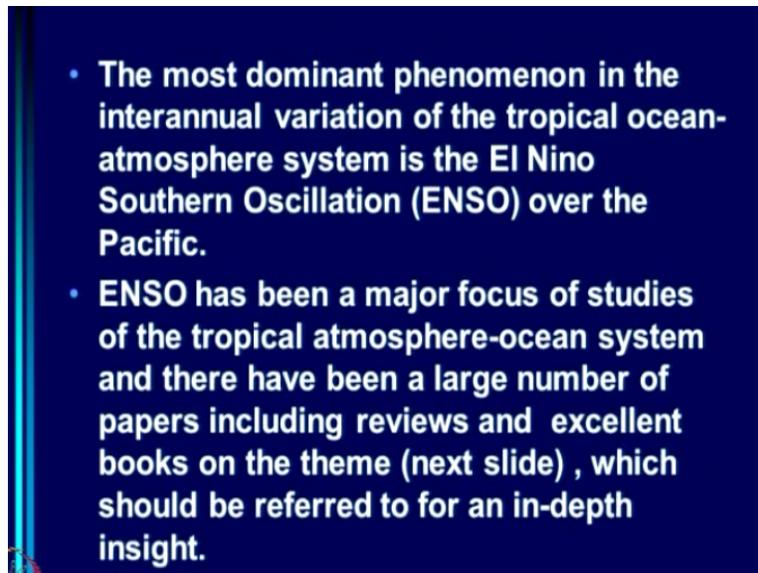


The Monsoon and Its Variability
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Lecture - 24
El Nino Southern Oscillation (ENSO) Part 1

We have prepared some background now about the ocean to start learning about one of the most fascinating phenomena in the tropics namely El Nino and Southern Oscillation. So today's will be the first set, first of a set of lectures on El Nino and Southern Oscillation.

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- The most dominant phenomenon in the interannual variation of the tropical ocean-atmosphere system is the El Nino Southern Oscillation (ENSO) over the Pacific.
 - ENSO has been a major focus of studies of the tropical atmosphere-ocean system and there have been a large number of papers including reviews and excellent books on the theme (next slide) , which should be referred to for an in-depth insight.

So the most dominant phenomenon in the interannual that is to say year-to-year variation of the tropical ocean atmosphere system is the El Nino Southern Oscillation that is ENSO over the Pacific. Now ENSO has been a major focus of studies of the tropical atmosphere-ocean system and there have been a large number of papers including reviews and excellent books on the theme which should be referred to for an in-depth insight, what I will give is an introduction to this very fascinating phenomena.

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- 1. 'El Nino, La Nina and the Southern Oscillation' by S G H Philander Academic Press, 1990
- 2. 'Our affair with El Nino' by S G H Philander, Princeton University Press 2004
- 3. 'El Nino-Southern Oscillation Phenomenon' E S. Sarachik and Mark A Cane, Cambridge University Press, 2010

So the 3 books I strongly recommend first is 'El Nino, La Nina and the Southern Oscillation' by George Philander Academic Press, this came out in 1990. Subsequently, he wrote another book semi popular on 'Our affair with El Nino', Princeton University Press 2004. And recent book which is actually meant has a textbook for graduate level which also includes the mathematical part the mathematical modeling part is 'El Nino and Southern Oscillation Phenomenon by Sarachik and Cane. So I recommend these books.

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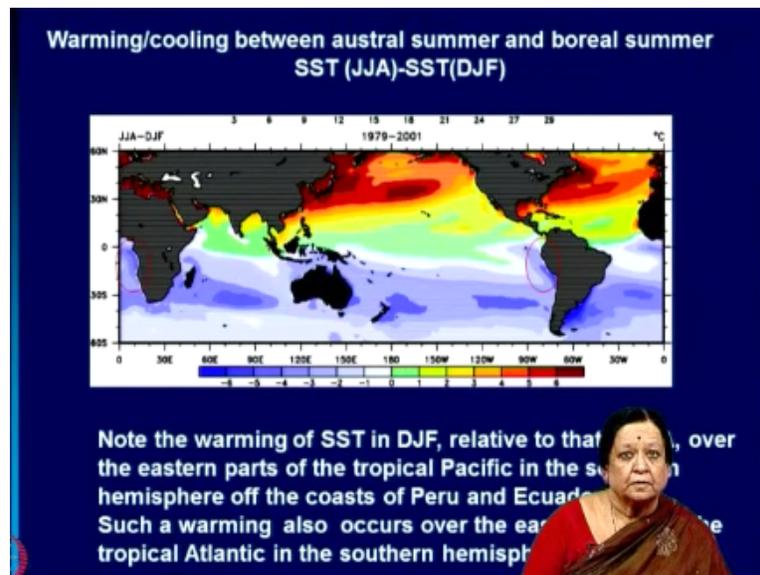
- The name El Nino means Child Jesus in Spanish and it was originally given to the warm seasonal current that appears off the coast of Peru around Christmas when it moderates the low temperatures of the eastern tropical Pacific Ocean.

And in fact, these 3 players these 3 authors Philander, Cane and Sarachik have been major players in actually unraveling the mysteries of the El Nino and particularly it is physics in the last 2 decades. So it is very nice that they have written those books and I strongly recommend

that readers who are interested or excited by these phenomena should go to these original books. Now, what is El Nino?

The name El Nino means 'Child Jesus' in Spanish, and it was originally given to the warm seasonal current that appears off the coast of Peru around Christmas when it moderates the low temperatures of the eastern tropical Pacific Ocean.

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Now, we just mentioned that one gets warm current on the coast of Peru, what you see here is the difference between the boreal summer or June, July, August Sea Surface Temperature-SST and the DJF which is December, January, February. So these are—this is the difference between the two temperatures, so it tells you how much warming or cooling has occurred between the boreal summer JJA and DJF.

Now notice that this is a negative sign here these are all blues, so off the coasts of Peru and Ecuador what you are getting is large negative changes. What does that mean? That means that SST DJF is getting warm relative to SST JJA. So SST DJF is warm relative to SST JJA so a warming is occurring off the coast of Peru. Okay. So there is a warming of SST in DJF relative to that of JJA over eastern parts of the tropical Pacific in the southern hemisphere off the coast of Peru and Ecuador. This is the warming.

And such a warming also occurs over the eastern parts of the tropical Atlantic and the Southern Hemisphere. You see this, here also one get warming in December, January, February relative to the June, July, August situation.

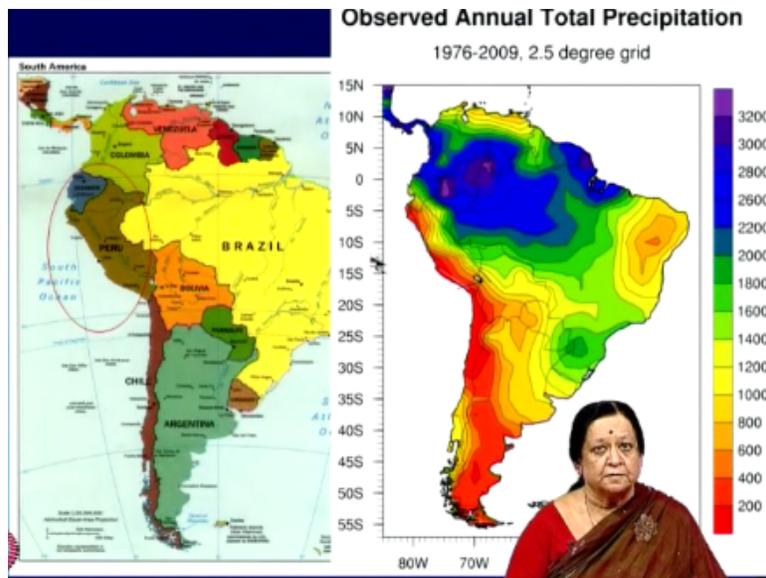
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- **Every few years this current is more intense than normal, penetrates unusually far south and brings heavy rains to the otherwise arid coasts of Ecuador and Peru. Such an occurrence was originally known as 'year of abundance' when the desert becomes a garden and within a few weeks the whole country is covered by abundant pasture.**

Now, so every year there is a warming of the ocean of the coast of Peru in around Christmas December, January, February relative to what it was in the boreal summer June, July, August. Now this is an annual phenomenon. However, every few years this current is more intense than normal, penetrates unusually far south and brings heavy rains to the otherwise arid coasts of Ecuador and Peru.

So what you are saying is something that you use to occur annually in some years comes with a much larger magnitude penetrates much deeper and last much longer, okay. And this use to be called an 'year of abundance' because you get such heavy rain in what is really a desert part.

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Now remember this is just to remind you this is Peru and Ecuador on the map here near the hump here of South America and this is the mean temperature that you – mean precipitation annual mean precipitation and what you see here is that all of them are 20 centimeters below, very, very little rain over the year, so this is the arid region to which El Nino brings rain and that is why it used to be called ‘year of abundance.’

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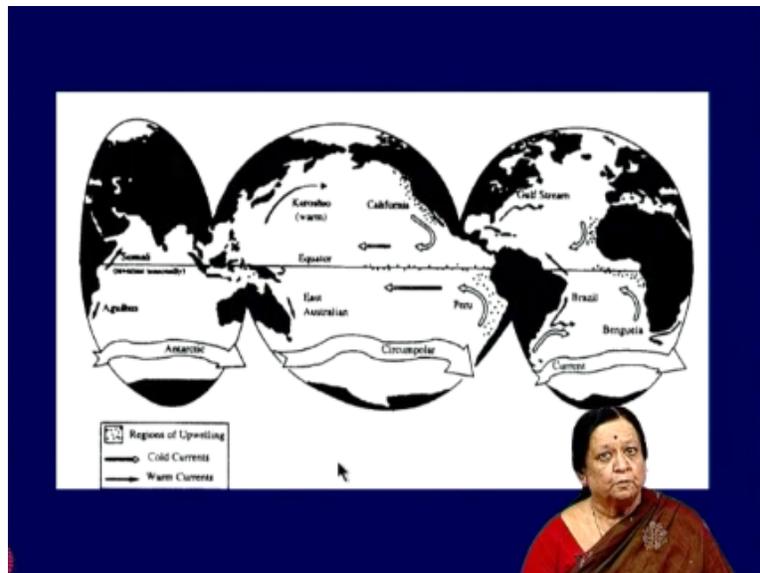
- However, the warm SST anomaly is associated with reduced upwelling-reduced nutrients in the surface layer and hence the disappearance of fish and birds on which the economies of Ecuador and Peru have now become dependent.
- Thus the El Nino, which was named after an event which was as welcome as Child Christ has become a dreaded phenomenon.

However, this connotation that it is associated with Child Jesus that means it is a good thing and that it is also associated with ‘year of abundance’ has now changed over the years. Why is that? Because the warm SST anomaly is associated with reduced upwelling that is to say reduced

nutrients in the surface layer and hence disappearance of fish and birds on which the economies of Ecuador and Peru have now become dependent.

So El Nino, which was named after an event which was as welcome as Child Christ has become a dreaded phenomenon.

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Now, I will show you why this happens. See, this is what we have seen before, this is of course the circumpolar current and this is the (()) (06:31) we were talking about earlier. This is the anti-clockwise (()) (06:33) in the Southern Hemisphere and this is the Peru current okay. And you know that the winds here along the South American coast are parallel to the South American coast, so you get a lot of upwelling here, okay.

And we have also seen that the nutrients in the ocean are maximum in the deep water. So upwelling leads to replenishment of nutrients, supply of lot of nutrients to this region which leads to lot of growth of phytoplankton zone, plankton fish and also birds that feed on the fish. So these are the regions are upwelling you get similar region here as well.

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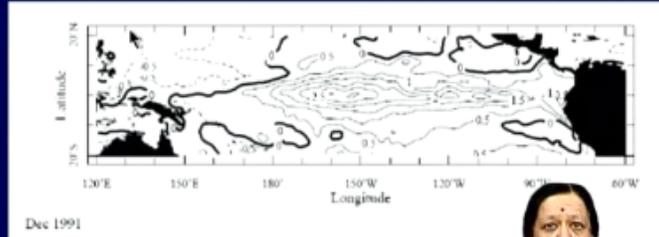
So the rocky islands along the coast of Peru provide nesting sites for this guano birds. You can see one of them here, and in the absents of El Nino event the birds are highly productive. Because, you know in the absents of El Nino event cold water with full of nutrition have come up and so the surface layers are very reaching nutrition they give rise to a lot of phytoplankton, lot of zoo of plankton, a lot of fish particularly anchovies and therefore make it an ideal situation for these birds who feed anchovies, guano birds.

So in the absent of an El Nino event the birds are highly productive consuming a large quantity of fish primarily anchovies that are in the surface layer of the East-Pacific Ocean. Now this is converted in to guano which are bird droppings, okay that were use now as fertilizer for agriculture. So this is a major source of income for Peru and Ecuador. On a regular basis they can export and use this fertilizer for agriculture.

Now with a coming of an El Nino what happens, that upwelling decreases you get much warmer seas and with much warmer seas there, there is an enough nutrition and that means that the fish numbers decline and become inaccessible to guanos. So there is a big negative impact on the production of guano, the bird dropping that come during an El Nino and this is why now the El Nino is considered phenomenon to be dreaded because of the large negative impact on the economy.

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- What we refer to now as El Nino, or a warm event, is a much larger scale phenomenon characterized by warm SST anomalies stretching from eastern to central equatorial Pacific.



SST anomalies for the El Nino event

Now should mention that originally El Nino was defined as a warm event namely along the coast of South America particular Peru and Ecuador. But now what we refer to as an El Nino is of a much larger spatial scale phenomenon which is characterized by warm anomaly, see these are the anomaly around Peru and Ecuador of 1.2 degrees or so, which we had which was originally associated with the original definition of El Nino.

But we will come to this since the events of 1957 and so on, it came to be realized that El Nino is not restricted to the coast of South America on the contrary the warm anomaly extent to over a very larger region here. Okay. This is now this is 150 west this is 180, so this is the dateline. So you have warm anomalies extending up to the dateline, very high SST anomalies, positive SST anomalies extending right up to the deadline.

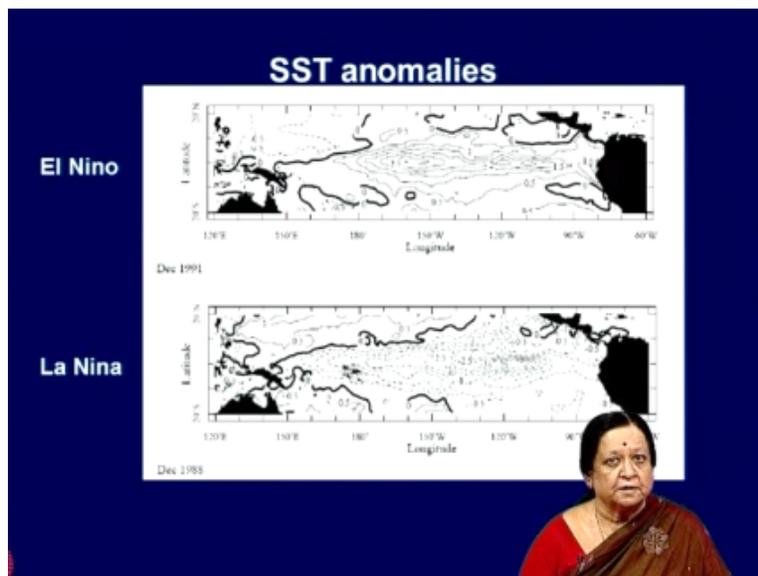
So now what we call an El Nino is not something that is restricted to the coast of South America but rather something that occurs in the equatorial region of the Central and East Pacific. This part is Central Pacific and this Part is East Pacific. Okay. So now what we refer to as El Nino is a much larger scale phenomenon.

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- In some years, cold anomalies of SST are observed over the central and eastern Pacific (next slide). These cold events are now known as, La Nina (the girl in Spanish) .

Now in some years, cold anomalies of SST are observed over that same region where we observed warm anomalies during and El Nino.

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And that you can see here, so this is the same El Nino picture you saw and this is La Nina event, the dash lines are all cold anomaly and you can see that the same region over which we had warm anomaly during El Nino now there are cold anomalies during what are called Cold Events, and you know El Nino means a Boy Child, so La Nina is a girl in Spanish. So El Nino is a boy and La Nina is a girl, so these cold events are called La Nina.

In fact, the term coined by George Philander who happens to have a Spanish speaking wife.

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- **The eastern and central tropical Pacific exhibit an irregular cycle of warming and cooling oscillating between the warm events, El Nino, and the cold events, La Nina with the period ranging between 2-7 years.**

So we have 2 phenomena here the warm and the cold warm being El Nino and cold being La Nina and Eastern and Central Tropical Pacific exhibit an irregular cycle of warming and cooling. Remember it is a cycle, but it is not a regular cycle like a pendulum it is an irregular cycle of warming and cooling, oscillating between warm events El Nino and cold events La Nina with the period ranging typically between 2-7 years. Okay.

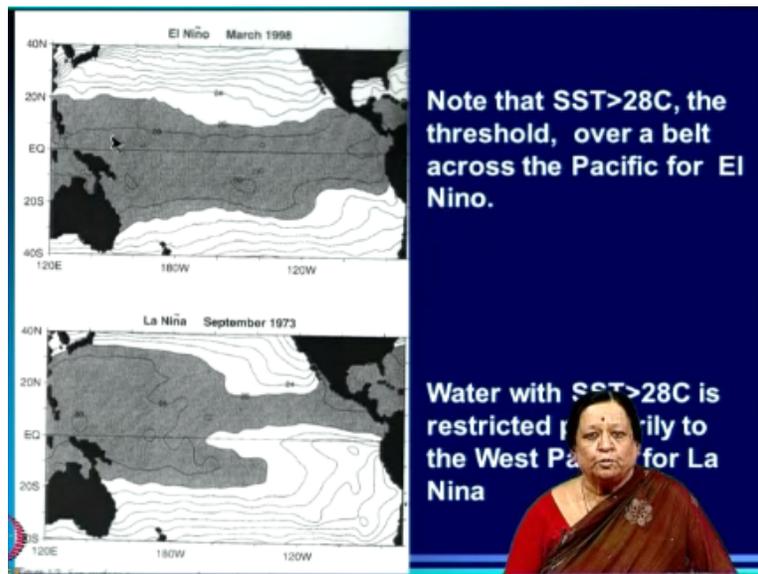
So the period of the oscillation is not fixed it is an irregular oscillation and the period is typically between 2-7 years.

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- **El Nino: warm phase; La Nina : cold phase**
- **During El Nino, the eastern Pacific as well as the central Pacific warms and can warm to such an extent that the temperature across the entire tropical Pacific assumes an almost uniform temperature (e.g. next slide).**

So now what happens during El Nino and what happens during La Nina? During El Nino, the eastern Pacific as well as central Pacific warms we have seen these. And can warm to such an extent that the temperature across the entire tropical Pacific assumes an almost uniform temperature.

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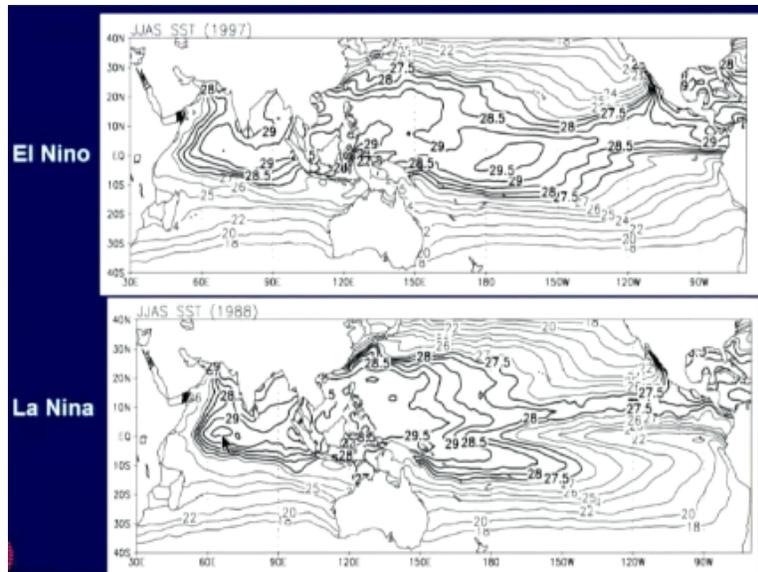


And you see that here. See this is the El Nino and what has been done is that the region above 26 or so this is 27, 28 so above 27 the region has been shaded and what you see is a river of warm water flowing right across the specific here. So this is the El Nino story and this is 26, so what you see here is the cold event, so what has happened in this, the region above 26 has been shaded so 28 is here, so this is 26 and this 28.

So this whole region has become above 26 whereas during La Nina in fact, the region is all above 26 in a relatively narrow belt but the region above 28 is much more restricted. See here the region above 28 is right across the Pacific here whereas here the region above 28 is restricted to this part of the Pacific. So this is why SST, note that SST > 28 degree centigrade is the threshold for convection which we have considered before and which I will consider, discuss again later.

So what is happening is the entire ocean has become warm during El Nino and this part of it is colder than usual during La Nina.

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This is another example and what you see here again is an El Niño of 1997 more recent one of the strongest El Niño of the century and again you see this is the 28-degree isotherm here and there is a whole stretch of water that is above 28 here whereas during La Niña, this is of 1988, what you see is that the 28 degree isotherm is just around here, so the warm water is just around west and central Pacific and here it is not above 28 anywhere, this is the La Niña case.

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- That the temperature of the east Pacific is close to that of the western Pacific indicates that the warm phase of ENSO is due to a failure of the eastern Pacific to stay cold.
- Before discussing the characteristics of El Niño and La Niña, I consider the mean state of the tropical Pacific.

Now, that the temperature of the east Pacific is close to that of the western Pacific indicates that the warm phase of ENSO is due to a failure of the eastern Pacific to stay cold, right. We had seen why the eastern Pacific stays cold but what seems to be, this is-- but what seems to be happening

is that in some years on some occasions the east Pacific does not stay cold. Okay, that is to say the temperature becomes close to that of the western Pacific.

And this is to be kept in mind. So this is a major departure from the mean and before we can understand this major change from the mean circulation let us discuss what we know about the mean state of the tropical Pacific and the atmosphere above it. So when we understand the physics of the mean state we will be able to understand what happens during the El Nino and La Nina.

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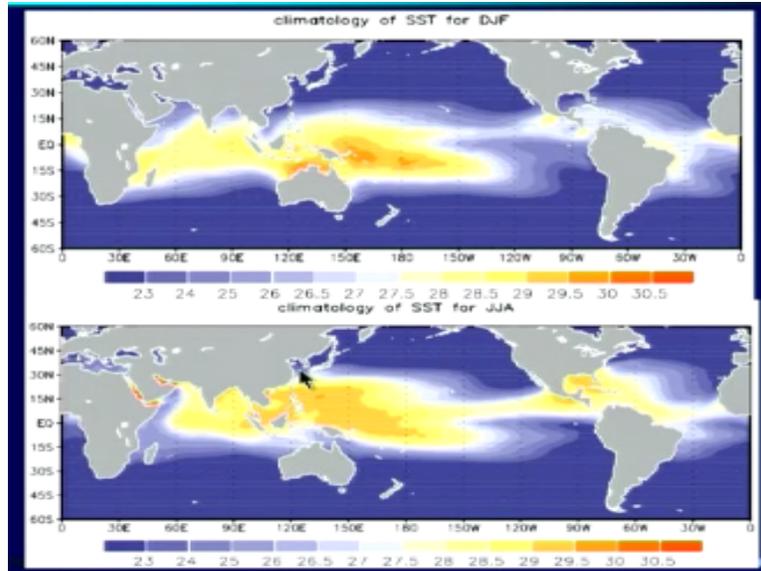
Mean climate of the tropical Pacific

- The most important characteristic of the tropical Pacific is the large variation between the West Pacific and the East Pacific.
- Consider first the ocean component.

The slide features a dark blue background with white text. In the bottom right corner, there is a small portrait of a woman with dark hair, wearing a red and brown sari, looking towards the camera.

So let us look at the mean climate of the tropical Pacific. First the most important characteristic of the tropical Pacific is the large variation between West Pacific and East Pacific.

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So let us first consider the ocean component. And this is something which we have seen before, that SST irrespective of the season shows an extremely large variation west and east. You see in particular this part is cold irrespective of the season and this part is warm irrespective of the season, so on the whole west is much warmer higher SST than the east and SST is become somewhat comparable only over very, very small portion in boreal winter which is December, January, February over somewhat larger portion in June, July, August.

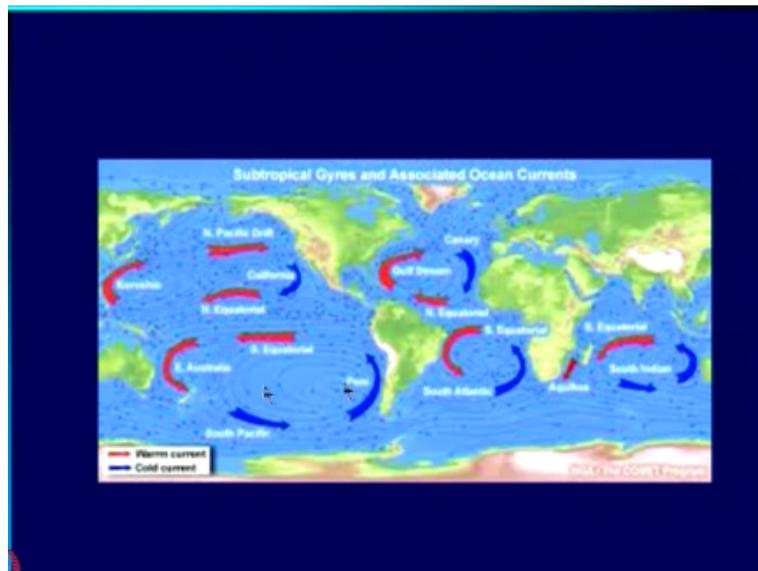
But there is no doubt that the west is different from the east that is a large variation between west and east, we have noted before that the extent over which we get warm water over the west is much, much larger than that over the east. So there is a major variation in SST.

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- The SST is higher over the western equatorial Pacific than the eastern one.
- That warm SSTs will occur over a region of larger latitudinal extent over the western relative to the eastern oceans, is only to be expected from the cold equatorward currents over the eastern ocean.

Now SST is higher over the western equatorial Pacific than the eastern one and that warm SSTs will occur over a region of a larger latitudinal extent over the west-- western relative to the eastern oceans, is only to be expected from the cold equatorward currents over the eastern ocean. We have talked about this before that currents emanating from the poles are coming towards the equator near the eastern boundaries near the eastern Pacific and that is why it is colder and the latitudinal extent of warm water is less.

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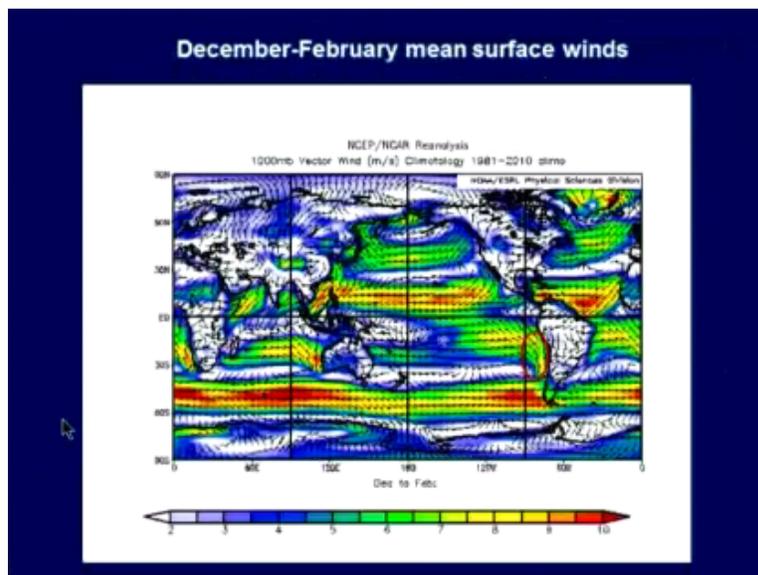
And this is something you see here; these are the cold currents so this is the cold current coming here and that whereas this is the warm current going this way and this is why we have a much larger extent of warm SST over west than east.

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- Low SSTs off the south American coast in the southern hemisphere also arise from the strong upwelling occurring in association with winds which are northward and parallel to the south American coast throughout the year (as seen in the following slides).
- This leads to Ekman transport to the left (because it is in the southern hemisphere) i.e. westward and away from the coast.
- This has to be balanced by upwelling along the coast which leads to the low SST along the coast.

Now low SSTs is off the south American coast in the southern hemisphere arise not only from the fact that you have cold currents coming from high latitudes in there but also arise from the strong upwelling occurring in association with winds which are northward and parallel to the south American coast throughout the year. Okay. And this we will show in the following slides.

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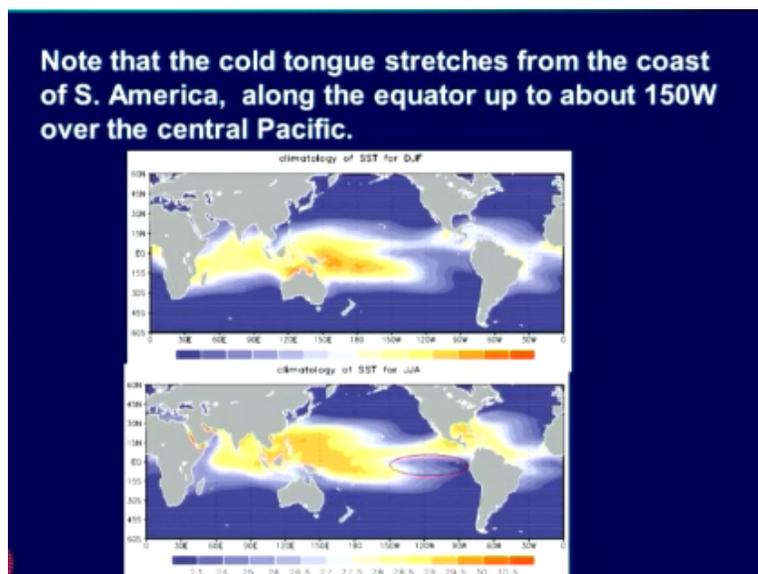
So what do we find? See we find here you see this is the region, you see the winds are all going northward here this is the-- within this red circle that have marked and they are very strong winds as you can see they are all greens. These are wind vectors and the magnitude is large. So

you have strong winds coming from the south to the north blowing parallel to this coast. Okay. And this happens in June, July, August also just as it happens in December, January, February.

And then in the same place you have very high winds coming from the south to the north during June, July, August. Now, what happens when we have winds going parallel the coast of South America? What happens is this leads to Ekman transport to the left that is to say towards the west because this is in the southern hemisphere. So, there is Ekman transport westward in this direction away from the coast.

Now if the wind is pushing the water away from the coast in the Ekman layer then it has to be balanced by upwelling along the coast. Because the water rate is pushed away in the Ekman layer away from the coast has to be replaced by water coming from below the Ekman layer which is to say upwelling along the coast. And if you have upwelling since the lower water is colder you will get lower SSTs along the coast.

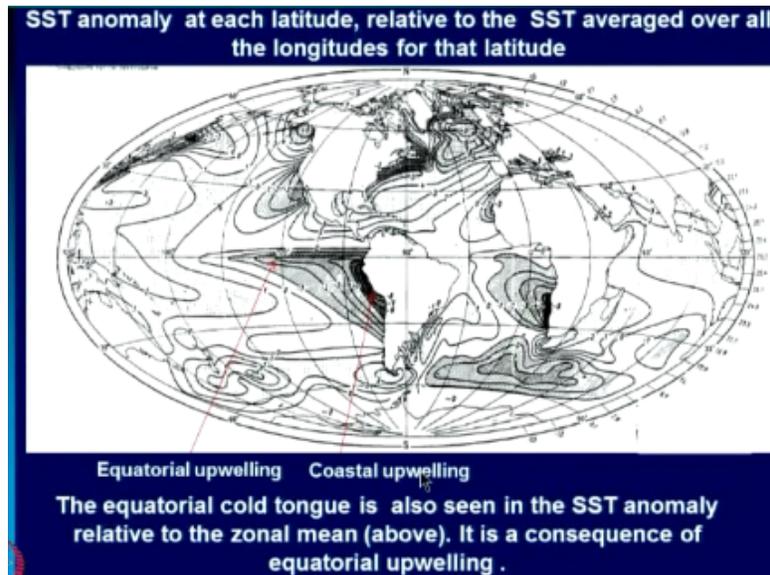
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So we expect in fact low SSTs along the coast here simply because coast of South America because of the upwelling that is generated by winds which are going parallel to this coast from south to north. But notice, that the cold tongue stretches from the coast of South America right up to about 150 west you see this, this is the cold tongue here, and it is there in both the seasons June, July, August, as well as December, January, February.

There is a cold tongue which is along the equator. This part of the equatorial Pacific that is the eastern Pacific; eastern and central Pacific also has a cold tongue at the equator.

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That is very nicely seen the another by another kind of map. This is the map of the anomaly, SST anomaly at each latitude, relative to the SST average over all longitudes. So what is the anomaly at each longitude, okay relative to the SST anomaly-- SST average over all the longitudes there, so if you take this particular longitude of the coast of Peru then you see that there is a huge negative SST anomaly relative to the zonal average SST of this latitude, okay?

So equatorial cold tongue is also very nicely seen here in this kind of a picture, so you see the Pacific you have a huge anomaly, negative anomaly of the SST relative to the rest of the regions in the same latitudinal belt both off the coast of America as well as in the equator. So these are the upwelling regions notice also there are upwelling regions here of the coast of Africa as well.

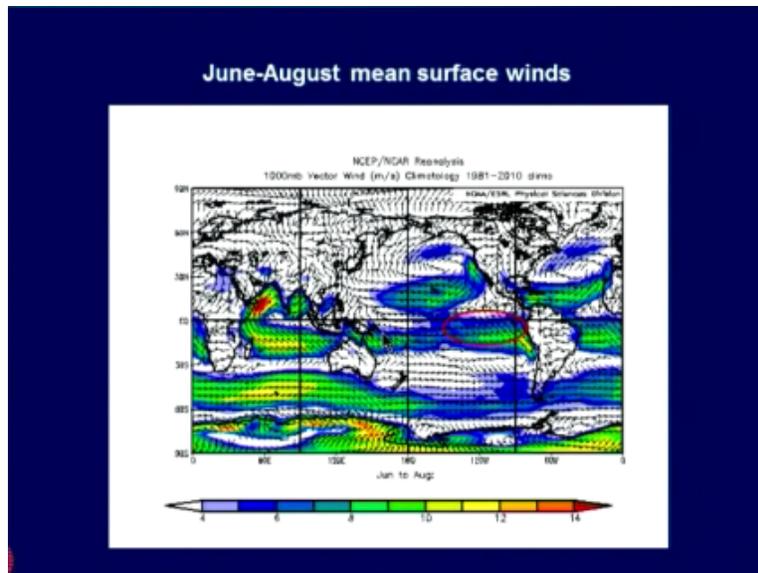
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Equatorial cold tongue

- The winds along the equator are westward (next two slides); hence the Ekman transport in the oceanic region to the north of the equator is to the north while that in the region south of the equator is towards the south.
- The water thus moving poleward on either side of the equator, has to be replaced by water from beneath the surface layer at the equator i.e. by equatorial upwelling.

So we have seen then that there is a very prominent in addition to the coastal region here there is a prominent belt of cold water along the equator, equatorial cold tongue. Okay. Now why do we have cold water along the equator? See this again has to do with the winds; the winds along the equator are westward.

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Let us see that. See along the equator the winds—you know these are the trade winds, so they are going from east to west. These have the easterly components, south easterly in the northern hemisphere, in the southern hemisphere and north easterly in the northern hemisphere but both have an easterly component and easterly is going some east to west. So winds along the equator then are going from east to the west okay.

Now the winds along the equator are westward, so how will the Ekman transport be in the oceanic region to the north and south of the equator. So let us consider this region here. Now if this is the equator and we are slightly to the north of the equator the winds are westerly anyway as we have seen. So since we are now in the northern hemisphere the Ekman layer will push water to the right, right? That means it will push water to the north.

Similarly, in the southern hemisphere the Ekman layer transport will be to the left of the winds that is to say towards the south, so what is happening is if we look at the equator water to the north of the equator is being pushed northward by the wind driven Ekman layer where as water to the south of the equator is being pushed southward by the wind driven Ekman layer.

And because of this you know there is water is being lost from the surface layer by this diversion that is force water going north in the northern hemisphere water going south in the southern hemisphere. This water has to be replenish somehow and the way it is replenish is again upwelling of the deep water so the water that is going north and south is replaced by water which comes from below the Ekman layer here.

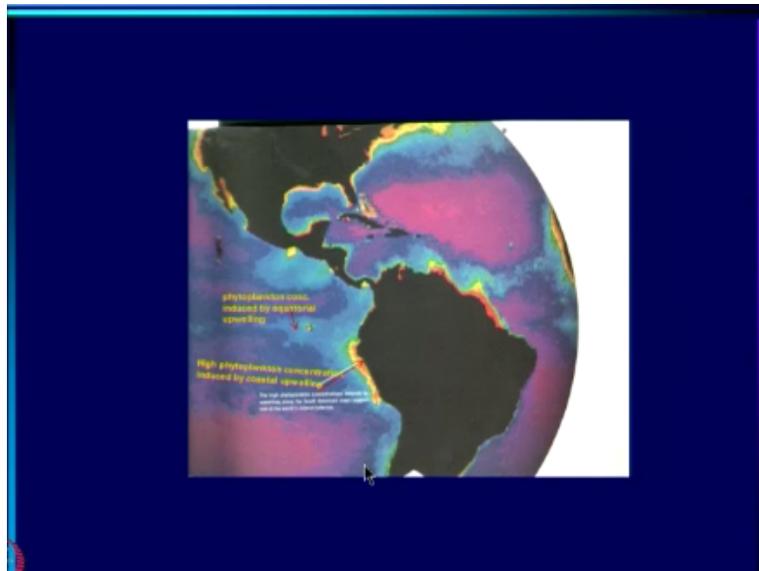
And again water from below the Ekman layer will be colder from than that in the Ekman layer so what you get is low SSTs right along the equator and that is the equatorial tongue that you have seen.

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- The cold tongue extending along the equator from east to central Pacific is attributed to such equatorial upwelling.
- Supply of nutrients associated with upwelling leads to concentration of phytoplankton over the region of equatorial upwelling and even higher concentration off the coast of Peru and Ecuador (next slide).

So the cold tongue extending along the equator from east to central Pacific is attributed to such equatorial upwelling. Now supply of nutrients associated with upwelling, leads to concentration of phytoplankton over the region of equatorial upwelling and even higher concentration off the coast of Peru and Ecuador.

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And nowadays satellite pictures show very beautifully where the phytoplankton are, what you see here is high phytoplankton concentration induced by coastal upwelling, this is the one and this one here is the phytoplankton concentration induced by equatorial upwelling. So this is the equatorial upwelling and this is coastal upwelling where you have highest concentration of Peru and Ecuador.

So you see the result, you see the impact of upwelling on the phytoplankton and hence on the rest of the (()) (26:12) in the ocean. So this is an important thing to remember.

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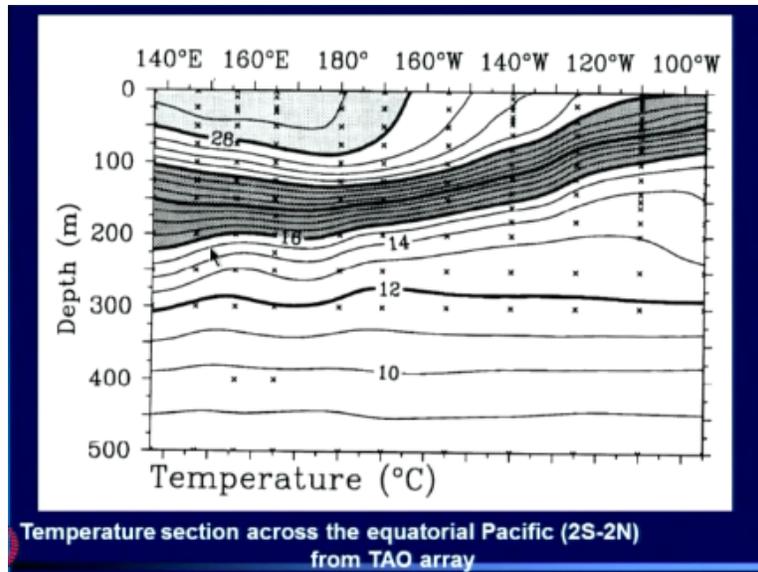
East-west variation of the depth of the thermocline

- **Another feature of the Pacific Ocean which shows a marked variation from the east to west is the depth of the thermocline.**
- **The thermocline is shallow in the east and deep in the west.**

Now so far we have seen the sea surface temperature variation from east to west. But there is more to this East to West variation than surface properties alone. In fact, we have seen in the last lecture that thermocline is the region of the ocean the layer of the ocean in which the temperature decreases very rapidly from that any other surface to that of the bottom or deeper layers of the ocean.

So thermocline you remember is the layer in which there is a very sharp decrease in temperature and another feature of the Pacific Ocean show is the variation of the thermocline from east to west, okay. So what we see is a market variation from east to west in the depth of the thermocline.

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Now this is the depth of the thermocline. You can see it, these are actually temperature, this is equatorial belt 140 to 100 west and just to give you a feel for what, we are going to keep encountering these kind of longitudes now 140 east to 100 west, just to give you a feel for what they imply, I have drawn for you on a map of SST turns where is 140? So 140 cuts across the Pacific here okay, it cuts across Australia. This is 140 east and this is 100 west. Okay.

So this is clear ocean or at 100 west, and this is the equator. So along the equatorial region we take if you wish how does temperature vary with depth, right from west to east from 140 to 100 west. And what you see is here. So at 140 which is in the west Pacific what you find is that the ocean is very warm in fact you see this is 28 this is 29 okay. So it is very, very warm and below that this is the thermocline.

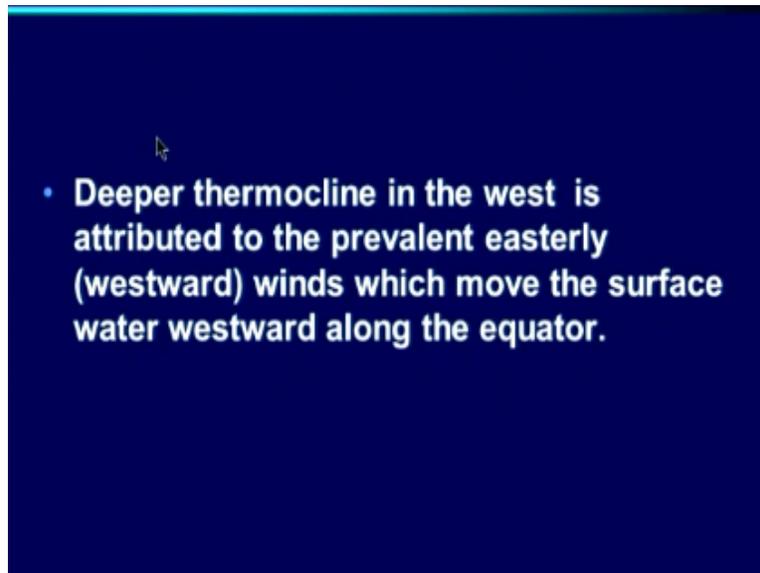
The thermocline is between 100 and 250 meter in which the temperature is decrease very rapidly from above 26 to about 14. So this is 16. So this shaded region is the thermocline which is between 102 to 200 roughly over the west Pacific, and we can go now, this is dateline and roughly the same story. As we start going eastward what is happening? See the cold of water is coming higher.

So the thermocline is rising, and you can see that here the surface itself this is 27, 26, 25 so the surface of the ocean is getting colder and colder and actually the thermocline is rising. So the

thermocline is very shallow over eastern Pacific and it is deep over western Pacific. There is a deep layer of warm water over western Pacific below which the thermocline is whereas eastern Pacific the cold water has come to the surface.

So there is a very large variation from west to east not only in the sea surface temperature which you see that part of here but also in the depth of the thermocline in the depth of this warm layer, also there is a larger variation this is very shallow thermocline is very shallow in the east and very warm in the west, very deep in the west.

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So deeper thermocline in the west and shallower thermocline in the east is what we see. Now why do we get a deep thermocline in the west? This is attributed to the prevalent easterly winds. We have seen that the winds along the equatorial region or in the tropical Pacific or have an easterly component. So because the winds are to the west they will move the surface water westward along the equator, right.

Along the equator the winds will push the surface water towards a west Pacific.

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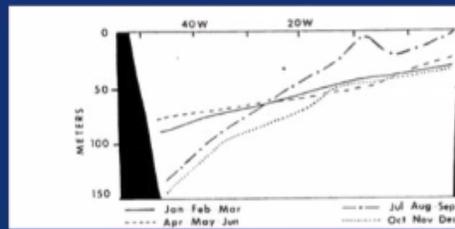
- Since the pressure at any point in the ocean, is the weight of the total column of water above it, the piling up of water in the west leads to a higher pressure in the west and hence a pressure gradient in the water in a direction opposite to the wind.
- The water piles up to a point at which the pressure gradient due to the piling up of the water in the west balances the westward wind stress.

Since the pressure at any point, so the winds are pushing the water there, so what will happen that means the sea-level will rise over the west Pacific relative to the east Pacific. Okay. So now if the sea-level rises, remember that if one considers a point in the ocean when the pressure at any point in the ocean is the weight of the total column of the water above it. This is hydrostatic balance.

So the larger the amount of water over that point the higher will be the pressure. So what happens is over the west Pacific if we consider same height or same depth in the ocean then the pressure over the west Pacific will be higher than pressure over the east Pacific, that is to say the pressure gradient is going from west to east. So it is opposing the wind stress. So the piling of the water will continue until a point at which the pressure gradient force which is in the opposite direction to the wind balances in the westward wind stress.

So the result of the piling up of the water is that in the ocean there is a pressure gradient which goes from the west to the east.

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Depth of the 23°C isotherm in the equatorial plane of the Atlantic Ocean for different seasons:
 The slope of the isotherm is small in the first half of the year when the winds are weak and large when the winds are strong in the northern summer and autumn.

Now similar thing is seen also in the Atlantic because we have similar winds in the Atlantic with easterly component northeast in the northern hemisphere, southeast in the southern hemisphere throughout the year. So that also leads to east west variation in the Atlantic, but if you notice here in January, February, March the thermocline is tilting this way again it is swallowing in the east, deeper in the west.

But in other seasons like June, July, August it is even more deep in the west than it is in the east. So there is considerable variation of this tilting of the thermocline in the east west direction which season in the Atlantic.

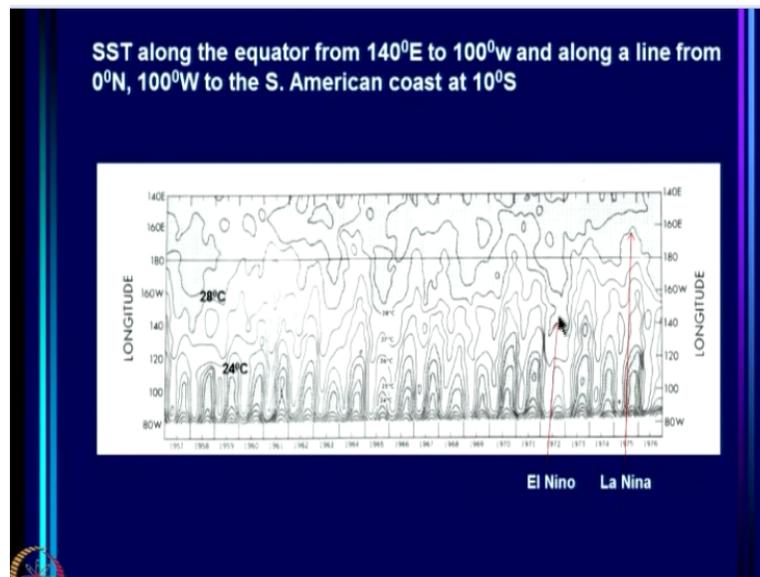
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- It should be noted that the Pacific is either in a warm state 'EL Nino' or a cold state 'La Nina', with brief periods in which neither are seen. Hence, although the mean or normal condition can be defined statistically, it is not often observed.

Now it should be noted, so far we are talking of the mean state right. In the mean, the SST is much higher over the west than the east, in the mean the thermocline is deeper over the further west Pacific than the east Pacific. But you know, what is mean state? Is the mean state ever observed? In fact, it should be noted that most often the Pacific is either in the warm state or in the cold state El Nino or La Nina with brief periods in which neither are seen.

So although the mean is normal condition can be defined statically because we can always average all that data and find out what the mean is. It is not often observed because the mean is the mean of 2 states which are totally different.

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So you have—this is sea surface temperature going from 100 west to going along the equator from 140 east to 100 west, and along a line from 0 north to 100 west and then to the south American coast. So this is the sea surface temperature variation along the equator and then along a line which sort of is going slanting towards the south American coast from about this. And what you see here is this is warm water here.

This is warm and this is cold, and this is South American coast, and you see here this is an El Nino because the warm water has come right up to south American coast whereas this is a La Nina in which the cold, see the warm water has retreated to the west Pacific side and the cold water has

spread much more. So what you see is events of warm and cold alternating very often. So this is 28 degrees and this is 24 degrees, so you get El Nino and La Nina alternating.

And you can see that often here and the mean state is very is observed only for brief periods in between these 2 states, that has to be kept in the mind.

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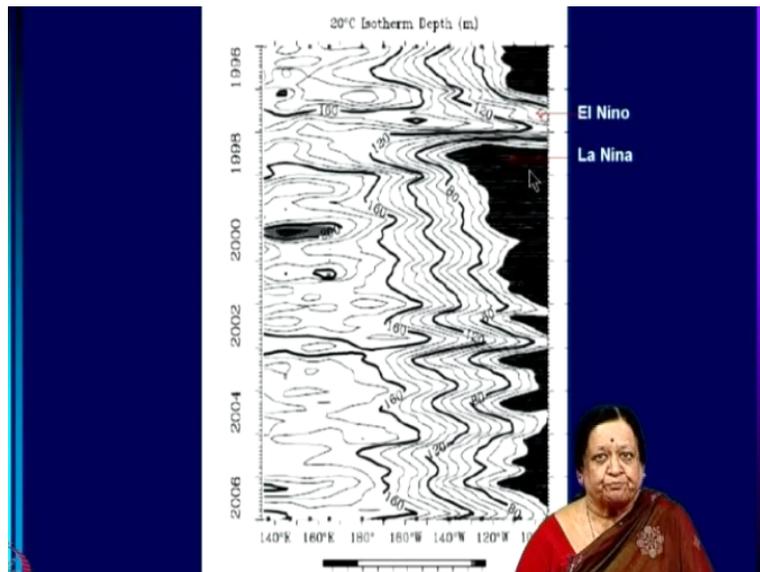
- The depth of the thermocline of the east Pacific increases during El Nino whereas it decreases during La Nina. (next slide).
- Thus the east-west tilt of the thermocline decreases during El Nino and increases during La Nina.

Now what happens during El Nino and La Nina to the thermocline? We have seen that the thermocline tilts with the-- in the mean the thermocline is deeper in the west than the east. So what happens during El Nino and La Nina is schematically shown here. See this is the thermocline; this is west Pacific and what you see here is the sea surface temperature in colors. So during El Nino actually the thermocline which is normally shallow here has become slightly deeper.

So the thermocline is deeper in the east during El Nino than normal, whereas during La Nina it is become more shallow, and when it has become deeper you see that the warm water extending all the way from west to east and during La Nina when the thermocline is become very shallow the warm water is restricted to part of the western Pacific. So we have 2 important changes between the warm phase and the cold phase.

First is of course temperature and the basis in which we define the warm phase, but second which is a very important thing is this thermocline tilt which is much more during La Nina the tilt which is much more during La Nina then during then the mean whereas it is much less during El Nino than the mean. So this is an important thing to remember.

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And we see that here often to trace where the thermocline ocean (()) (36:54) the depth of the 20 degree centigrade isotherm okay and that is given here these black patches correspond to a depth < about 70 meters. So these are all depth < 70 meters. Now you see here, this is the case where the depth, this is 120 meters and this is 100 meters. So what has happen-- this is 80 meters here, the other solid line is 80 meters.

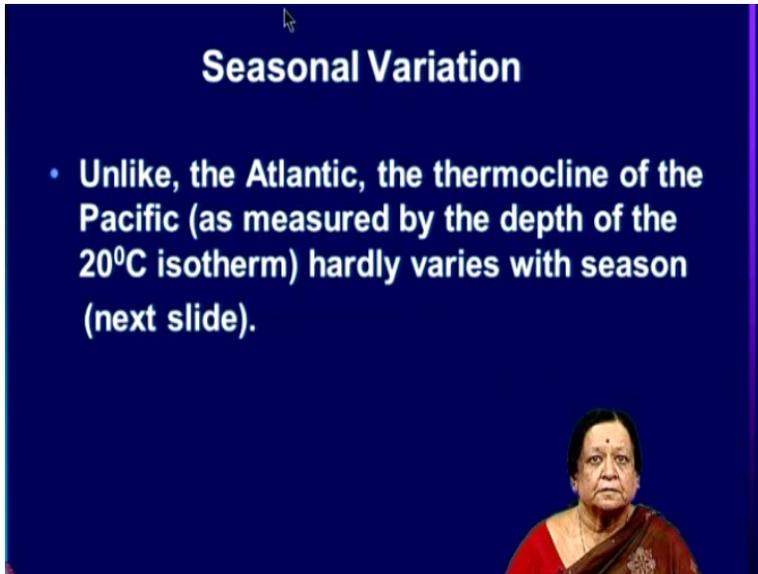
So what has happened is that during El Niño the 20 degree centigrade isotherm has become much deeper right, this is simply showing that the thermocline is deeper during El Niño, so the cold isotherm has become deeper whereas during La Niña it will become very, very shallow. So that is the surfacing of the thermocline during La Niña.

And you see that here in the SST as well that this is during El Niño when all the SST is warmed throughout whereas during La Niña you see the 27 degree isotherm has come all the way here to almost 100-- beyond 180 east. So this is El Niño and La Niña cycles.

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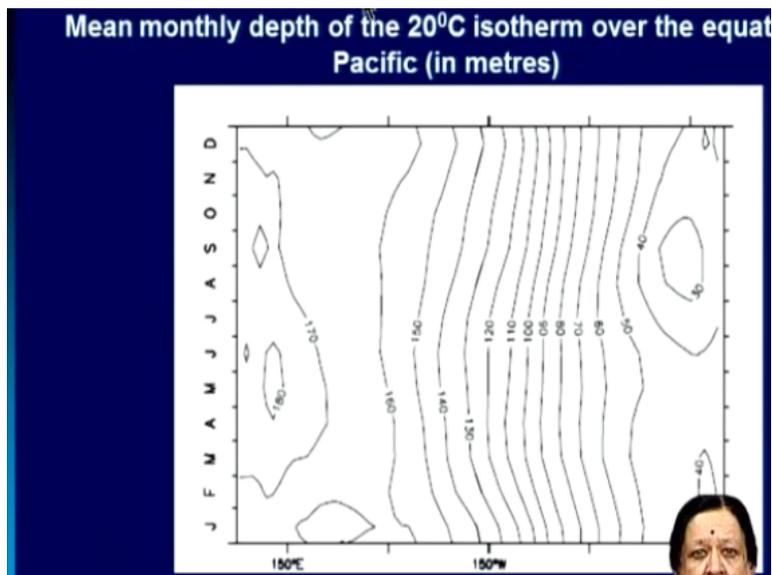
Seasonal Variation

- Unlike, the Atlantic, the thermocline of the Pacific (as measured by the depth of the 20°C isotherm) hardly varies with season (next slide).



Now, Seasonal Variation. So what is the seasonal variation over the Pacific? Unlike the Atlantic, the thermocline of the Pacific as measured by the depth of the 20 degrees isotherm hardly varies with season.

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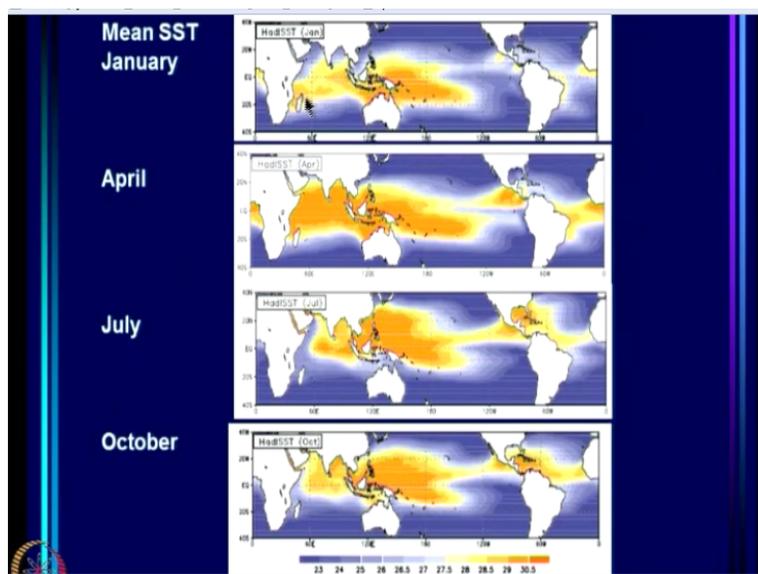
So what you see here is this is the, these are the calendar months and this is the going from east to west in the Pacific and basically these are just vertical lines which is saying it is hardly varying with season, okay the thermocline depth hardly varies with season over the Pacific but over Atlantic we saw much more variation.

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- However, there is considerable variation of the SST with season (following slide).
- The SST of the Pacific west of the dateline is high westward of the dateline, from about 20° in the summer hemisphere to about 10° in the winter hemisphere.

However, that is not true of—the sea surface temperature we have already seen. Sea Surface Temperature does vary with season. And we can now see it in here.

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Now what you see is the snapshot of the mean SST for January, April which is the boreal spring, July, boreal summer and October which is the austral spring. Now what you see is actually you can see very easily that in January it is-- see the warm thing is almost touching Australia here. It is at its southern most location. This is the warm SST belt. But throughout of course this part remains cold.

The southern hemisphere and equatorial region over this part remains cold January, April, July and October. That is the permanent feature that does not change. But this belt of warm water that does show a change and you can see between January where is more to the south and July now you see it has shifted northward so that the it has gone north of the tip of Australia as well. So there is a northward shift of the belt.

Secondly, you see a major change in the northern hemisphere in the east Pacific. In January, it is all cold, all below 27.5. Remember, yellow and orange and so on corresponds to temperature above 27.5. So January this part entire Pacific is cold and west Pacific is warm here. But from April onwards you begin to see, warm ocean here, but only in the northern hemisphere in the east Pacific not in the southern hemisphere because of the upwelling cause by winds.

So this block that you see here is warm water is there from April; is there in July but remember it is only in the northern hemisphere and is in October as well. It is very strong in April relative to October. So there I considerable variation in SST; you see that also over Indian Ocean and we will look at it in greater detail when we discuss the coupled Indian Ocean atmosphere system and you see this is January when it is to its southern most location and not has high SST.

But April, this is one of the hottest region toward the world Indian Ocean. And you see that it is warm over a very large latitudinal extent relative to the Pacific. And by July the Monson has setting and you see still there is warm water here but Pacific is now much warmer and October again now SST is weakening but this Pacific region remains hot. Now however it is now slowly moving to the south.

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- **Over the east Pacific (east of 120°W), the SST is low except in small patches in January. However, during April to October, the ocean is warmest along the coast of America from about 5°N to 20°N and warm in a thin belt around 5°N over 170°W - 120°W .**

So over east Pacific the SST is low except in small patches in January. However, during April to October ocean is warmest along the coast of America from about 5 degrees to 20 degrees north and warm in a thin belt around 5 degrees north. So what happens from here on April onwards SST is high here and in a thin belt around 5 degrees north here, same thing here, July you see is hot hear much warmer.

And along a thin belt it is just above 27.5 and very, very thin 28 degrees. So there is a thin belt connecting this rather large region of warm SSTs here and much large region of warm SSTs over the west Pacific is connected by thinner belt of warm SSTs. Okay.

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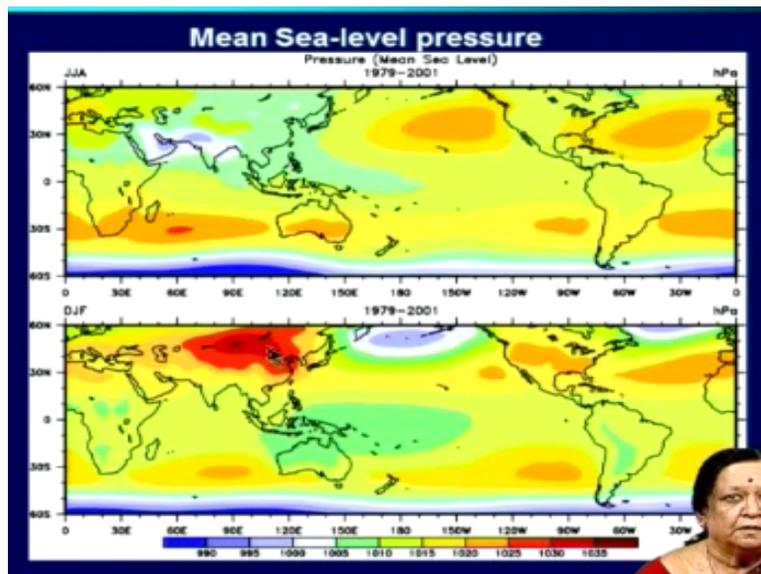
Mean atmospheric circulation and convection over the tropical Pacific

- **In the boreal as well as austral summer, the SST and hence the air temperature is higher over the West Pacific than the east.**
- **The mean sea-level pressure is lower over the West Pacific than over the east Pacific (next slide).**

Now we go to the mean atmospheric circulation and convection over the tropical Pacific. Now the main tool we use for this is the OLR of course, the outgoing longwave radiation measured by satellite which is a very robust measure and for which measurements are available for a very long time very stable OLR data from 82 onwards to today. So already more than 30 years.

Now in the boreal as well as austral summer the SST and hence the air temperature is higher over the West Pacific than the east, we have seen this.

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What this? This is now the Mean Sea-level pressure because remember now we are looking at features of the atmosphere over the Pacific and pressure is low greens means pressure is low and this means it is higher. So for both the seasons pressure is lower over the west Pacific than it is over the east Pacific.

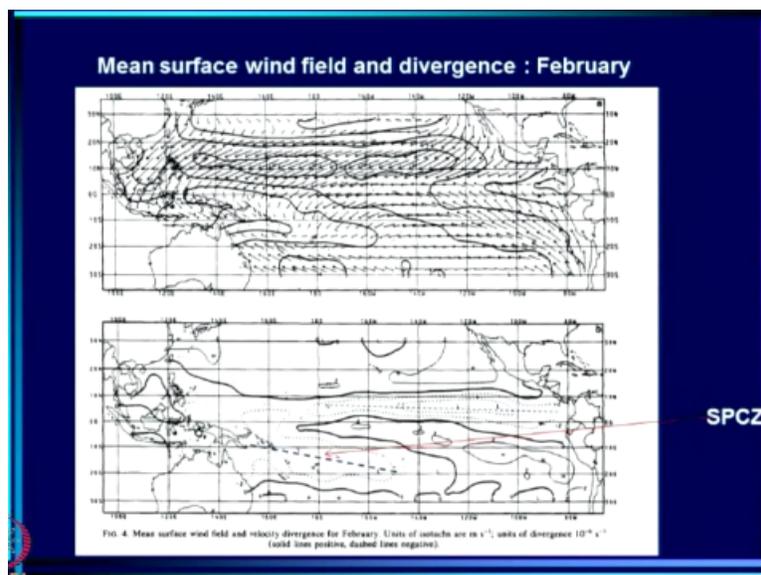
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I consider first the boreal winter i.e. December-January-February season which is generally the focus of most of the discussions of ENSO.

The mean surface wind and divergence for February, derived by Rasmusson and Carpenter (1982) by analysis of a data set consolidated by them is shown in the next slide.

So first let us less consider the boreal winter, that is December, January, February season which is generally the focus of most of the discussion of ENSO because they generally began with a discussion of the boreal winter. Now the mean surface wind and divergence for February, this was derived by Rasmusson and Carpenter by collection of a huge data set including SPCZ data is here.

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Now these are the mean winds and you can see here very clearly. See these are the winds from south to north to which cause the coast upwelling and these are the winds which are north easterly from the northern hemisphere, south easterly from the southern hemisphere, which have

converging over the equator. So as far as the atmosphere is concerned these are now belts of convergences so there is a very strong belt of convergences here, and this is called—

There is a convergence belt here, that you can see going this way this is called the south Pacific convergence and in addition this is called South Pacific Convergence Zone- SPCZ and in addition you see just here around 5 north there is another of convergence of this winds. So these were toward the 2 zones of convergences and remember zones of convergence are important because if you have zones of convergence that means the air has to ascent and this is moist tropical air.

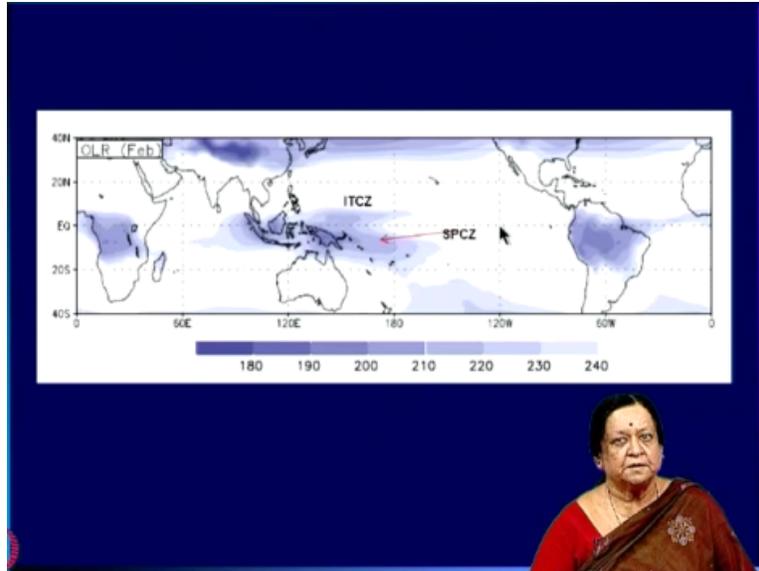
So if it is ascents with sufficient velocity then you can get condensation in rainfall; you can get a tropical convergence zone.

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- The mean OLR pattern (next slide) shows that the convergence zone over the Western and central part, with the axis tilting southeastward from 150°E and 10°S to 150°W and 20°S , is associated with a belt of low OLR-delineating the South Pacific Convergence zone (SPCZ).
- The low OLR belt around the equator (the ITCZ) stretching eastward from the Indian Ocean, is also over a region of convergence. However, in February, the SPCZ is stronger than the ITCZ over the western Pacific.

So the mean OLR pattern, again we are looking at boreal winter now first, what does it show?

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This is the mean OLR pattern and remember lighter shades from about 240 so on monthly seasonal scale < 240 watts per meter square outgoing longwave radiation indicates deep convection presence of deep convection. And as you go to darker and darker shades you are getting deeper and deeper clouds, clouds which are taller and therefore emanating less and less radiation.

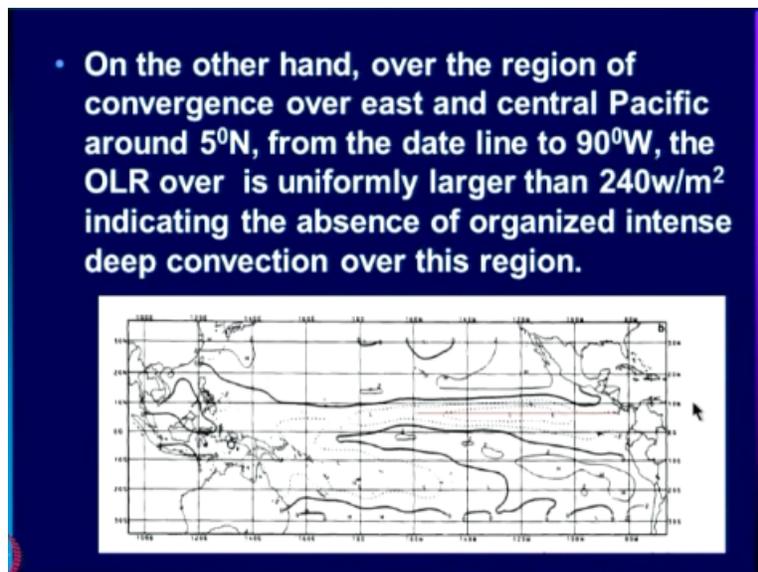
So now what you see here is there is one band this we call the ITCZ Inter Tropical Convergence Zone. And in addition to the there is the SPCZ, this is the South Pacific Convergence Zone. So for February then you see, in fact the ITCZ over the Indian Ocean is also nicely seen here, so you have an ITCZ extending from the Indian Ocean going along here and in addition to that another convergence zone SPCZ, note there is nothing in this whole region.

No organized convection, no organized deep convection in the east Pacific. Okay. So what we saw as that convergence zone over the western and central part with the axis tilting southeastward from 150 East is this is associated with a belt of low OLR-delineating the south Pacific convergence zone. So here we can I have marked the convergence zone ocean, see this is the convergence zone tilting; this is the convergence air remember, it is titling, this way, it is going southeastward in this way.

So from there derive that there is a convergence zone here and there is another convergent zone which is all along here okay. So now the convergences here we see but the convergence here we do not see as a low OLR region and that is what we will see here. Though low OLR belt around the equator the ITCZ is stretching from the eastward from the Indian Ocean, it is over the region of convergences, so this is the region of convergence here.

And of course we saw the convergences only for the Pacific, so that corresponds to this zone here and we had this tilted zone which was of convergences which actually now showing a deep cloudy here, this is the South Pacific Convergence Zone.

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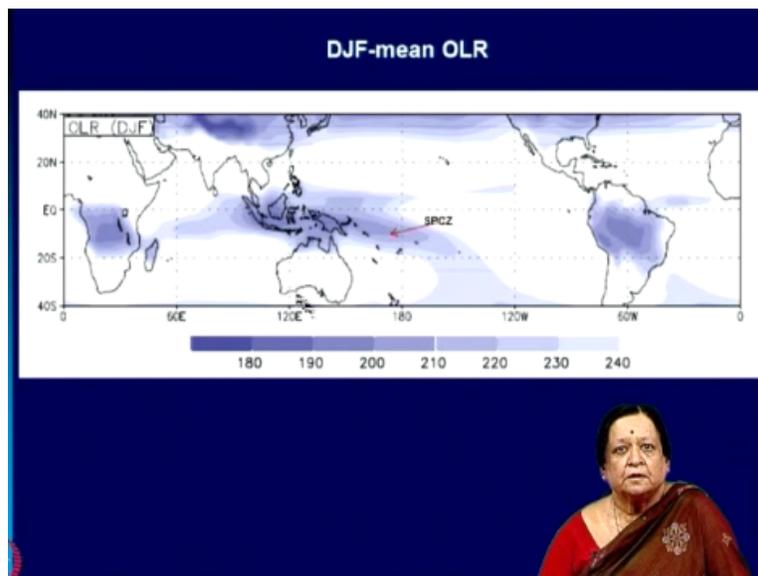
But on the other hand, over the region of convergence over east and central Pacific that is to say this part here, east and central Pacific also there was a zone convergence, what we saw what came over this zone of convergence and this zone. But over this zone we do not see any low OLR region at all. You see here, that zone was around here 5 north or so. But you do not see any low OLR region OLR is above 240 over the entire region.

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- The OLR pattern for the boreal winter (next slide) is seen to be similar to that for February with the SPCZ stronger than the ITCZ over the West Pacific. There is no low OLR region over central and east Pacific.

So the OLR pattern for the boreal winter is seen to be similar to that of the February with SPCZ stronger than the ITCZ over the West Pacific and no low OLR region.

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So we have here SPCZ, we have the ITCZ which is coming all the way from the Indian Ocean here. This is the ITCZ, SPCZ is stronger stretching more and there is no low OLR region at all over this region.

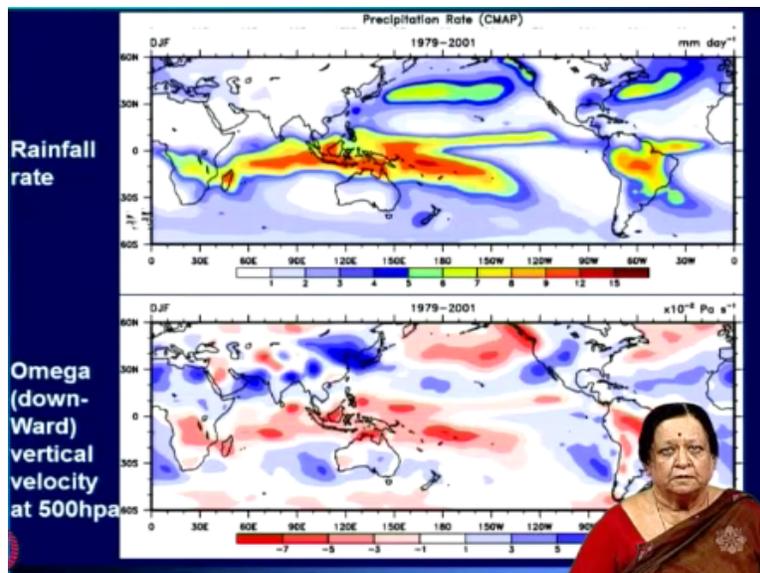
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- The rainfall pattern (next slide) is consistent with the OLR pattern for DJF. As expected, there is intense upward velocity and copious rainfall over the warm waters of the West Pacific.
- However, over 180⁰-90⁰W there is only a thin belt with low rainfall (and low upward velocity at 500 hpa) around 10⁰N.



The rainfall pattern.

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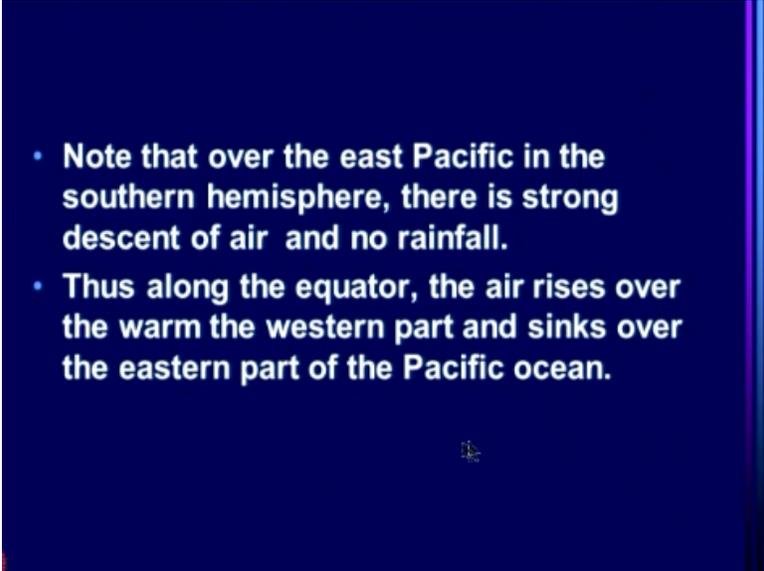
So actually their rainfall—this is the precipitation rate from sea map data. This is the precipitation in millimeters per day and the scale is down here. Now what you see is bright green and red is reasonable rainfall. What you see is bright green and red is reasonable rainfall. What you see is a lot of rain occurring over this Indian Ocean ITCZ and over SPCZ. This is part of the ITCZ here. And this is the ITCZ convergence stretching here.

And where you did not see much a low LR region now you are seeing some rain occurring okay. This is between 5 and 6 millimeters per day, so there is some rain occurring. Now what you see

below is omega at 500 HPA that is to say halfway up in the troposphere, mid-troposphere is the air rising or sinking. You can see air is rising very much strong ascent here where we already saw low LR, okay, this region here including over southern parts of Africa.

This is the African monsoon. So you see air rising here and air is also rising to some extent here where there is weak rain, okay. So although there are no regions of deep clouds no low OLR region there is region of weak rain and weak ascent stretching right across the Pacific.

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- Note that over the east Pacific in the southern hemisphere, there is strong descent of air and no rainfall.
 - Thus along the equator, the air rises over the warm the western part and sinks over the eastern part of the Pacific ocean.

So over the East Pacific in the Southern Hemisphere there is a strong descent of air and no rainfall, okay. So over the East Pacific here this is a strong descent of air and there is no rainfall. So if we look at the equatorial region then what you are getting is strong ascent over the west, strong descent over the east. This is the picture that you see in the equatorial region and also in the Southern Hemispheric tropics. So there is strong descent of air over the east.

So along the equator the air rises over the warm western part and sinks over the eastern part of the Pacific Ocean, okay. So this is what is happening here and so air is rising here and sinking here, okay.

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East-west variation of organized convection over the tropical Pacific

- **TCZ over the West Pacific:**
- **The surface of the western Pacific is warm, with the SST well above the threshold. Warm regions tend to have lighter air above these regions as the air is warmed by the surface. Warm air is light and since surface pressure is the total weight of the air above it, the surface pressure tends to be smaller above warm tropical regions.**

And, so there is east west variation of organized convection over tropic in Pacific we have seen this. There is a TCZ over the West Pacific which we have seen here in the OLR picture as well, okay. This is the huge tropical convection zone comprising 2 of them actually over the West Pacific and this is over the warm oceans. So the surface of the Western Pacific is warm with the SST well above the threshold.

Warm reasons tend to have lighter air above these regions as the air is warm by the surface. Now warm air is light since the surface pressure is the low total weight of the air above it. The surface pressure tends to be smaller above warm tropical regions, okay.

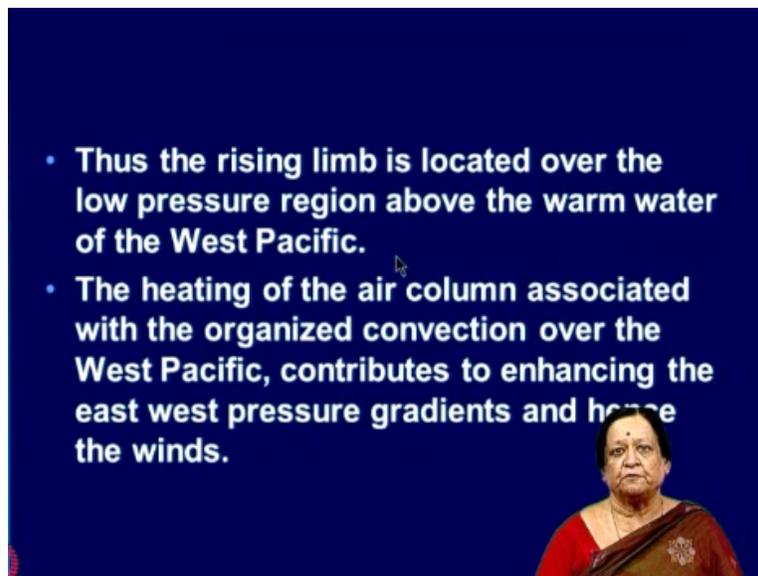
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- **Moist air from surrounding higher pressure regions converges over the warm water, and rises. The moisture in the rising air condenses and the heat of condensation raises the air further.**
- **If the underlying SST is warm enough, (above the threshold), the clouds can reach to the top of the atmosphere (the tropopause), leading to organized deep convection.**

So you have warm air over the West Pacific and surface pressure is lower. So moist air from surrounding higher pressure regions converges over the warm water and rises. The moisture in the rising air condenses and the heat of condensation raises the air further. So you have in fact convection, deep convection triggered here because of convergence which is generated by this special difference here, which in turn is generated by the sea surface temperature gradient.

So if the underlying SST is warm enough the clouds can reach the top of the atmosphere leading to organized deep convection. Remember this is the way we had analyzed how tropical convective zones arise.

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So the rising limb of the atmosphere is located over the low pressure region above the warm water of the West Pacific. The heating of the air column associated with organized convection over the West Pacific contributes to enhancing the east west pressure gradient and hence the winds. So you have in addition to the surface temperature gradient which is warm in over the west we also have heating over the west once the clouds are triggered. So this will enhance the pressure gradient.

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- The winds across the surface of the tropical Pacific blow westward into the region of low pressure. The rising motion in the warm region reaches the tropopause and returns eastward aloft and completes the circuit by descending over the eastern Pacific leading to higher pressure at the surface.



Now winds across the surface of the tropical Pacific we know low westward into the region of low pressure. The rising motion in the warm region reaches the tropopause and returns eastward aloft completing the circuit.

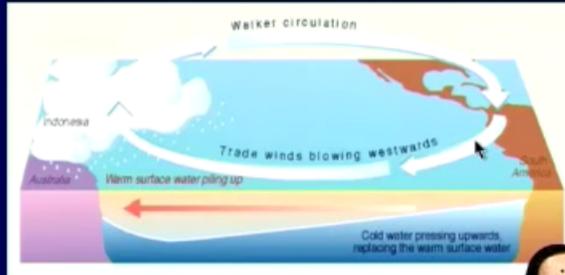
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- This tropical Pacific-wide circuit of air proceeding westward at the surface, rising over the (warm) region of organized convection and persistent precipitation, returning eastward aloft, and descending over the cool eastern Pacific, is called the **Walker circulation**. Associated with the Walker circulation is the low surface pressure in the western Pacific and the high surface pressure in the east.



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The rising of air in the west and sinking over the east Pacific associated with this convection pattern is called the Walker Circulation.



So this tropical Pacific wide circuit of air proceeding westward at the surface rising over the west Pacific then rising here in the deep convection generated over the West Pacific then moving towards the east and sinking over the Eastern Pacific. Now, this kind of circulation here is called Walker Circulation. Bjerknes called it Walker Circulation and this is an east-west circulation.

Remember we have seen Hadley Circulation which is a meridional or north-south circulation. This is an east-west overturning if you wish which is called the Walker Circulation.

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- Thus Walker circulation is an important facet of the atmosphere in the boreal winter (DJF)
- In the next lecture, I consider the mean state of the tropical atmosphere over the Pacific in the other seasons.

Thus, Walker Circulation is a very important part of the boreal winter. Now in that next lecture I will consider the mean state of the tropical atmosphere over the Pacific India, The Seasons.
Thank you.