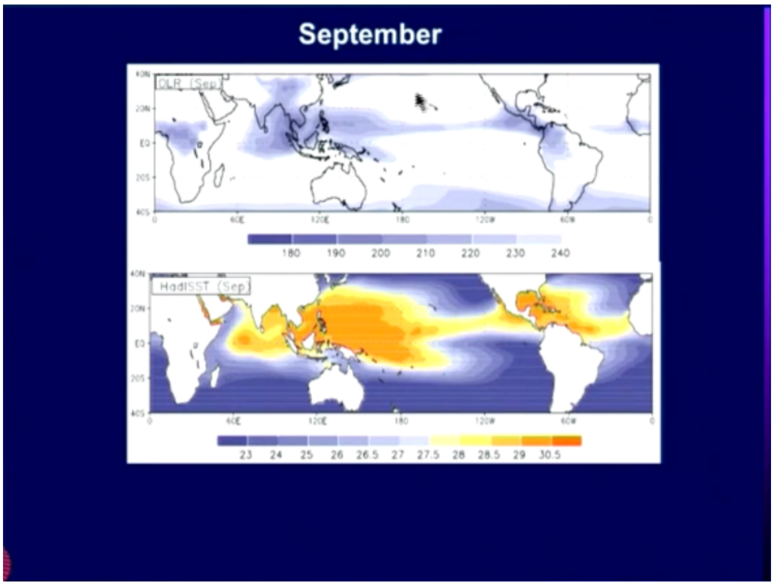

Now, September the system has become weaker, the monsoon has started to withdraw from the country and of course the warm pool region remains on a coherent band of warm water remains and so does the coherent band of low OLR stretching right across the Pacific and same thing continues in October as well.

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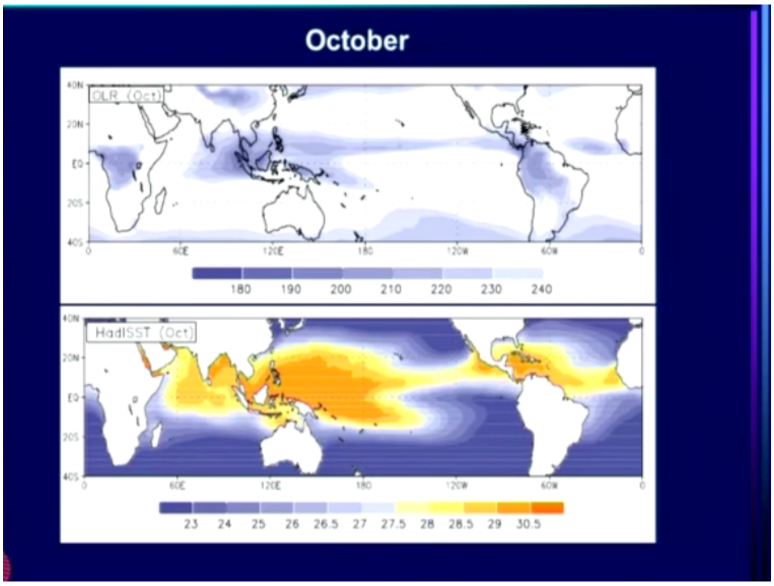

But notice that, now in October the monsoon has withdrawn from much of the Indian land mass and what you have here is the band more or less on the same latitude going all the way from the Indian region where the latitudinal extent is somewhat larger going right across the Pacific up to the America. So this is around 5 north or so 5 to 10 north, this is where the ITCZ is and of course it is consistent with the sea surface temperature.

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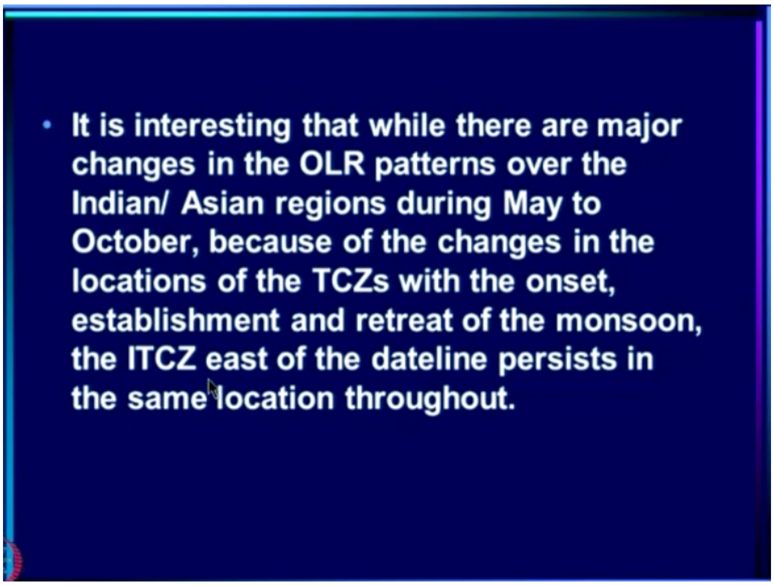

It is interesting that while there are major changes in the OLR patterns over the Indian and Asian regions during May to October because of the changes in the locations of the TCZs with the onset, establishment and retreat of the monsoon, the ITCZ east of the dateline persists in the same location throughout, there is no seasonality at all.

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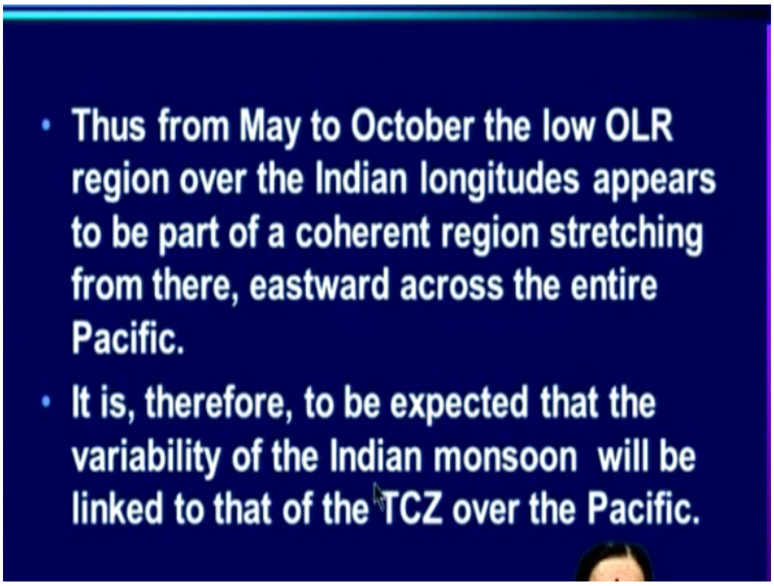

Well, in aware it has nowhere to go, it was not very prominent during December to February, January, February March, but, since April it stays more or less in the same place. Thus from May to October the low OLR region over the Indian longitudes appears to be a part of a coherent region stretching from there, eastward across the entire Pacific.

Now this is the point to be emphasized that we have to remember that our Indian monsoon is a part of a system not only of the large scale Asian monsoon but what you could call part of the system that is stretching across the Indo-Pacific. It is, therefore, to be expected that variability of the Indian monsoon will be linked to the TCZ over the Pacific.

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Now in November and December, the warm SST region over the eastern most part has almost disappeared and you see that here.

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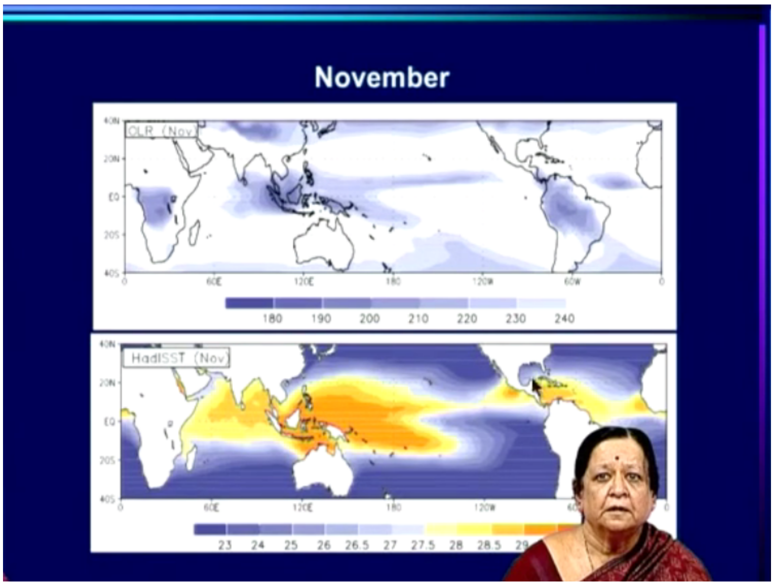

You see the warm ocean region here has become much smaller than it was earlier and with that the low OLR region here has disappeared, still we see an ITCZ from central Pacific but it does not quite reach the coast of America in November.

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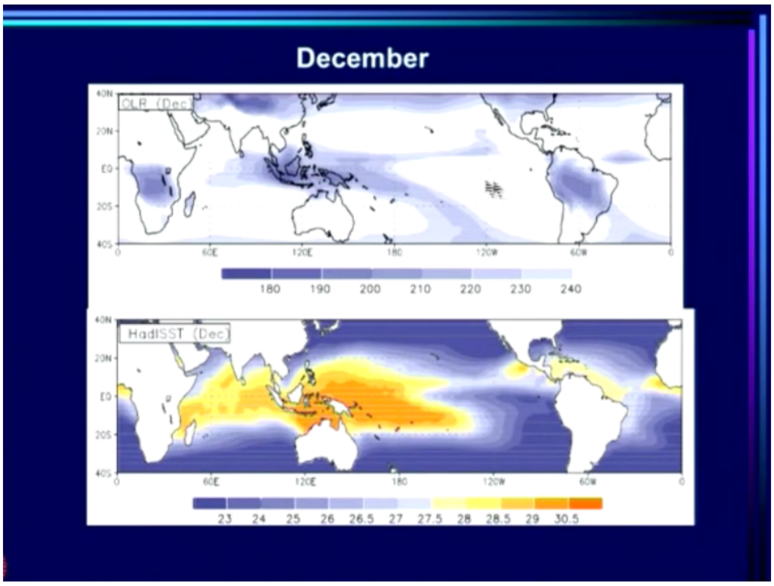

And in December the same story but now actually the SST region has shrunk even further, the warm SST region has shrunk even further and this also has shrunk to some extent and no region of low OLR at the coast of America. So the zone of low OLR stretches from about 60 degrees east over the Indian Ocean across the west Pacific only up to 120 west and does not quite go up to South America.

But still what is happening over the Indian Ocean is the part of a large scale system, but this time the longitudinal extent is somewhat less than it was from M ay to October. It does not quite reach South America.

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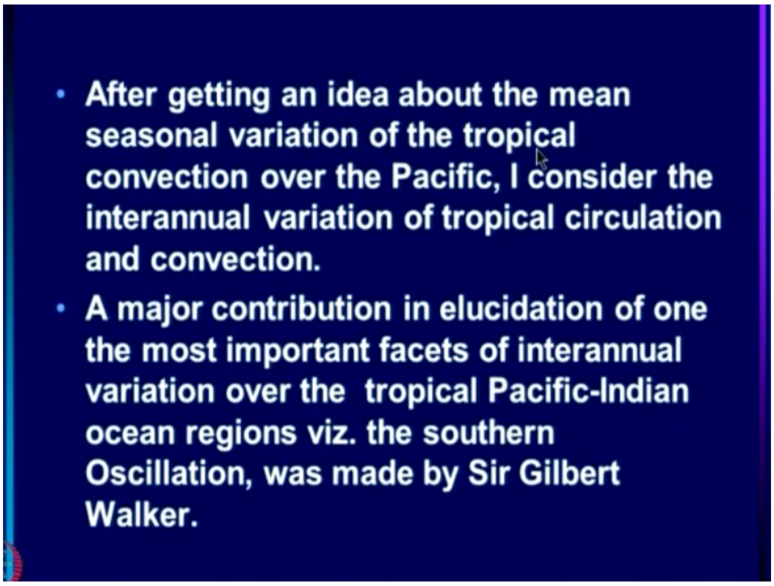

This is so much about the mean seasonal variation of the tropical convection. Now, we have to consider the interannual variation of tropical circulation and convection. Now this is where in a major contribution in elucidation of one the most important facets of interannual variation over the tropical Pacific-Indian ocean regions namely the southern oscillation, was made by Sir Gilbert Walker in the 1930s.So this is a very important facet of interannual variation of the tropical circulation discovered by Sir Gilbert Walker and his colleagues.

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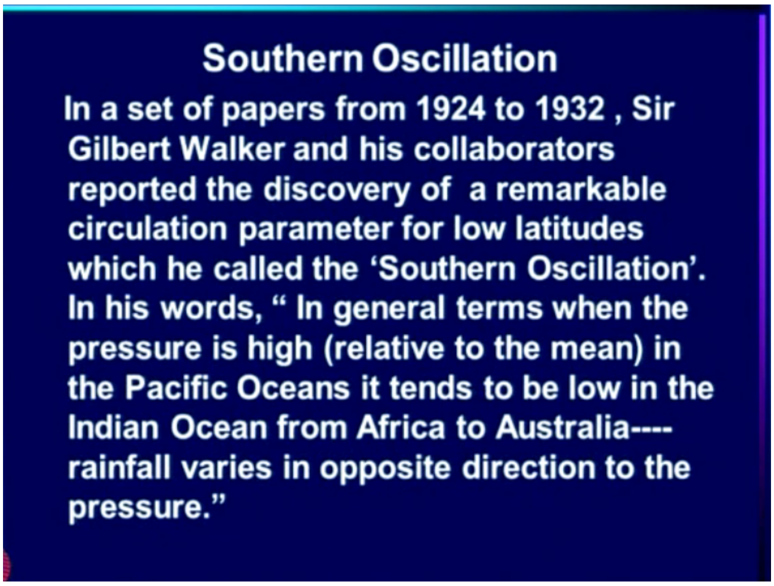

This is the southern oscillation. So in a set of papers from 1924 to 32, Sir Gilbert Walker and his collaborators reported the discovery of a remarkable circulation parameter for a remarkable circulation parameter for low latitudes which he called the 'Southern Oscillation'. In his words, "in general terms when the pressure is high, relative to mean in the Pacific Oceans it tends to be low in the Indian Ocean from Africa to Australia rainfall varies in opposite direction to the pressure.

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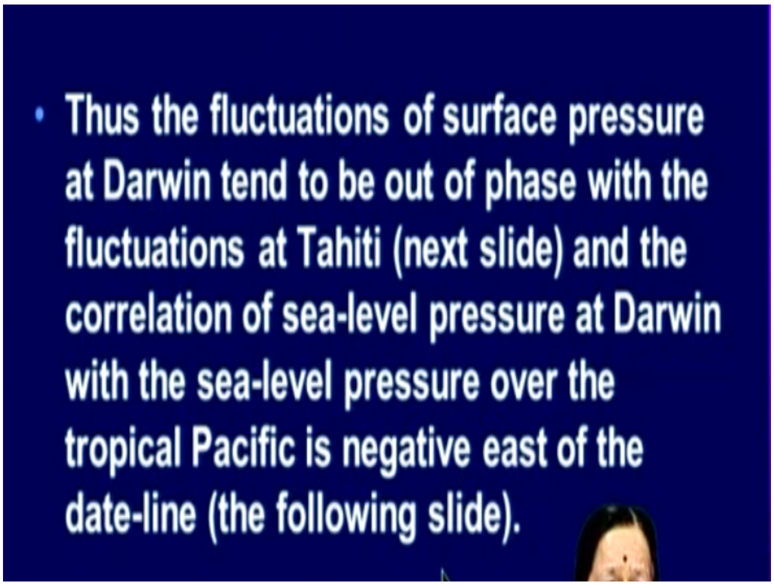

So the fluctuations of surface pressure at Darwin in Australia tend to be out of phase with the fluctuations at Tahiti which is in the central Pacific and the correlation of sea-level pressure at Darwin with the sea-level pressure over the tropical Pacific is negative east of the date-line.

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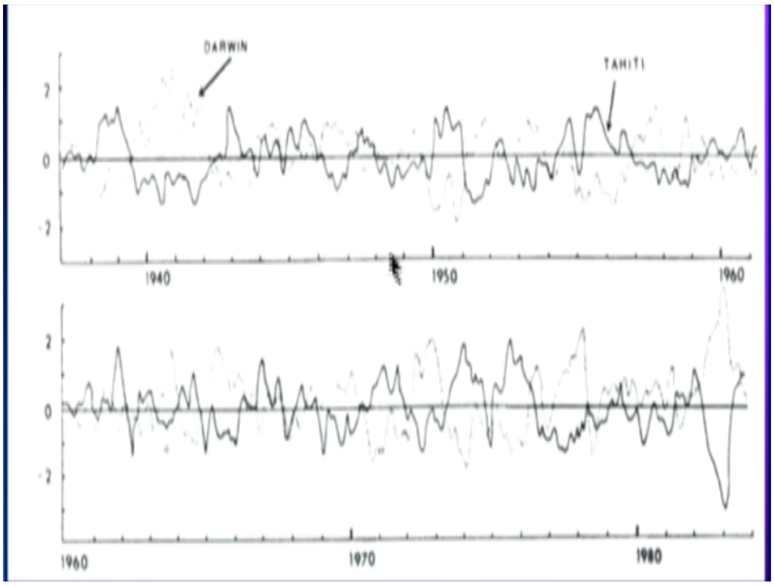

And what you see here is the time series, one of them is Darwin, this dotted line is Darwin and the solid line is Tahiti and you can just see by the eye the (()) (13:15) the variations tend to be out of phase. So you had here, Tahiti anomaly positive, so Darwin was negative, sorry! Darwin was positive, Tahiti was negative. Here Tahiti is positive, Darwin is negative. So on then whole these are in opposite phase and that is why you get negative correlation.

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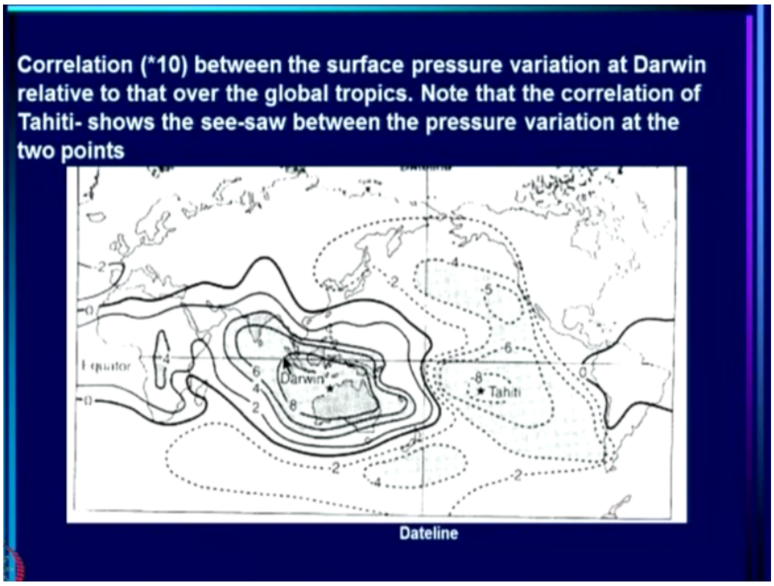

So what you see here is a very famous diagram now. This is the correlation (*10) of the surface pressure variation at Darwin which is here, this is Australia. So this is the correlation between the surface pressure variation at Darwin relative to that over the global tropics and you notice that over this part of the thing see the Indian longitudes varies along mid Darwin same we have a positive correlation. But you see this side of the dateline, this is the dateline.

This side of the date-line Tahiti has a large negative correlation,-0.8.So there is a see-saw between the pressure variations here, the correlations are out of phase, the variations are out of phase as far as the pressure is concerned.

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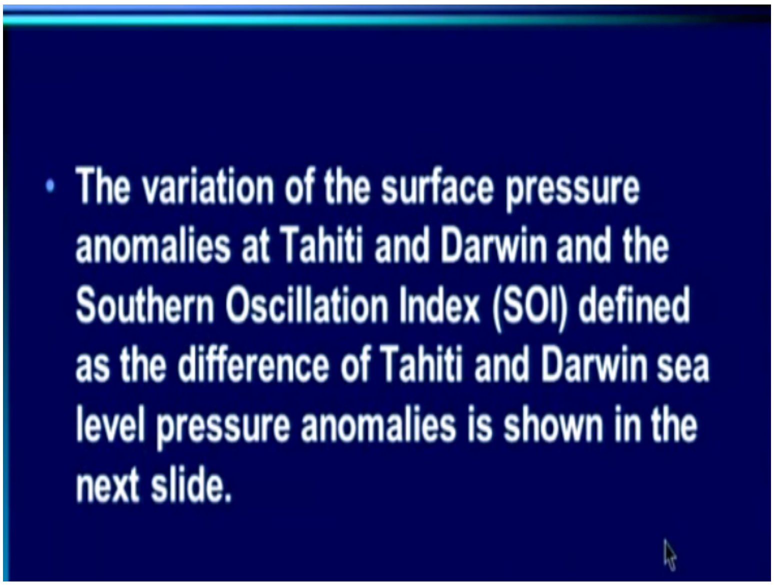

So thus the variation of the surface pressure anomalies at Tahiti and Darwin and the Southern Oscillation Index defined as the difference of Tahiti and Darwin sea-level pressure anomalies is what we see here.

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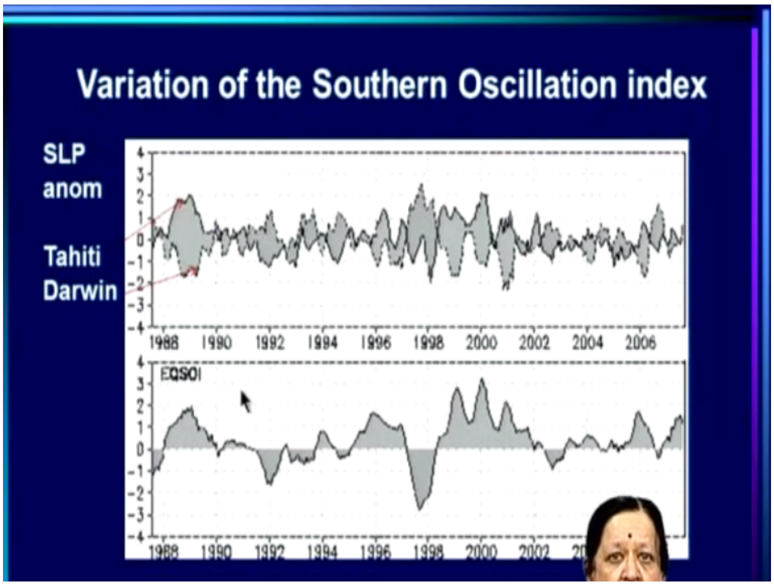

So these are now what you saw there how the pressure varied out of phase, now this is the Sea-level Pressure anomaly. This is Tahiti and this is Darwin. So the difference between the 2 gives you an index which is the Southern Oscillation Index. This is the difference and these are the actual SLP anomalies and you can see that they are out of phase, when one is positive the other tends to be negative.

So the difference is the very robust measure and it is the measure of what we called the Southern Oscillation Index rather what Sir Gilbert Walker calls the Southern Oscillation Index

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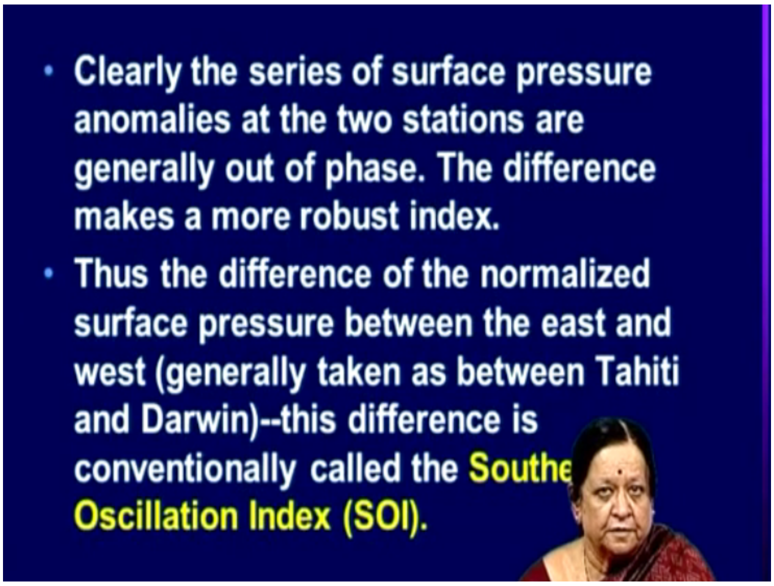

Now clearly the series of surface pressure anomalies at the 2 stations are generally out of phase and the difference makes a robust index. Thus the difference of the normalized surface pressure between the east and the west, generally taken as between Tahiti and Darwin, this difference is conventionally called the Southern Oscillation Index.

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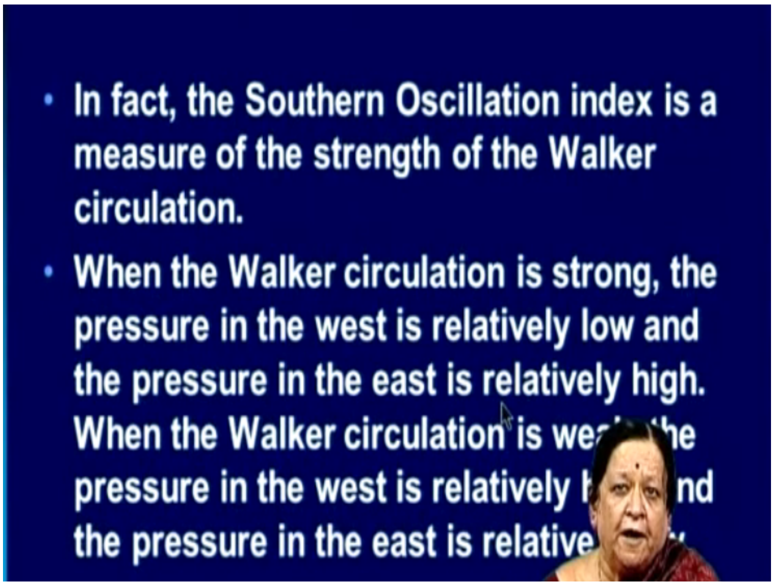

In fact, the Southern Oscillation Index is a measure of the strength of the Walker circulation. When the Walker circulation is strong, the pressure in the west is relatively low and the pressure in the east is relatively high, right. And when the Walker circulation is weak the pressure in the west is relatively high and the pressure in the east.

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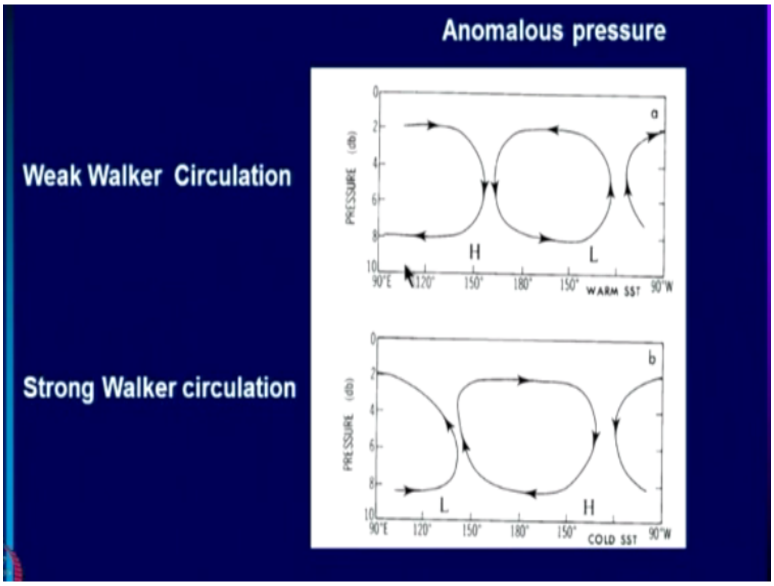

So you have, this is the case of a weak circulation where the pressure in the west is relatively high, now this is relative to mean or climatology and pressure in the east is relatively low. This is when the actual pressure gradient which is from high pressure here to low pressure here weakens. So this is the weaker Walker circulation and what you see is, this is the stronger Walker circulation where you have very strong, the TCZ located, the rising limb located right over west Pacific and sinking limb here.

Now what has happened in weak case is that the rising limb gets shifted to the central Pacific.

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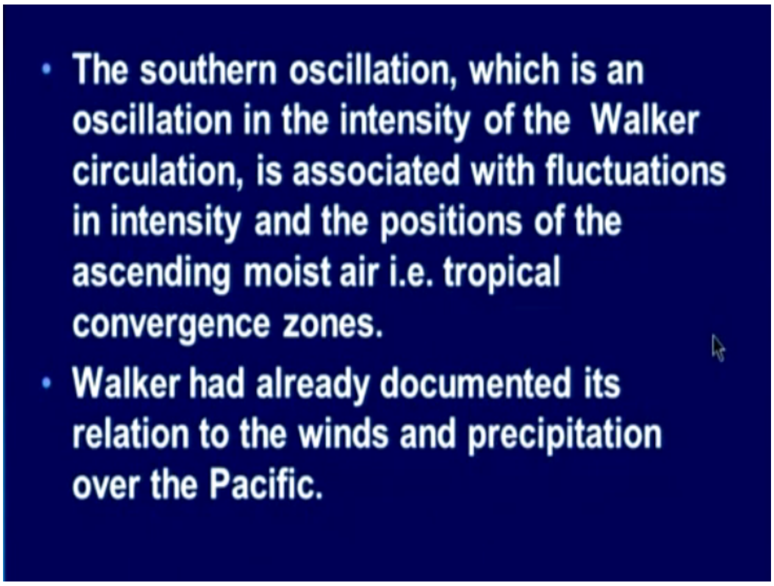

So the southern oscillation, which is an oscillation in the intensity of Walker circulation, is associated with fluctuations in intensity and positions of the ascending moist air that is tropical convergence zones. And Walker had already documented its relation to the winds and precipitation over the Pacific.

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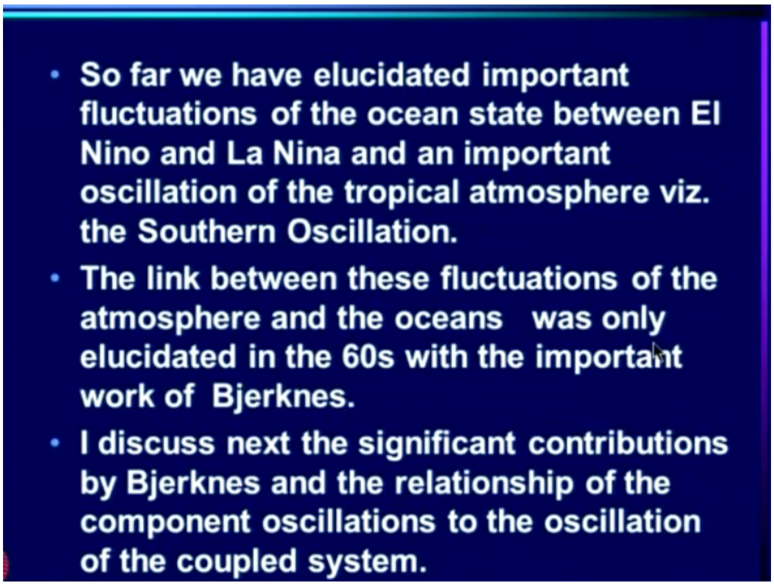

Now, so far we have elucidated important fluctuations of the ocean state between El Nino and La Nina and an important oscillation of the tropical atmosphere namely southern oscillation. Now this is an oscillation of the east west pressure gradient over the equatorial Pacific, so this is the pressure gradient in the atmosphere, oscillation of the pressure gradient in the atmosphere where as El Nino and La Nina are the warm and cold states of the Pacific which are seen as major oscillations in the sea surface temperature distribution over the Pacific.

Now the link between these fluctuations of the atmosphere and the oceans was only elucidated in the 60s with the important work of Bjerkness. Now the contribution of Bjerknes is so important to our present understanding of ENSO and I thought it was worthwhile to actually discuss those 2 very critical papers, seminal papers that Bjerknes wrote in 66 and 69 and what the contribution is.

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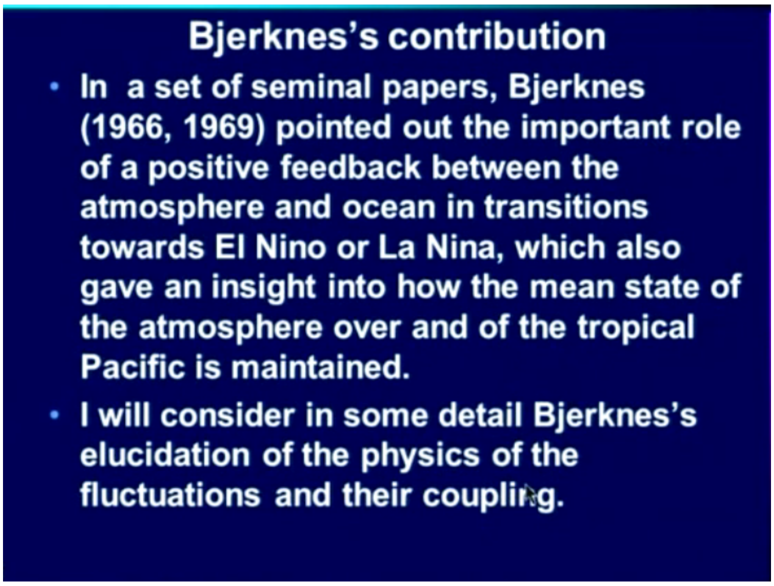

So in a set of seminal papers, Bjerknes in 66 and 69 pointed out the important role of a positive feedback between the atmosphere and ocean in transitions towards El Nino and La Nina, which also gave an insight into how the mean state of the atmosphere over and of the tropical Pacific is maintained. So now I am going to consider in some detail Bjerknes's elucidation of the physics of the fluctuations and their coupling.

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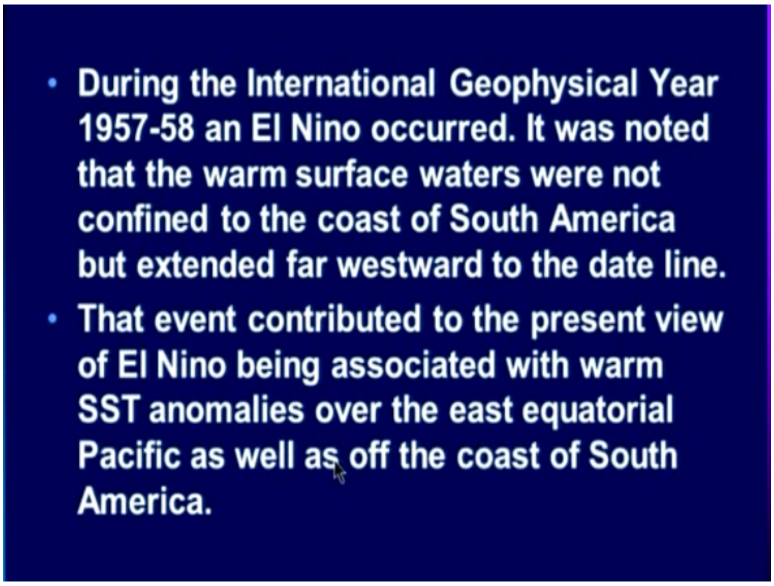

Now as you recall, originally El Nino was defined as the SST anomaly of the coast of Peru and Ecuador that is to say over east Pacific close to the South American coast. Now during the International Geophysical Year 1957-58 an El Nino occurred and because it was International Geophysical Year there were a lot of observations.

And it was noted that the warm surface waters were not confined to the coast of South America but extended far westward to the dateline. That event contributed to the present view of El Nino being associated with warm SST anomalies over the east equatorial Pacific as well as off the coast of South America.

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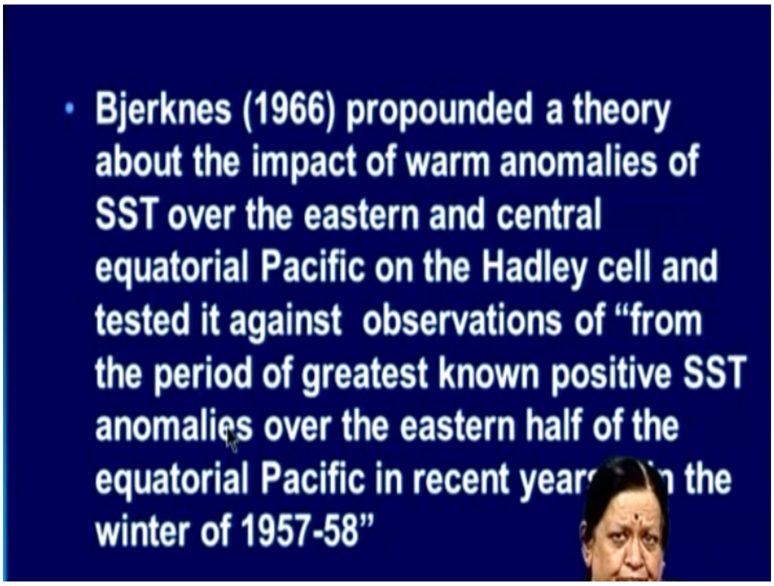

So Bjerknes propounded a theory about the impact of warm anomalies of SST over the eastern and central equatorial Pacific on the Hadley cell. See this is where the importance of coupling comes in, he actually propounded a theory about how these SST anomalies would impact on the convection in the atmosphere on the Hadley cell and tested against observations of “from the period of greatest known positive SST anomalies over the eastern half of the equatorial Pacific in recent years in the winter of 57 and 58.

So he actually propounded the theory on how SST have impact on the Hadley cell and compared it, tested against observations.

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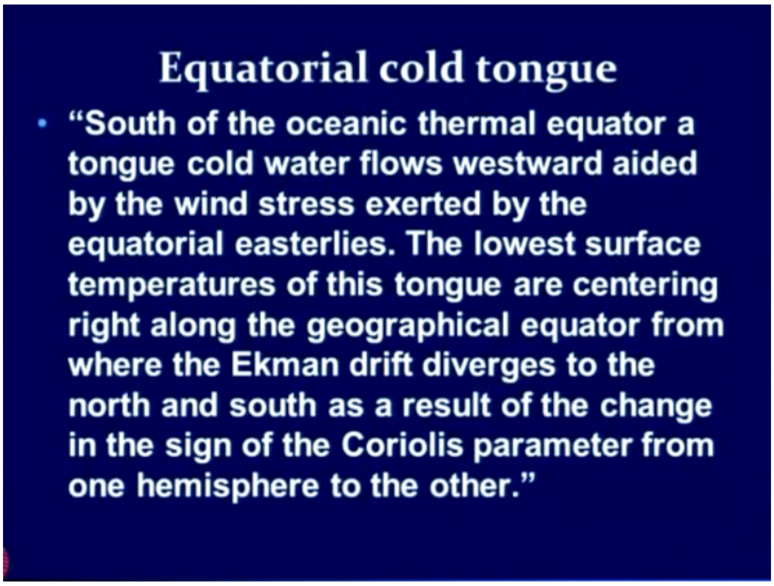

Now first of all, he talks about the equatorial cold tongue, “South of the oceanic thermal equator a tongue cold water flows westward aided by the wind stress exerted by the equatorial easterlies. Now, the lowest surface temperatures of this tongue are centering right along the geographical equator which is what we have seen in so many pictures of SST, that the center of the cold tongue is right along the geographical equator from where the Ekman drift diverges to the north and south as a result of the change in the sign of the Coriolis parameter from one hemisphere to another.

We have actually seen how equatorial upwelling occurs because of this Ekman flow diverging there

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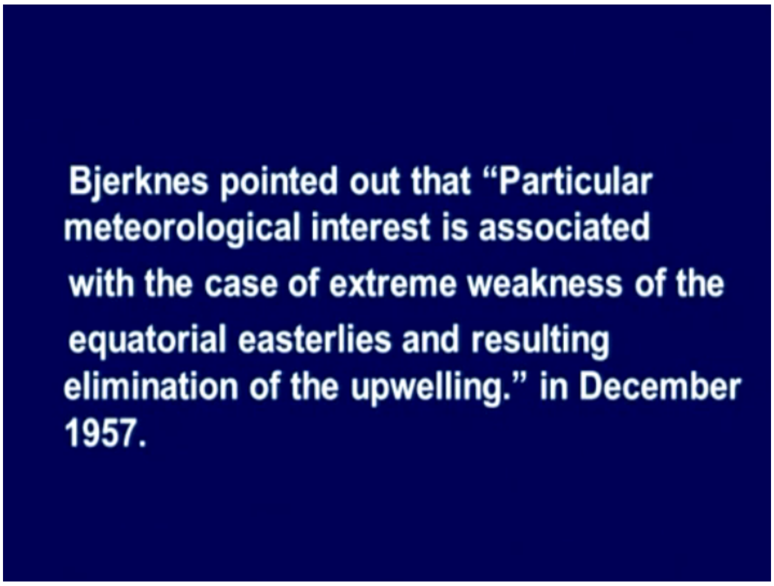

Bjerkness pointed out that "particular meteorological interest is associated with the case of extreme weakness of the equatorial easterlies and resulting elimination of the upwelling. So he has, this is again the link which was known before this time but pointed out by him that if the trade winds become weaker, these easterlies become weaker, then one can have much weaker upwelling including elimination of upwelling.

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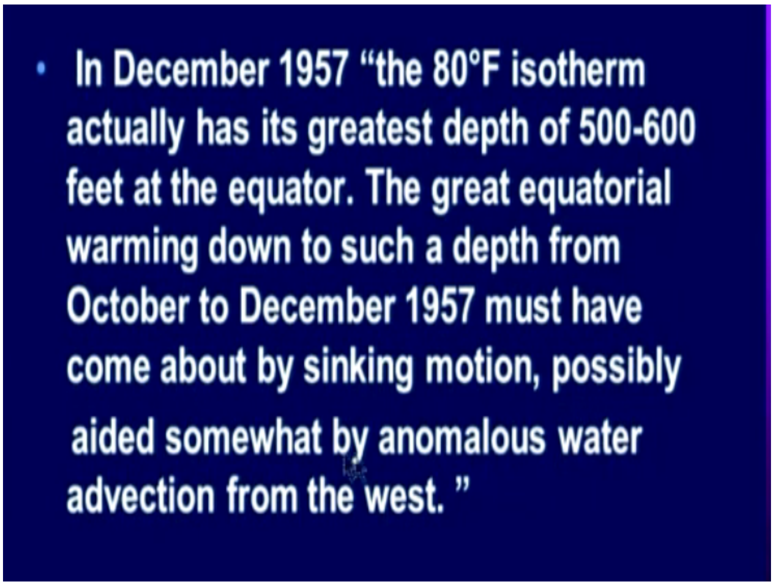

And he talks about how the upwelling has got eliminated, how the thermocline has become deeper, he said that "the 80 degrees Fahrenheit isotherm actually has its greatest depth of 500 to 600 feet at the equator, he said. The great equatorial warming down to such a depth from October to December 57 must have come about by sinking motion, possibly aided somewhat by anomalous water advection from the west.

So he is actually now elucidating the physics of the process how the thermocline became weaker when the upwelling was cut off and what else besides the cutting of upwelling could have contributed to the deepening of the thermocline

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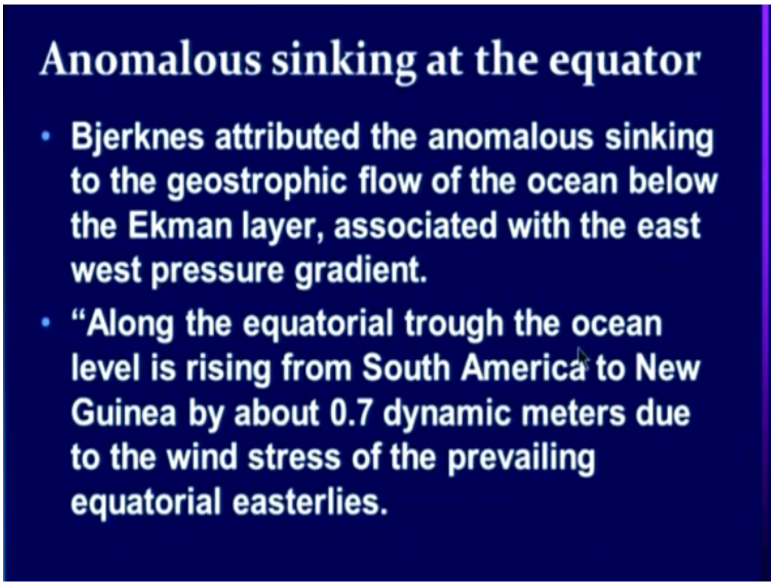

Now, this is where he talks of anomalous sinking at the equator, I mention all this because this still holds true, several years, 50 years after Bjerknes's paper, almost 50 years, Bjerkness attributed the anomalous sinking to the geostrophic flow of the ocean below the Ekman layer, associated with the east west pressure gradient. Remember, we had pointed out that the wind drives the ocean from east to west.

Because of this there is a piling of water on the west relative to the east, that is to say the sea-level on the west Pacific is higher than that in the east. So this means that within the ocean there is a pressure gradient, which is, pressure which is high on the west side where there is a larger column of water above any point relative to the east. So you have a pressure gradient which is high on the west and low in the east in the ocean.

And therefore to this pressure gradient will lead to geostrophic flow. Now along the equatorial trough he points out that the ocean level is rising from South America to New Guinea by about 0.7 dynamic meters due to the wind stress of the prevailing equatorial easterlies. So because the winds are piling up water against the west, we have a pressure gradient in the ocean. Well, there is high pressure in the west and lower pressure in the east.

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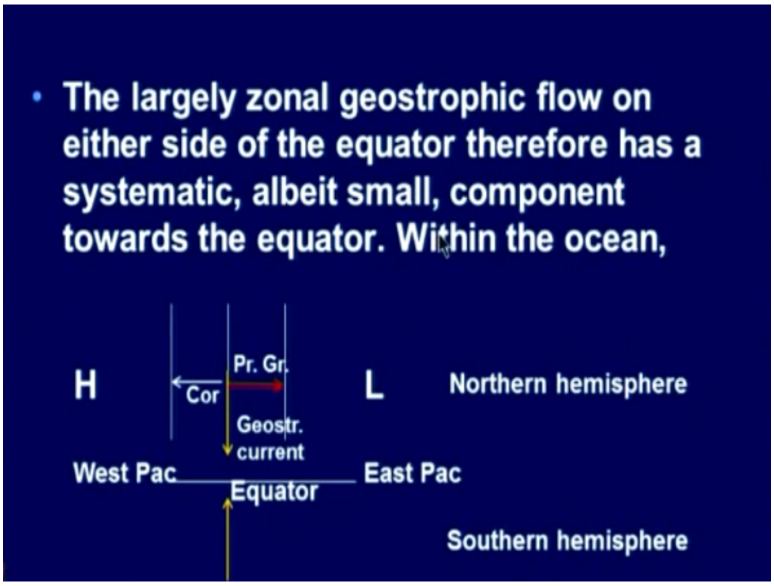

Now let us see how this geostrophic flow comes about. So we have in the ocean in the northern hemisphere, a high pressure to the west, low pressure to the east and this means that the pressure gradient force is this way and a geostrophic wind in which there is a balance between the pressure gradient and the Coriolis force has to be towards the south or towards the equator, because that is the only way, only when it is to the south can the Coriolis force balance the pressure gradient.

If it were, you know that the geostrophic wind is along lines of equal pressure, so it has to be along this line. But, if it were in the opposite direction say it was going northward, then pressure gradient and Coriolis force would be in the same direction, so there is no question of one balancing the other. So the geostrophic current in the ocean has to be towards the equator. Now in the southern hemisphere also it has to be towards the equator.

Remember, the pressure gradient is the same in the southern hemisphere. But, in the southern hemisphere since the Coriolis force acts to the left of the wind, when the wind, when the current is going towards the equator, you have the Coriolis force balancing the pressure gradient. So both in the northern and southern hemisphere, the geostrophic current which is generated by the east west pressure gradient is towards the equator.

So this is very interesting. Now in the Ekman layer the situation is different, geostrophic current is below the Ekman layer. So below the Ekman layer then you have convergence, in the Ekman layer you actually have divergence at the equator and that is why equatorial upwelling. But below the Ekman layer you actually have convergence from both north and south of currents at the equator

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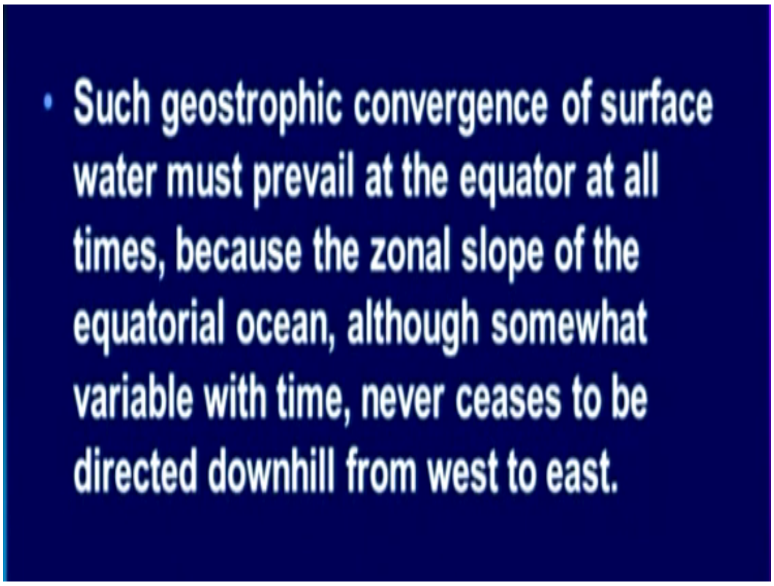

Now, such geostrophic convergence of surface water must prevail at the equator at all times, because the zonal slope of the equatorial ocean, although somewhat variable with time, never ceases to be directed downhill from west to east. So this pressure, easterlies are always maintained irrespective of what happen and so this gradient, pressure gradient is always maintained because the sea-level is higher over the west Pacific than over the east Pacific.

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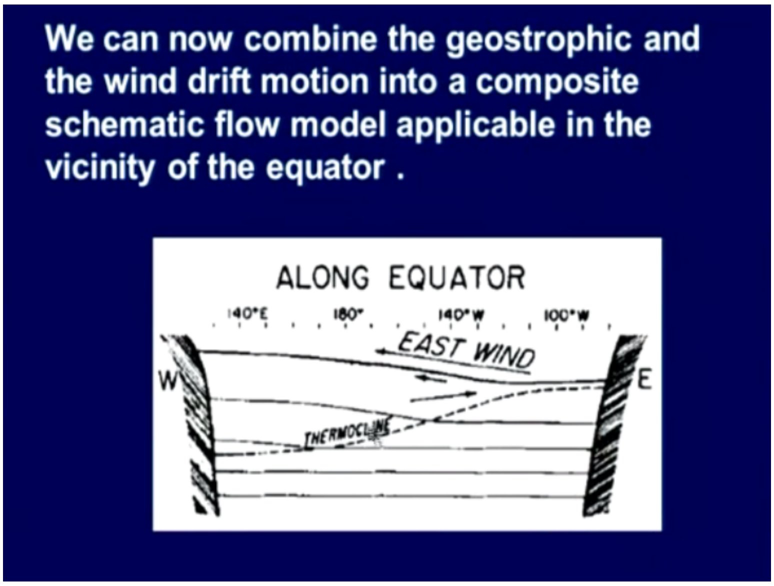

Now, we can combine geostrophic and the wind drift motion into a composite schematic flow model applicable to the vicinity of the equator. And this is the schematic model that Bjerknes proposed, what you have is eats wind here, okay. And this east wind will create along the equator current which goes in the same way from east to west. This is what is leading to piling up of water. But the geostrophic current which is below the Ekman layer is in fact going in this direction and this is the.

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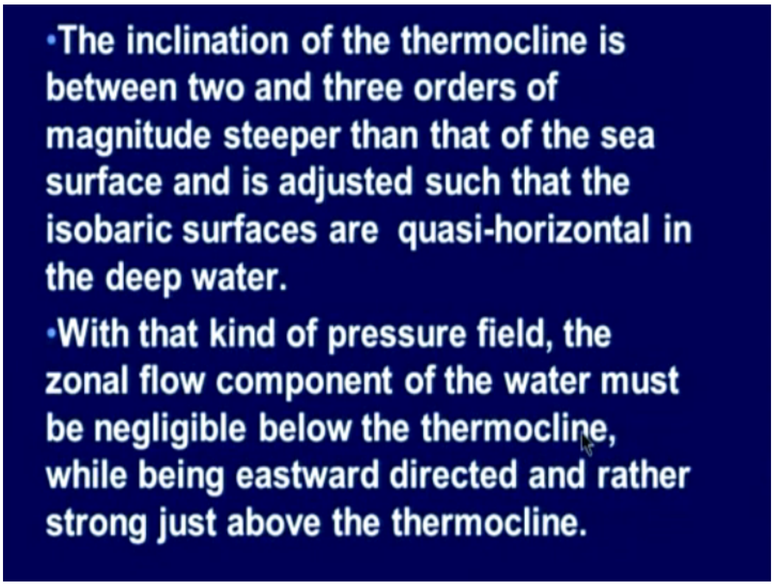

So the inclination, first we should look at the inclination of the thermocline, now we see that there is piling up of water here, and so there is deeper thermocline here then there is there. So this is the thermocline which is inclined here and actually the inclination with the thermocline is going to be much larger than the inclination of the surface here. See, surface is higher in the west Pacific than in the east Pacific, because the winds have pushed the water up.

But thermocline slope is in the opposite direction and if you go where much below the thermocline then the 2 have to balance each other and there can be any pressure gradient occurrence because in the deep ocean there can be hardly any current. This is why the thermocline is tilting the other way. And he mentions that the inclination of the thermocline is between 2 to 3 orders of magnitude steeper than that of the sea surface and is adjusted such that the isobaric surfaces are quasi-horizontal in the deep water.

So this is the way the pressure field is. With that kind of pressure field, the zonal flow component of the water must be negligible below the thermocline because there are no pressure gradients below the thermocline, while being eastward directed and rather strong just above the thermocline. So with this kind of pressure gradient just above the thermocline, it is going to be directed to the east.

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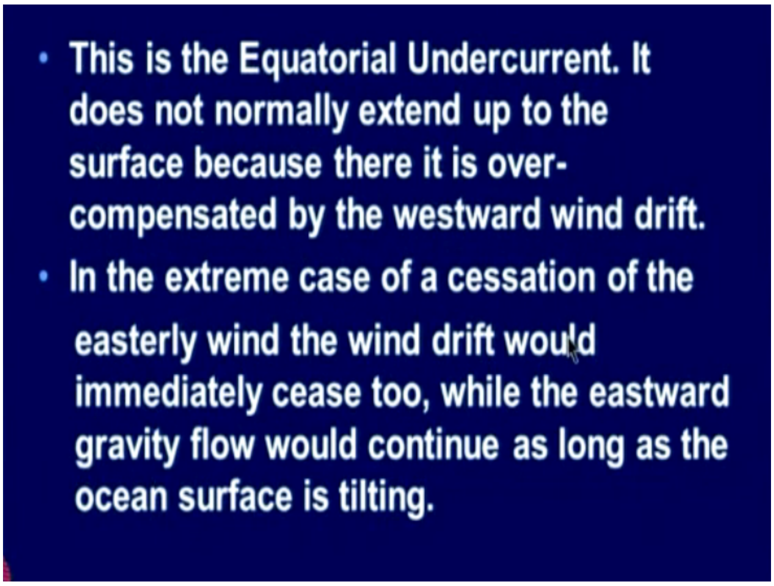

This is the equatorial under current which actually generated a lot of interest when it was first discovered and this was in the 50s.It does not normally extend to the surface because there is an over compensated, it was over-compensated by westward wind drift, okay. Because there is, water is being pushed by the wind towards the west but the geostrophic flow is towards the east, so that becomes an undercurrent.

In the extreme case of a cessation of the easterly wind the wind drift would immediately cease too, while the eastward gravity flow would continue as long as the ocean surface is tilting.

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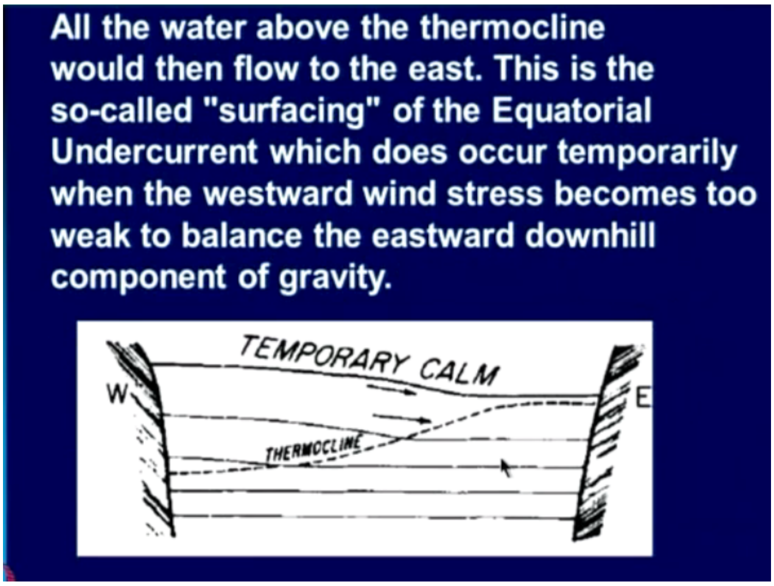

So what happens when you have calm is that because the ocean surface is tilting, you will get this kind of a gravity flow going towards the east. So this gravity flow which is occurring because the level here is higher than level here will be the only current that will be seen if there are no winds to push the water up. So all the water above the thermocline would then flow to the east.

This is the so called surfacing of the equatorial undercurrent which does occur temporarily when westward wind stress becomes too weak to balance the eastward downhill component of gravity.

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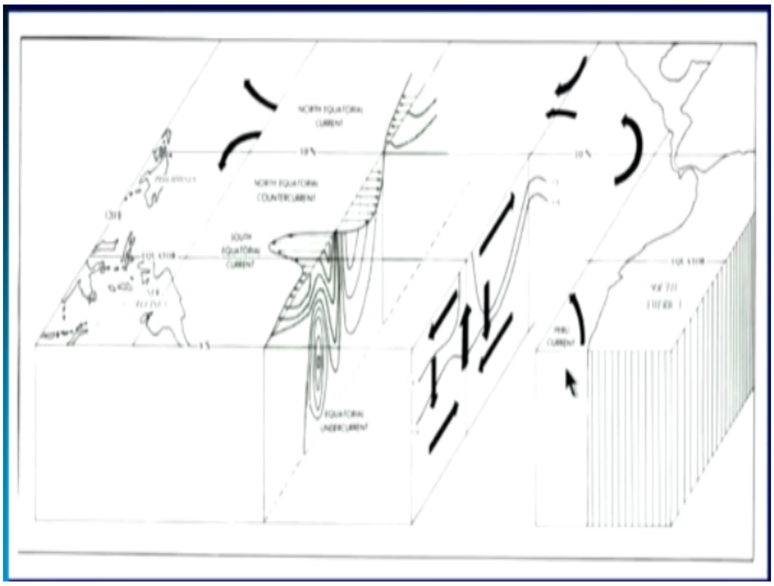

Now this is a picture from George Philander which shows how complicated things are here. This is the equatorial regions so you have, at the surface you have a flow like this going towards the west and this is the equatorial undercurrent. This is the section if you wish and you have divergence here because of Ekman drift, in Ekman layer but you actually have convergence here because of geostrophic.

This is what Bjerknes show and this is of course upwelling of the coast. So life is very complicated but it was very elegantly explained. This complicated slow pattern of the ocean by Bjerknes.

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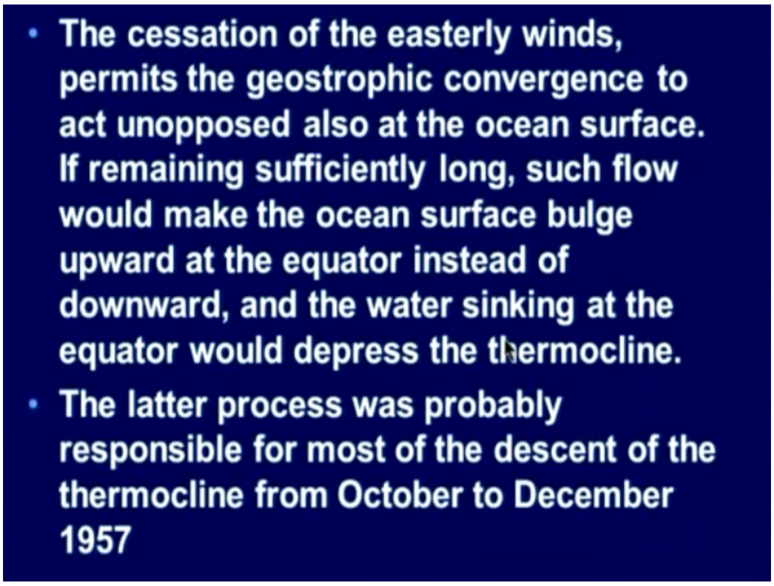

Now he says that the cessation of easterly winds permits the geostrophic convergence to act unopposed also at the ocean surface. If remaining sufficiently long, such flow would make the ocean surface bulge upward at the equator instead of downward, and the water sinking at the equator would depress the thermocline. Remember, we had shown that if you have an eastward flow.

You would have water bulging at the equator because of the convergence and that would, that can be only compensated by water sinking at the equator and depressing the thermocline. So the latter process was probably responsible for most of the descent of the thermocline in 57. So he explains how the warming occurred because sinking took place around the equator, instead of upwelling sinking took place because the winds were so weak.

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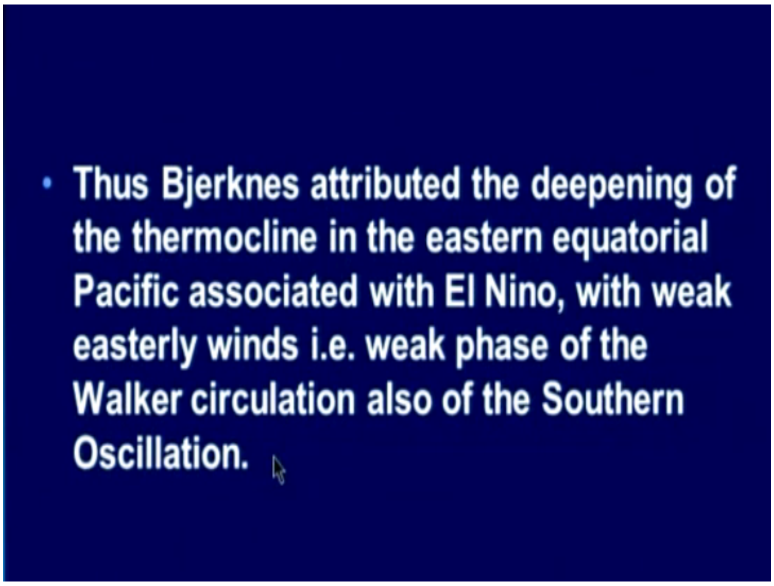

So Bjerknes attributed the deepening of the thermocline in the eastern equatorial Pacific associated with El Nino, with weak easterly winds, that is weak phase of the Walker circulation also of the southern oscillation.

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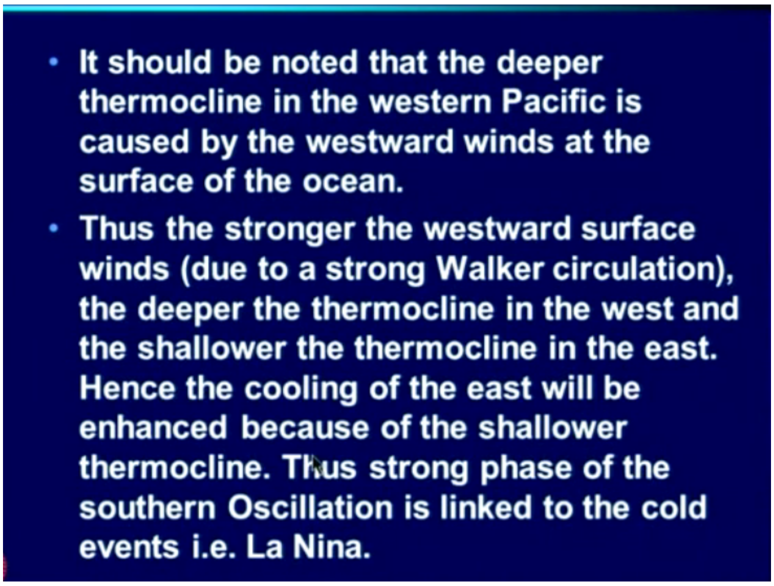

It should be noted that the deeper thermocline in the western Pacific is caused by the westward winds at the surface of the ocean. Thus the stronger the westward surface winds, so due to a strong Walker circulation, the deeper the thermocline in the west and the shallower the thermocline in the east. Hence the cooling of the east will be enhanced because of the shallow thermocline.

Thus, strong phase of the southern oscillation is linked to cold events, that is, La Nina.

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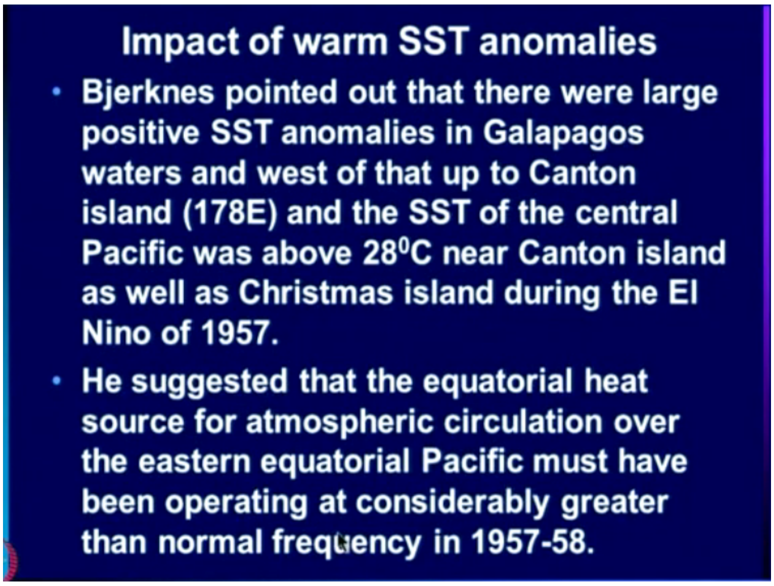

Now impact of warm SST anomalies. Bjerknes pointed out that there were large positive SST anomalies in Galapagos waters and west of that up to Canton island, we talked about Canton island, how it became warm and the rainfall increased enormously, and the SST of the central Pacific was above 28 degree centigrade near Canton island which we saw, as well as Christmas island during the El Nino of 57.

So Bjerkness suggested that the equatorial heat source for atmospheric circulation over the eastern equatorial Pacific must have been operating at considerably greater than normal frequency in 57-58. So he is saying because of the warm SSTs, the heat source is operating at a much higher frequency.

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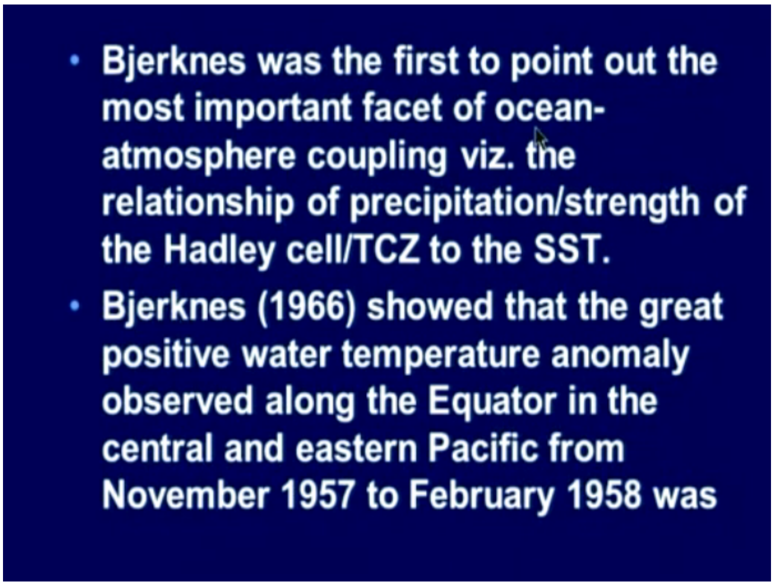

And Bjerknes was the first to point out the most important facet of ocean atmosphere coupling namely, the relationship of precipitation or strength of the Hadley cell or what we call the Tropical Convergent Zone to the SST.Now this actually Bjerknes showed that the great positive water temperature anomaly observed along the equator in central.

And eastern Pacific from November 57 to February 58 was accompanied by an anomalously great heat supply from the equatorial ocean to the ascending branch of the atmospheric Hadley circulation and intensification of that circulation.

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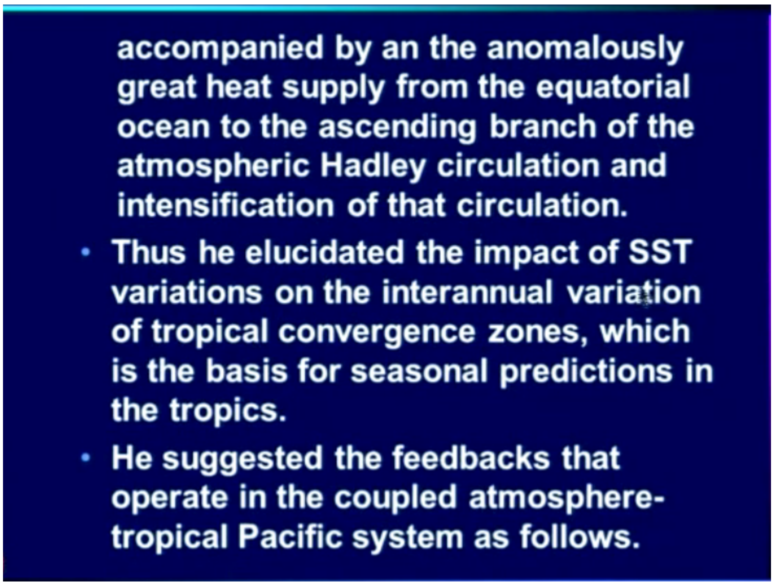

We saw manifestation of that in the increase of rainfall over Canton Island. Thus he elucidated the impact of SST variations on the interannual variation of tropical convergence zones, which is the basis for seasonal predictions in the tropics. Now you must remember that while atmosphere changes very fast, the ocean changes much slowly, much more slowly it is a sluggish fluid and so this is of great importance.

Because the atmosphere is responding very fast to the sea surface temperature as you saw the Canton Island case that Bjerknes showed. And because the atmosphere response fast but the SST is evolving slowly because it is a feature of the ocean, so it became possible to think of predictions because of the atmospheric phenomenon, because of the slowly evolving boundary condition. We will come to this when we talk of seasonal predictions.

This is what Charlie Neese pointed out that in the tropics we should be able to have predictions on the seasonal scale, because in the tropics a major, the most important part of the circulation, convection and precipitation is driven by sea surface temperature that is boundary forcing, which is evolving slowly. So we should be able to generate predictions of rainfall in the tropics.

This was suggested Charlie Neese and the basis of that is the relationship between SST and rainfall which Bjerknes first elucidated. Now Bjerknes also suggested the feedbacks that operate in the coupled atmosphere-tropical ocean system as follows.

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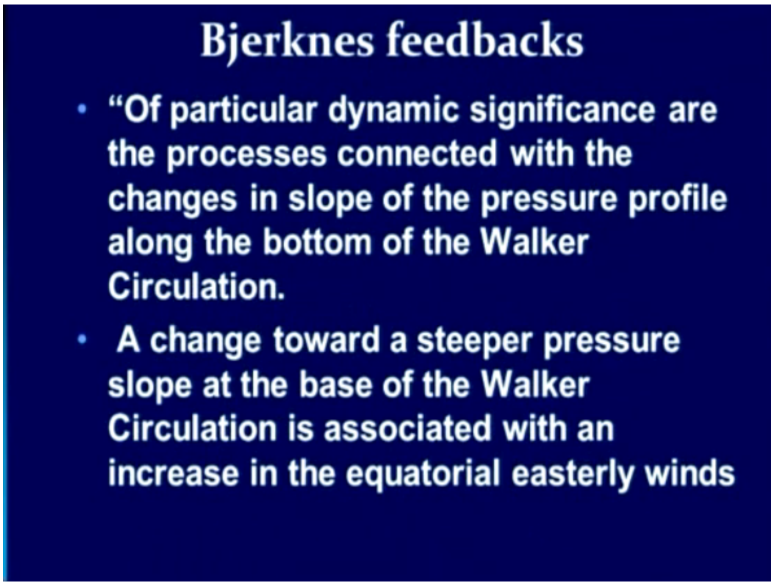

These are the Bjerknes feedbacks. Of particular dynamic significance are the processes connected with changes in slope of the pressure profile along the bottom of the Walker circulation. By bottom of the Walker circulation, he means that the pressure, the atmospheric pressure at sea-level, okay.

A change toward a steeper pressure slope at the base of the Walker circulation is associated with an increase in the equatorial easterly winds and hence also with an increase in the upwelling and a sharpening of the contrast of surface temperature between the eastern and western equatorial Pacific.

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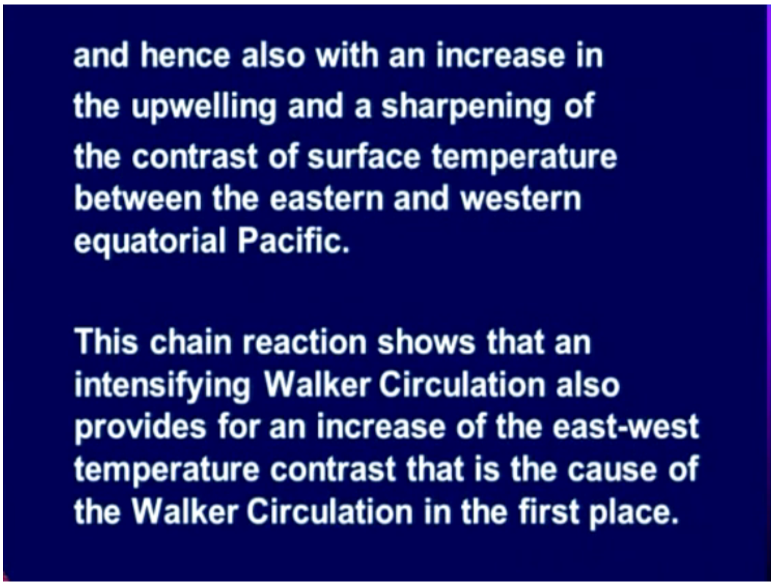

So, what is he saying? He is saying that if the pressure slope becomes steeper, okay, this means that the winds will strengthen and this means strengthening of the winds will give more upwelling. This means that the temperature gradient will also strengthen but this temperature gradient is which that drove the winds in first place. So you have a feedback or a chain reaction which shows that an intensifying.

Walker circulation also provides for an increase of the east-west temperature contrast that is the cause of the Walker circulation in the first place.

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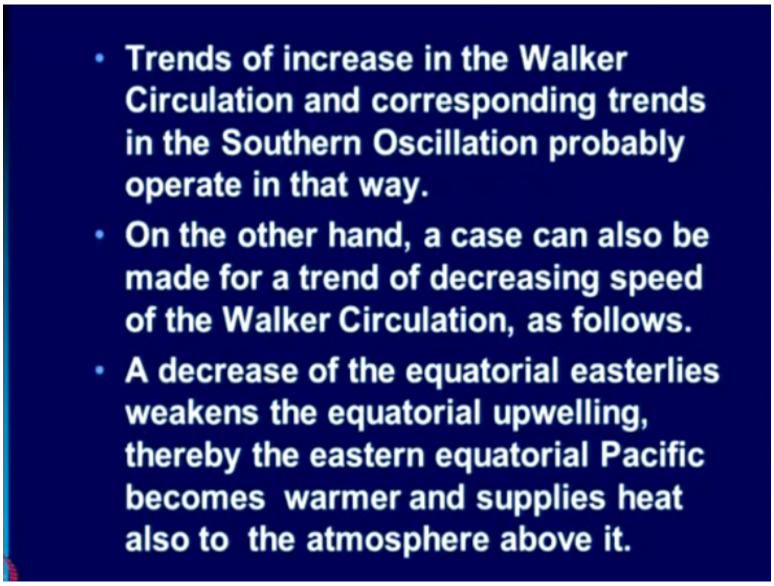

Trends of increase in the Walker circulation and corresponding trends in the southern oscillation probably operate in that way; this is what he pointed out. On the other hand, a case can also be made for a trend of decreasing speed of Walker circulation, as follows. See we looked at what happens when there is an increase of the slope. Now, if we had a decrease of the equatorial easterlies, that would weaken the equatorial upwelling.

And thereby the eastern equatorial Pacific becomes warmer and supplies heat also to the atmosphere above it.

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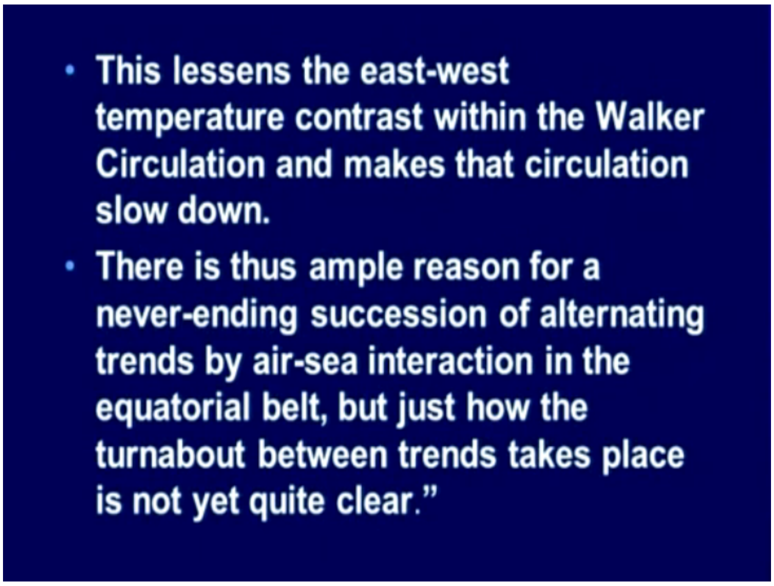

So this lessens the east-west temperature contrast within the Walker circulation and that will have an impact directly on the Walker circulation which will slow down. So here again you have a positive feedback and so there is ample reason to, for a never-ending succession of alternating trend by air-sea interaction in the equatorial belt, but just how the turnabout between trends takes place is not yet clear. This is from Bjerknes's paper.

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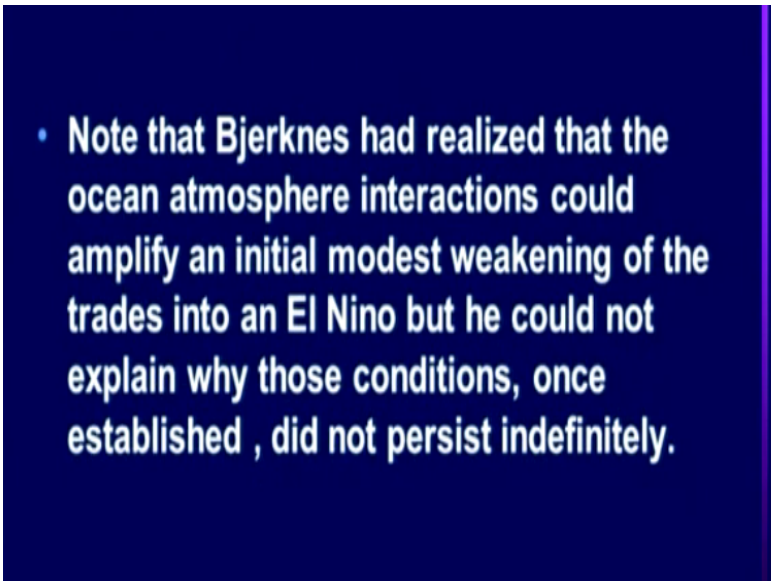

So we note that Bjerknes had realized that the ocean atmosphere interactions could amplify an initial modest weakening of the trades into an El Nino but he could not explain why those conditions, once established, did not persist indefinitely. Why is it that once El Nino is established it does not continue forever?

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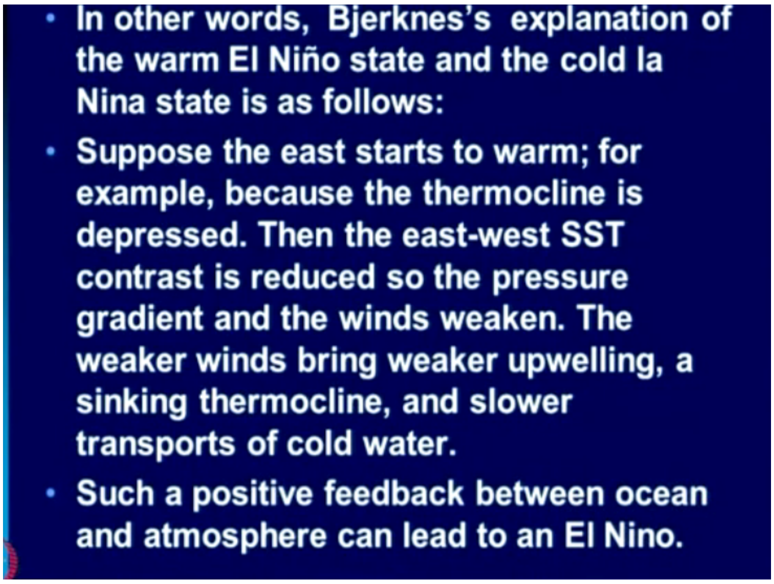

In other words, Bjerknes's explanation of the warm El Nino state and cold La Nina state is as follows: So I repeat again what are the basic feedbacks that Bjerknes proposed. Suppose the east starts to warm; for example, because the thermocline is depressed. Then the east-west SST contrast is reduced so the pressure gradient and the winds weaken. The weaker winds bring weaker upwelling, a sinking thermocline, and slower transports of water, cold water.

Such a positive feedback between the ocean and atmosphere can lead to an El Nino.

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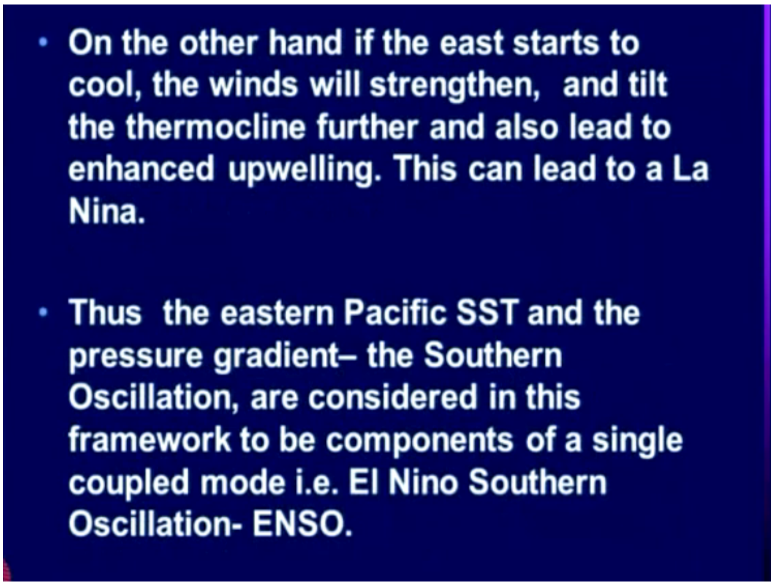

On the other hand, if the east starts to cool, the winds will strengthen, and tilt the thermocline further and also lead to enhanced upwelling. This can lead to a La Nina. Thus the eastern Pacific SST and the pressure gradient-the southern oscillation, are considered in this framework to be components of a single coupled mode namely, El Nino southern oscillation or what we call ENSO.

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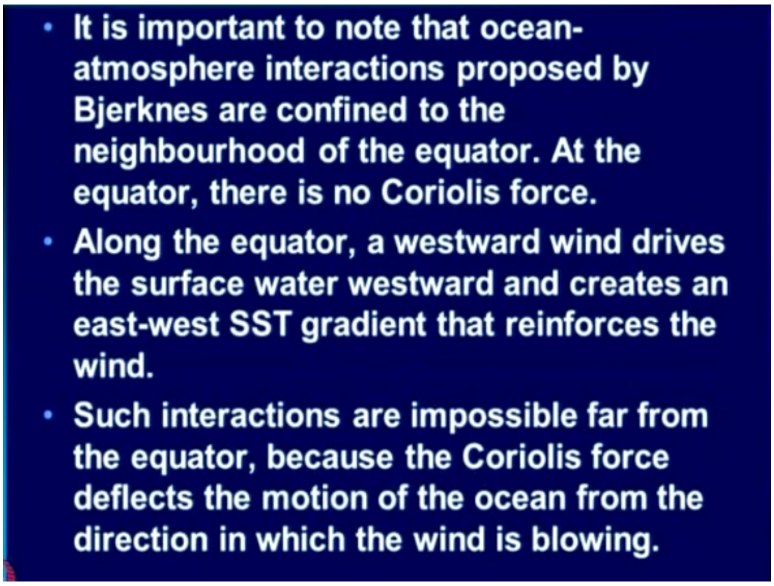

Now it is important to note some (()) (41:07). It is important to note that ocean-interactions proposed by Bjerknes are confined to the neighbourhood of the equator. At the equator, there is no Coriolis force. So along the equator, a westward wind drives the surface water westward and creates an east-west SST gradient that reinforces the wind, okay. So this is only at the equator because there is no Coriolis force and easterly wind will directly drive surface water westward.

A wind coming from east to west drives the surface water westward only at the equator. See, such interactions are impossible far from the equator, because the Coriolis force deflects the motion of the ocean from the direction in which the wind is blowing. We have seen that in the treatment of the Ekman layer, in fact because of the Coriolis force the transport of the, is actually at angle to the wind.

So it is very important to remember that all these atmosphere-ocean interactions actually work only at the equator.

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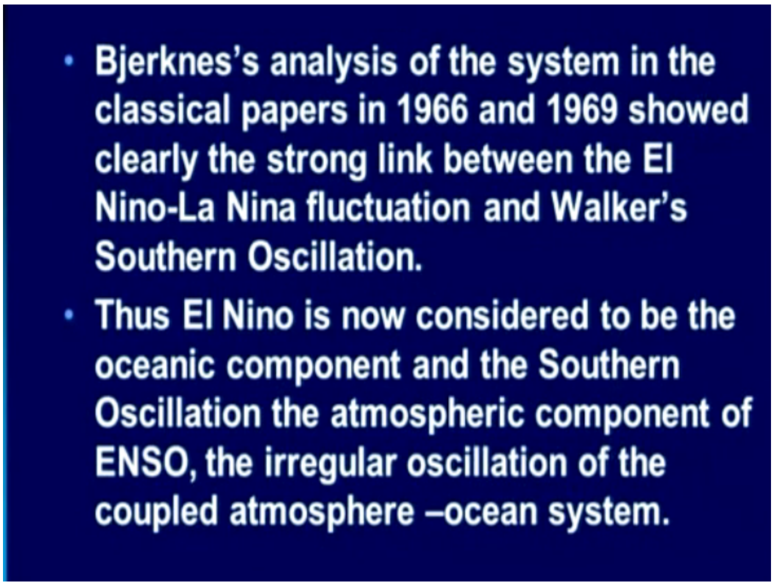

Now, Bjerknes's analysis of the system in the classical papers of 66 and 69 showed clearly the strong link between the El Nino and Walker's southern oscillation. Thus El Nino is now considered to be the oceanic component and the southern oscillation, the atmospheric component of ENSO, which is the irregular of a coupled atmosphere-ocean system.

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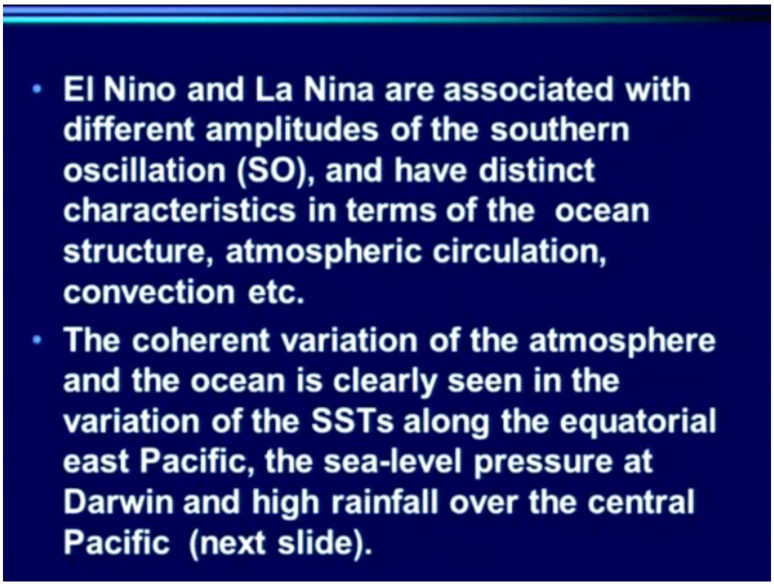

So now we talk of this oscillation as an oscillation of the coupled system. We do not talk of it as an oscillation only of the ocean component or the atmospheric component, because the 2 are intimately linked, the 2 oscillations are intimately linked. So El Nino and La Nina are associated with different amplitudes of the southern oscillation, and have distinct characteristics in terms of the ocean structure, the atmospheric circulation, convection etc.

Now the coherent variation of the atmosphere and the ocean is clearly seen in the variation of SSTs along the equatorial east Pacific, the sea-level pressure at Darwin and high rainfall over central Pacific.

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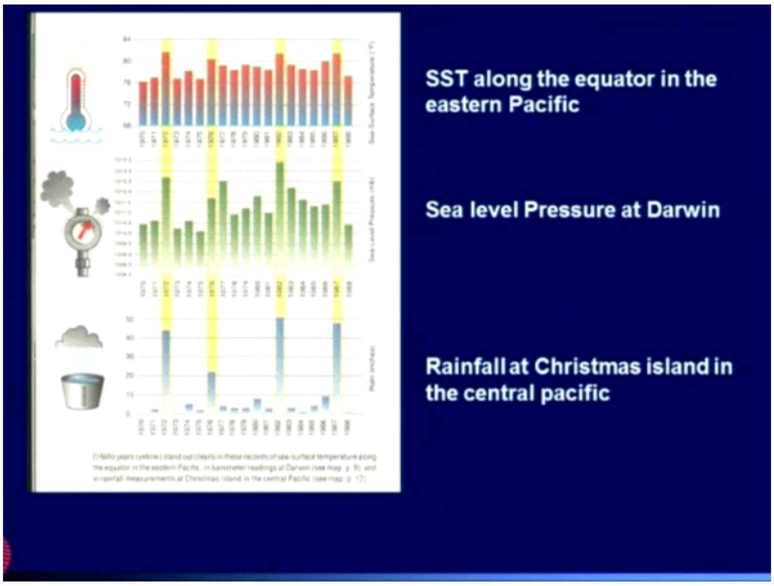

So this now, you know, found even popular in literature because El Nino has indeed become a popular topic. And what we see here is the SST along the equator in the eastern Pacific and you can see that the SST along the equator has becomes high and low. And coherent variations of the SST along the equator, as the SST varies along the equator, you see the sea-level pressure at Darwin is varying coherently.

You see here peaks coincide with peaks and troughs coincide with troughs. And rainfall at Christmas Island at central Pacific is again showing very similar thing. So as the ocean is warming these is El Nino conditions here, at the same time we see sea-level pressures at Darwin which has become higher and central Pacific there is very clear large amount of rainfall occurring like we saw in Bjerknes's case of Canton Island.

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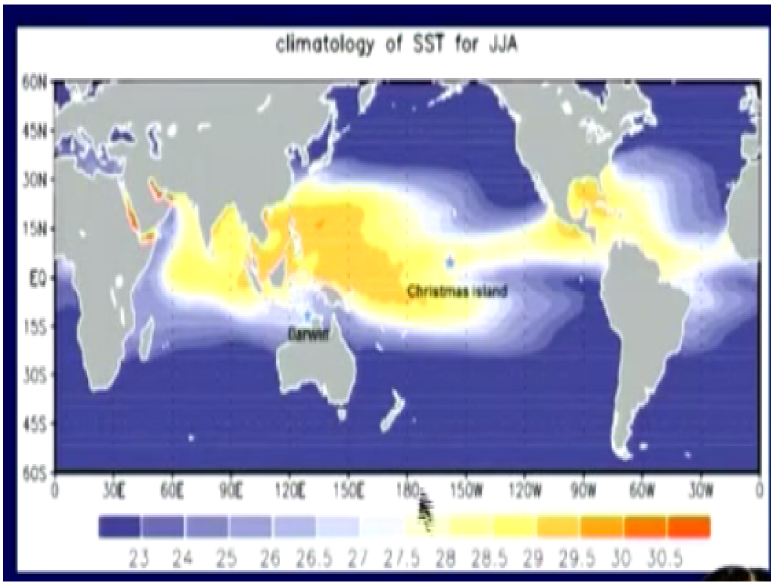

But this is time shown for Christmas island, so just to show you the location Darwin is here, Christmas island is here and we are looking at SST here. So what we see here is how coherent the variations are of SST along the equator in the eastern Pacific, so SST is along the equator in the eastern Pacific here, then the rain at Christmas island and the pressure right across the Pacific at Darwin. And what you see is the coherent variations here

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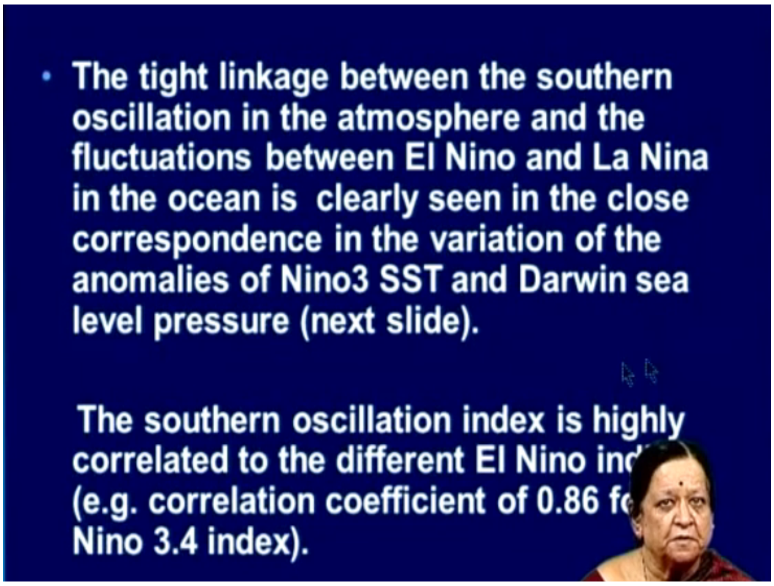

The tight linkage between the southern oscillation in the atmosphere and the fluctuations between El Nino and La Nina in the ocean is clearly seen in the close correspondence in the variation of the anomalies of Nino3 SST, I will define the regions later, but Nino3 is equatorial Pacific going right up to the east Pacific and Darwin sea-level pressure.

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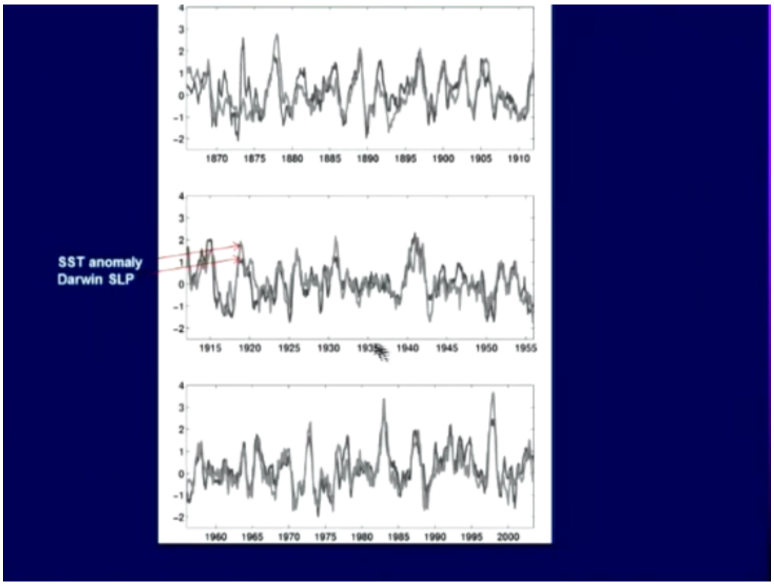

So the southern oscillation here we have, so this is the SST anomaly of the east Pacific and this is the Darwin sea-level pressure and this is for many years. And you can see even by eye how closely the 2 are being, the 2 are oscillating. So it is a very tightly linked system.

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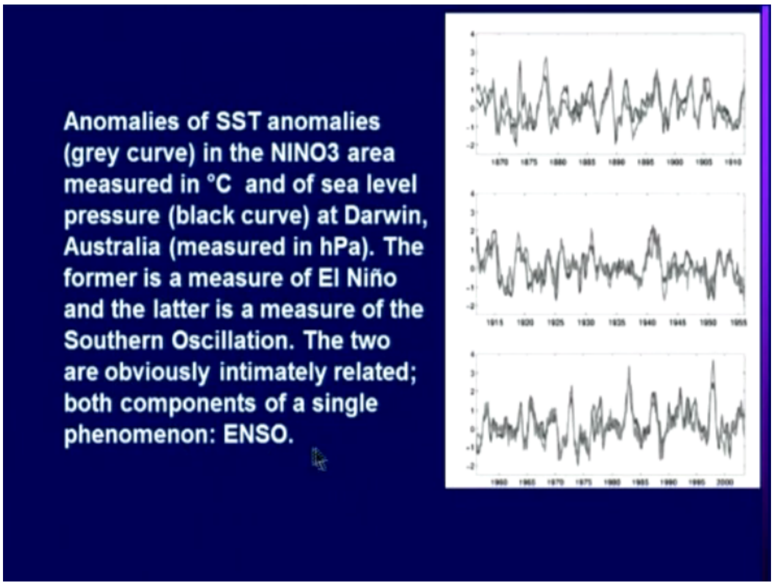

Anomalies of SST anomalies in the NINO3 area measured in degree centigrade and again the same thing and the sea-level pressure at Darwin. The former is a measure of El Nino and the 2 are obviously interrelated. So what we have now learnt is that what began as a, what was thought as a very exceptional event that occurs along the coast of South America, has major implications for Ecuador and Peru, namely, the El Nino and its opposite phase the La Nina or the cold phase.

Actually happened to be first of all, is not at all restricted to the coast of South America. It is much more a global phenomenon, a phenomenon that extends right across the Pacific with the SST anomalies extending over eastern equatorial Indian Ocean, Pacific Ocean as well. So the first recognition was that it was a much larger scale phenomenon than being restricted to the Pacific but still the El Nino and La Nina were identified by sea surface temperature anomalies.

But now, then this, side by side with this there was a recognition that atmosphere actually there is a southern oscillation with pressure variations at Darwin are on the towards west Pacific being negatively correlated with pressure variations over east Pacific, that is to say there is a see-saw. When the pressure tends to be high over one region it tends to be low over another, over the other region.

So there was a see-saw between east-west and we are talking now of atmospheric pressure, which meant that there is a variation in the easterlies across the Pacific, the trades, the easterly component of north-east and south-east trades. So that would vary along the equator and that would vary from time to time and this was called the southern oscillation.

And what Bjerknes did was to elucidate nicely the link between the warming and cooling of the coast of Peru, which also went coherently with warming and cooling on the equatorial east Pacific, link that with southern oscillation as well as very importantly the rainfall or the Hadley cell. So strengthening of Hadley cell during El Nino is what he showed.

So what has now been established very clearly is that El Nino-La Nino oscillation seen in the ocean and southern oscillation for seen in the atmosphere are all components of one interactive system, the El Nino southern oscillation coupled atmosphere ocean system, and these are manifestations of oscillation of this coupled system and now in fact, this is how the thing is treated as a coupled system.

And so the phenomenon is the manifestation of the coupled system and to understand the physics, we have to look at the coupled system and the coupling plays a very important role. So we will continue in the next lecture, with how, what was the progress in our understandings beyond Bjerknes, very pioneer in contribution to this field. Thank you.