The Monsoon and Its Variability
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Lecture - 23
The Tropical Oceans

Today, I am going to talk about Oceans, so far we have been focusing more on the atmosphere. But many important phenomena in the tropics such as El Nino Southern Oscillation and so on or phenomena of the coupled ocean atmosphere of the system, and therefore, oceans play a very important role we have also seen oceans play an important role in the monsoon as well. So today I will give the background necessary in terms of oceans as far as El Nino southern oscillation is concerned.

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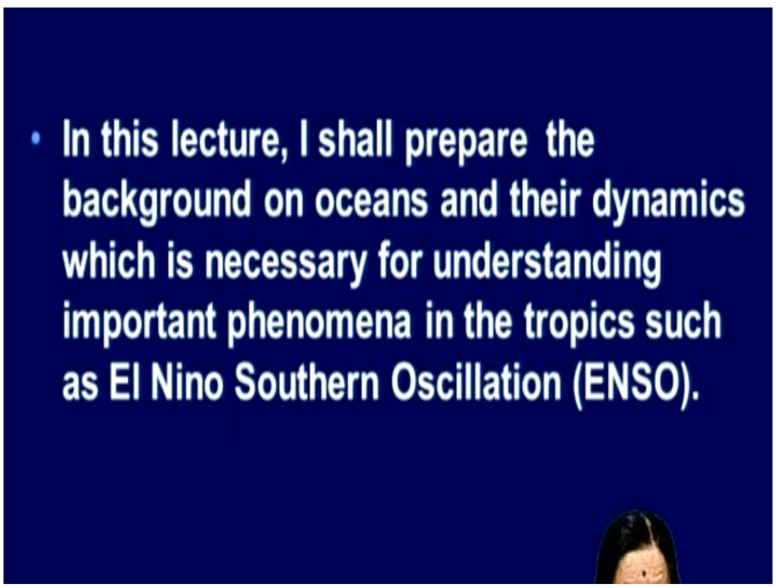

So in this lecture then I am going to prepare the background on oceans and their dynamics, and I am only going to cover those points which are necessary for understanding important phenomena in the tropics such as El Nino southern oscillation and because this phenomenon is in the over the Pacific in terms of Oceanography, we will also focus a little bit on the Pacific here.

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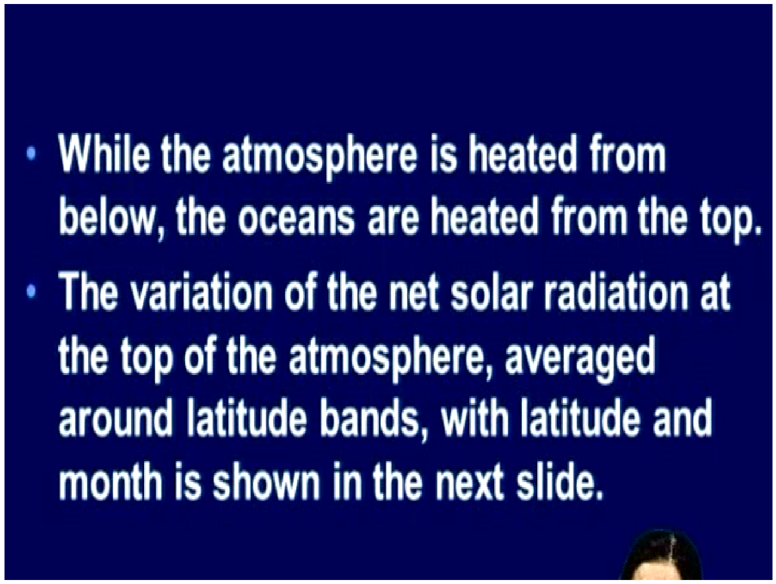

What is the important Oceanography of the Pacific? Now one thing we have to remember is you know atmosphere is heated from below, although the radiation comes from up above actually most of it passes unhampered to the surface of the earth beat land or ocean, and it is the radiation emitted from the surface of the earth along with sensible heat another fluxes that heat the atmosphere above.

So atmosphere as we saw in the earlier lecture is actually sitting on the earth plate it is heated from below, now oceans it is a different story because oceans are heated from the top because net solar radiation incident at the surface of the ocean is what heats the ocean. So it is a different system because you know that a fluid heated below is creating unstable situation because you are getting warm air which is lighter, whereas when a fluid is heated above the warm water is lighter but that may sit stable okay.

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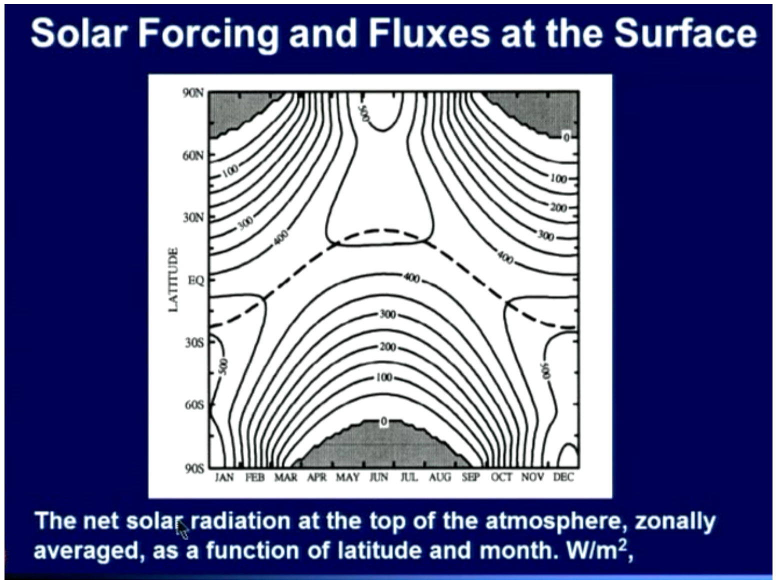

So this is this solar forcing and fluxes at the surface, and what you see here is actually average now, this is the solar radiation at the top of the atmosphere zonally averaged which means average across the longitudes as a function of latitude and month. And what you see is, see this is May-June-July this is what we called the northern hemispheric summer or the boreal summer okay, and in that you see a lot more radiation is incident on the northern hemisphere then on the southern hemisphere.

And the opposite is to in the December-January-February which is the austral summer where you get a lot more radiation here in the southern hemisphere as compared to the northern hemisphere. So the solar forcing and fluxes at the surface actually change in season and vary with latitude.

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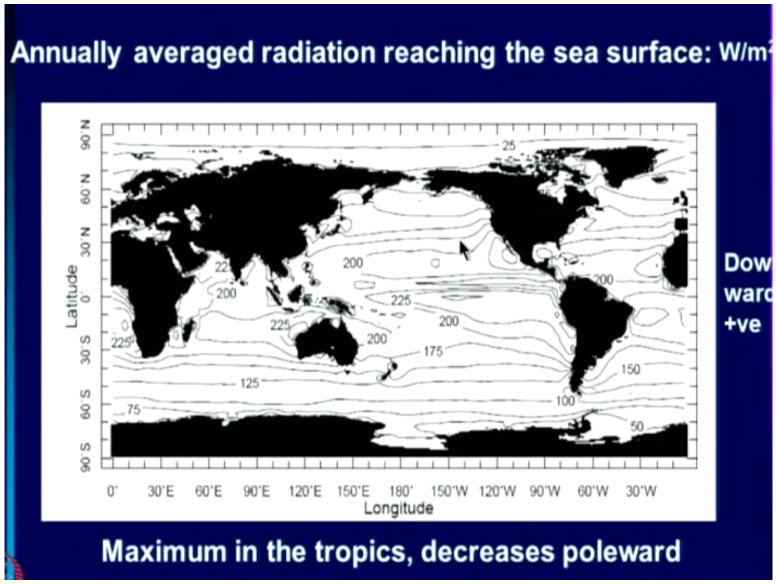

So if we look at the annual averaged radiation so far in the last slide we saw what would be the average across longitude, now we look at what happens to the annually average radiation that is we do not worry about variation from month to month, and look at what is the one that reaching the sea surface. And what we find is that in fact you see this is the highest radiation that is coming here, and it is in the tropical belt, annual average is highest in the tropical belt.

This is where it is 225 inside and 200, so annual average is highest in the tropical belt and as you were towards the pole the radiation reaching the sea surface decreases okay. So ocean is heated from top and the heating is maximum in the tropical regions decreases as we go away from the tropics.

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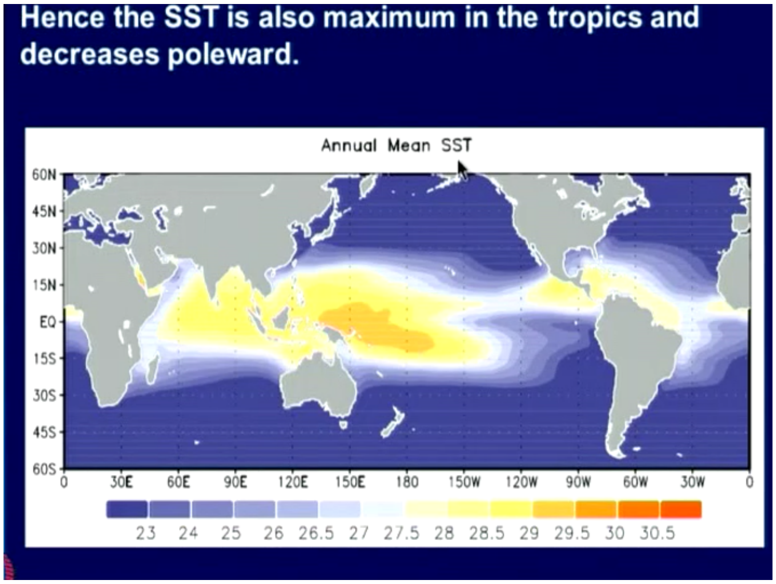

So naturally if you look at the annual mean SST and annual mean sea surface temperature, it is maximum in the tropical belt okay and decreases as we go poleward. Now there are differences within the same latitudinal band like you see here from west Pacific to east Pacific, and I will come to why they are rise. But basically the maximum sea surface temperature like the incident solar radiation is also maximum in the tropics and decreases poleward.

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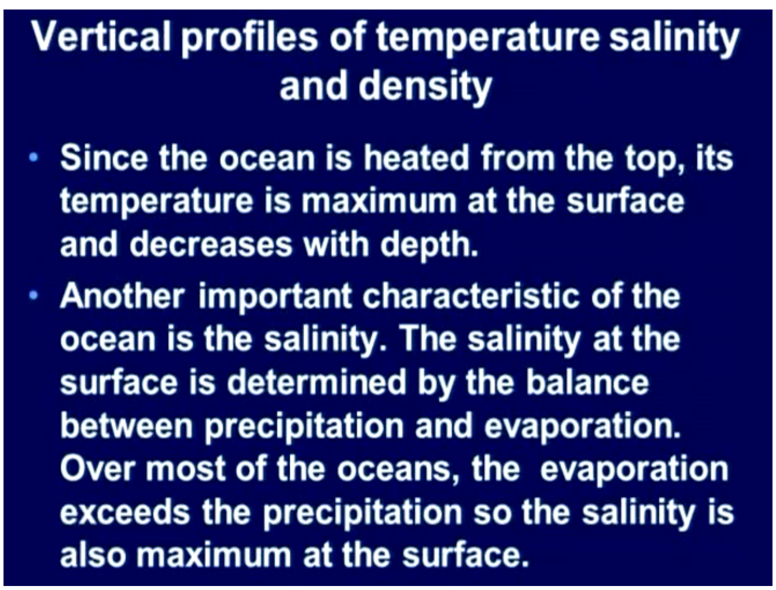

Now what is the vertical profiles of temperature, salinity and density over the ocean like, now since the ocean is heated from the top its temperature is maximum at the surface and decreases with depth, right. Another important characteristic of the ocean is the salinity, salinity is the salt in the water, the salinity at the surface is determined by the balance between precipitation and evaporation.

So if you have evaporation then the water evaporates salt gets left behind, so the water will become more saline salinity will increase, on the other hand if you get rain, rain is freshwater so fresh water will mix with salt water the salt content will decrease. So the balance between precipitation and evaporation determines the surface salinity. Now over most of the oceans the evaporation exceeds the precipitation, so the salinity is also maximum at the top of that thing.

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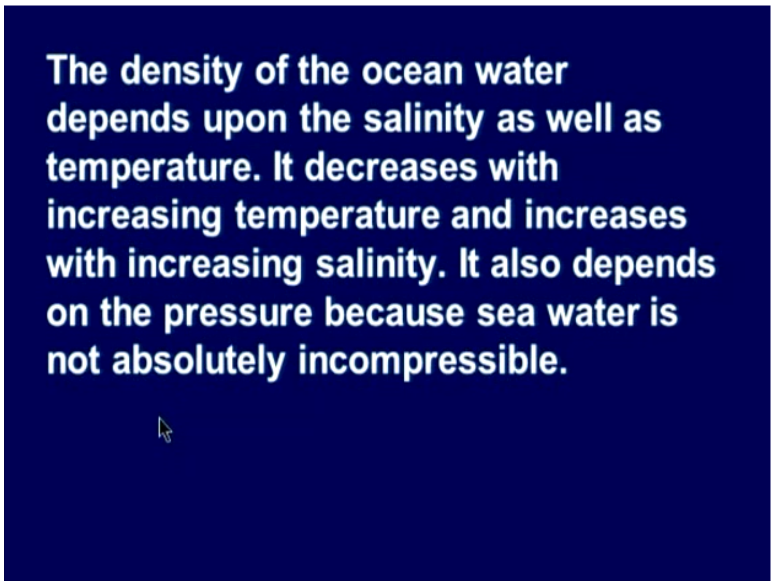

The density of the ocean water, so the salinity tends to be maximum near the surface of the ocean and decreases as you go down the density of the ocean water depends upon the salinity as well as temperature right. Now it decreases with increasing temperature right warmer water the density will be lower, but increases with increasing salinity, now near the surface you have warm water which is highly saline.

And so you have depending on you know the contribution of temperature and salinity you could have an increase or decrease of density with height. But density also depends on the pressure because sea water is not absolutely incompressible right.

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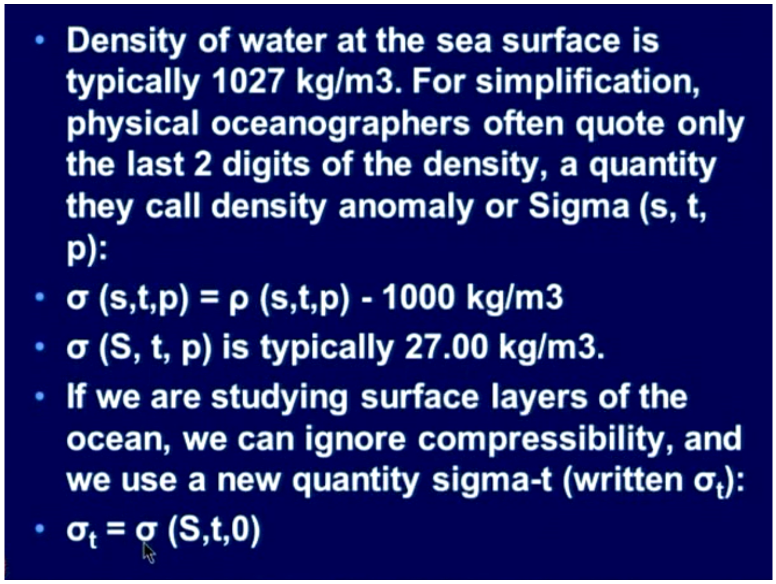

So density of water at the sea surface is typically about thousand kilograms per meter cube okay, so it is 1027 kilograms, and for simplification physical oceanographers do not go on using the big number 1000 instead they subtract the density from the actual value of density 1000, so they only used the last 2 digits of that number okay. So this is the quantity that they called density and anomaly which is the difference between 1000 and the actual density and this is what they call sigma.

So sigma s, t, p which is the density anomaly okay, which means rho is the density here is the density -1000 is the sigma s, t, p and sigma s, t, p is typically 27.00 grams per meter cube. Now if we are studying surface layers of the ocean we can ignore compressibility and we use the new quantity sigma-t which we write as S, t, 0 no pressure variation is here.

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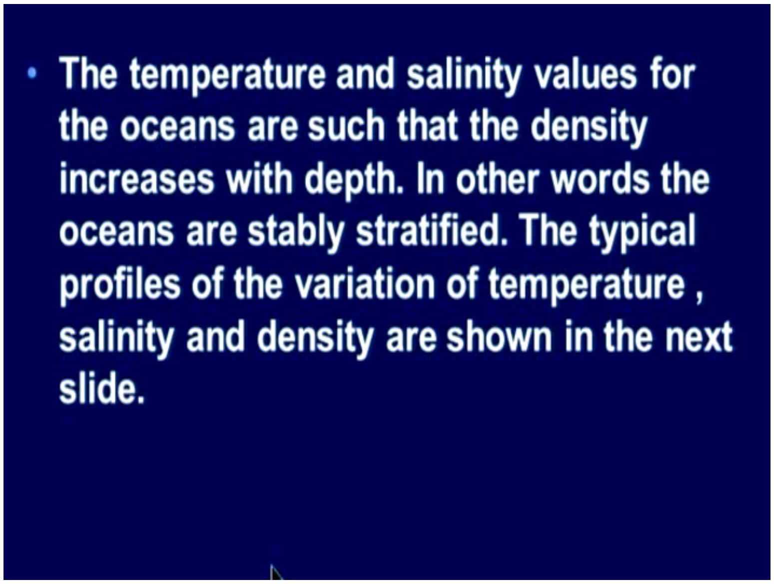

And the temperature and salinity values for the oceans are such that the density increases with depth, in other words the oceans are stably stratified. The typical profiles of the variation of temperature salinity and density for the world ocean now are shown here.

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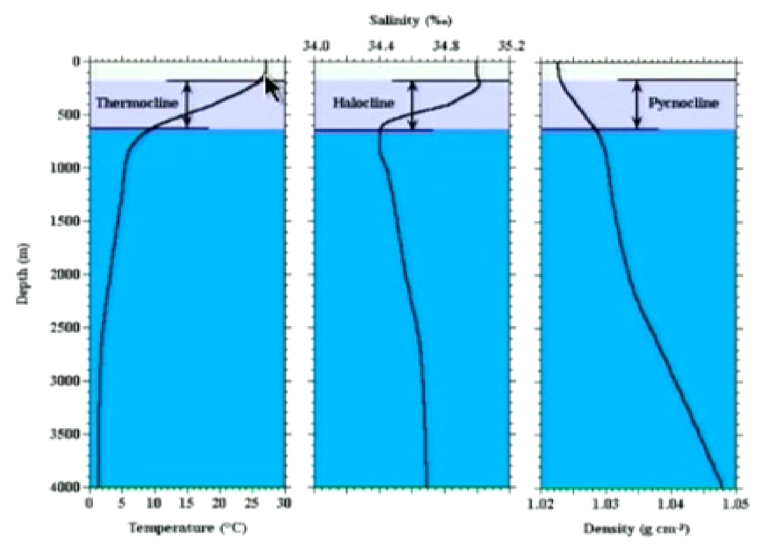

So the first typical variation of temperature this is the surface now, and remember as we go down we are going deeper and deeper into the ocean, so we have an ocean have to say 4000 meters 4 km. So this is the temperature on this axis and this is the depth, and what you see is in the upper layer here the temperature does not change much okay, this is the layer about 100 meters in deep, then the temperature decreases very rapidly this region is called the thermocline okay.

Where you have a very rapid decline of the temperature thermocline, so this is a very important part of the profile the thermocline where it decreases very rapidly and below the thermocline then the temperature decreases very slowly until we reach the bottom okay. Now what happens to the halocline, as I mentioned you know in most of the oceans the evaporation exceeds precipitation so salinity is maximum near the surface.

So here you have a mixed layer in which the temperature is more or less constant and in which the salinity also does not vary with depth, so this is the mixed layer and then the salinity decreases this is the halocline and then it increases slowly. So the major changes are in this mixed layer thermocline mixed layer halocline. Now what does the density look like as I mentioned it would have been something else.

But it so happens that the combination of t and s that occur in our oceans are such that the density actually increases with depth all the times, so you see it is very stably stratified fluid with heavy fluid under light fluid right. So even if you were to disturb it, it will revert to its original position that is why we call it stably stratified, so this is the typical distribution then, so you have a mixed layer in which temperature salinity and density are constant.

Then a layer from the bottom of the mixed layer up to a depth of you know this varies of course from place to place, from ocean to ocean, but up to a depth of about 600 meters or so in which salinity decreases rapidly, temperature decreases rapidly and density increases okay, and this is called the thermocline, halocline and pycnocline. This is the distribution of temperature and salinity.

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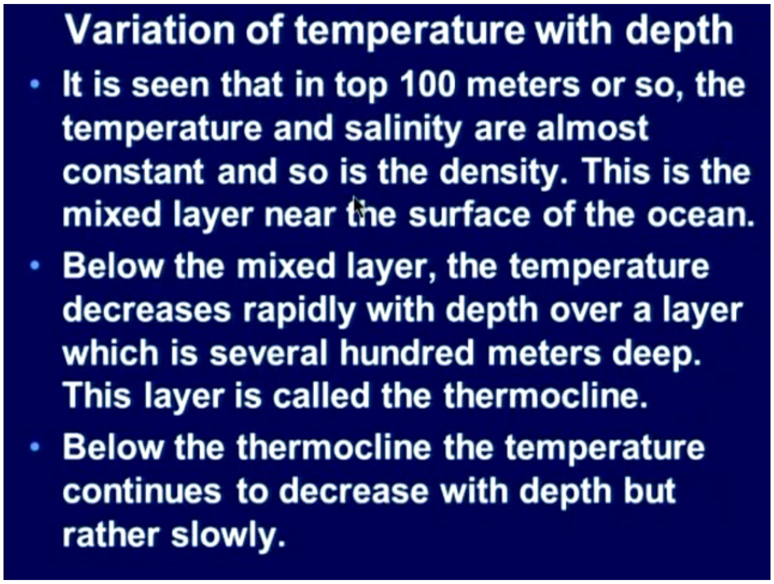

Now so we have already seen this that in the top 100 meters or so, the temperature and salinity are almost constant and so is the density. This is the mixed layer near the surface of the ocean below the mixed layer the temperature decreases rapidly with the depth over layer, which is several 100 meters deep and this is called the thermocline, and below the thermocline the temperature continues to decrease with depth but rather slowly.

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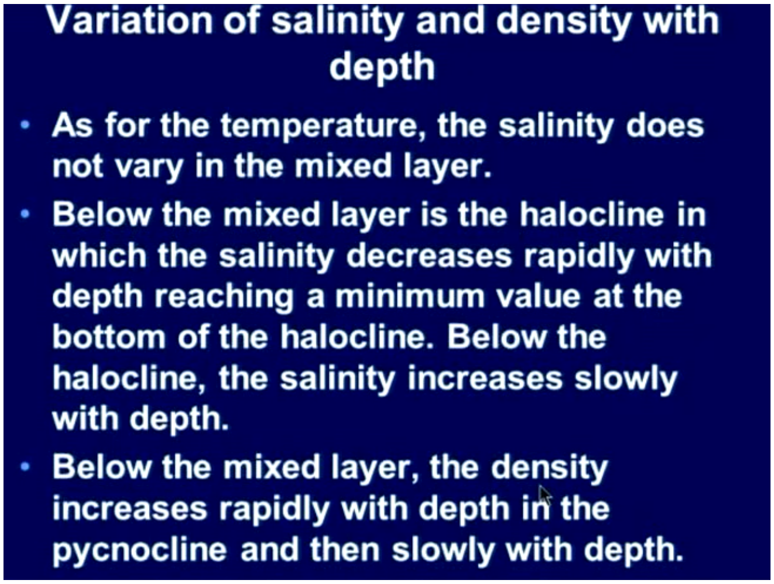

Now variation of salinity and density with depth, we have seen this as well as for the temperature the salinity does not vary in the mixed player, below the mixed player we have a halocline in which does it decreases rapidly to a minimum value, and below the halocline it increases slowly with depth, below the mixed player the density increases rapidly with depth in the pycnocline which actually coincides with thermocline and halocline, and then slowly with depth. So we have very rapid increase in this region of the thermocline of the density very very stable situation.

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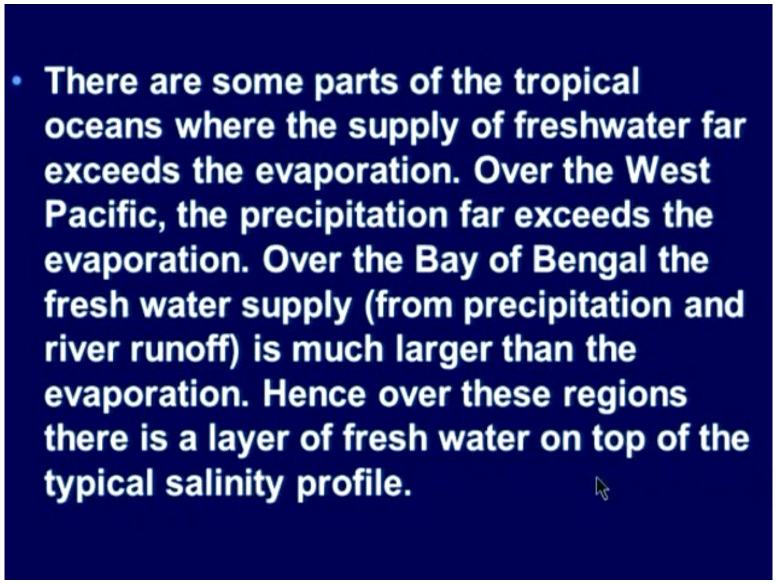

Now there are some parts of the tropical oceans where the supply of fresh water far exceeds the evaporation, now for example over the west Pacific the precipitation far exceeds the evaporation. Over our own Bay of Bengal, the fresh water supply and in this case is not only precipitation but it is also river run off, you know a lot of rivers end in the Bay of Bengal, and so they bring a lot of fresh water to the Bay of Bengal.

And so together they give a lot of freshwater to the surface of the Bay of Bengal, these 2 sources rainfall as well as river run off. And so with the result that the precipitation is much fresh water supply is much larger than the evaporation, so what happens over these regions there is a layer of freshwater on top of the typical salinity profiles.

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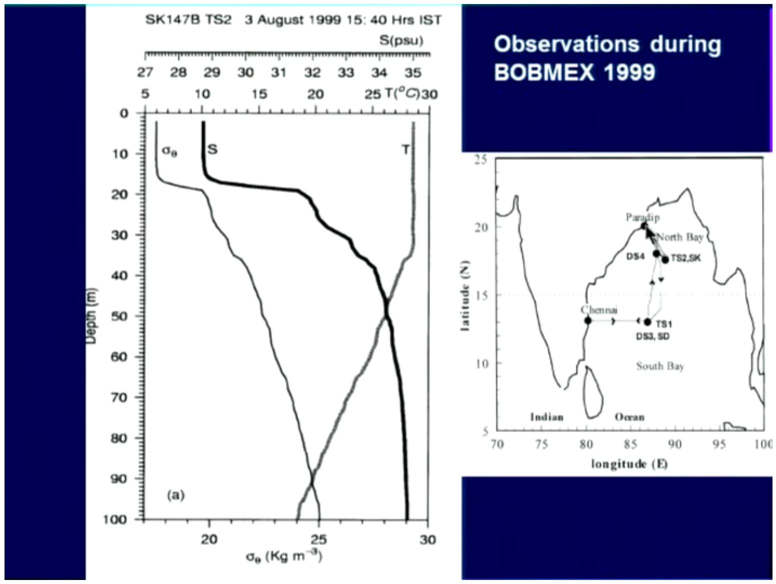

See typical salinity profile we already saw that, typical salinity profile we actually have salinity maximum near the surface, and what happens over the bay? And this is actually observations taken by in a national experiment called Bay of Bengal monsoon experiment conducted in 1999 by people from our Institute, from National Institute of Oceanography and a whole national team and what they did was they had 2 ships and they measure temperature, salinity as well as many many properties of the atmosphere and currents as well.

So this is data from that crews and what you see here is on a specific day 3rd August 1999 at a specific location, what you see is that see this is the temperature okay, and this is the mixed layer of the temperature and it is deep it is not 100 meters but it is 35 or so. On the other hand, you see on top of actually you should have had a mixed layer of the salinity right which is high, but instead of that what you get is a freshwater layer you see salinity is minimum here.

This is fresh water overlying more saline water okay, and then this is the decrease here, and this corresponds to the density here. So density also so in this upper layer density is constant because both temperature and salinity are constant, and then density starts to change here because salinity starts to change although the temperature is constant. So in this kind of situation is the salinity that determines how the density varies in the upper layers of the ocean.

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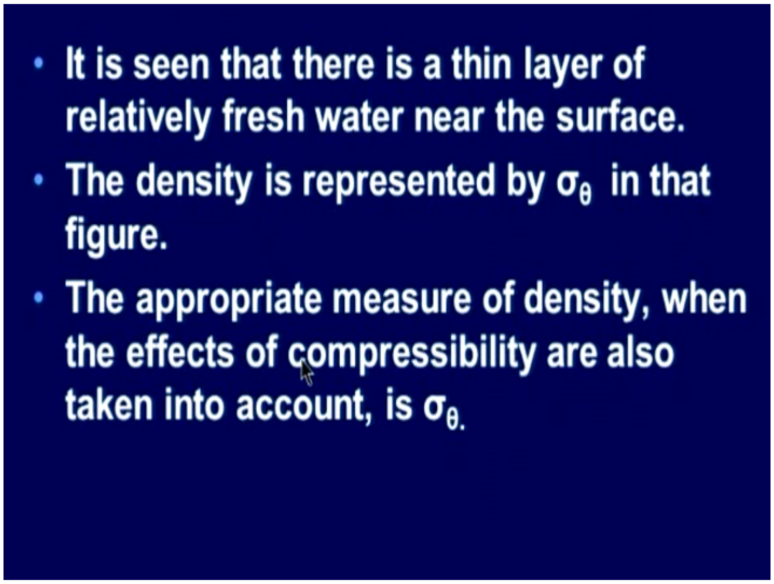

So there is a thin layer of relatively freshwater near the surface, the density is represented by sigma theta in that figure. Now the appropriate measure of density when the effects of compressibility are also taken into account is sigma theta, remember we said density depends on temperature salinity as well as pressure.

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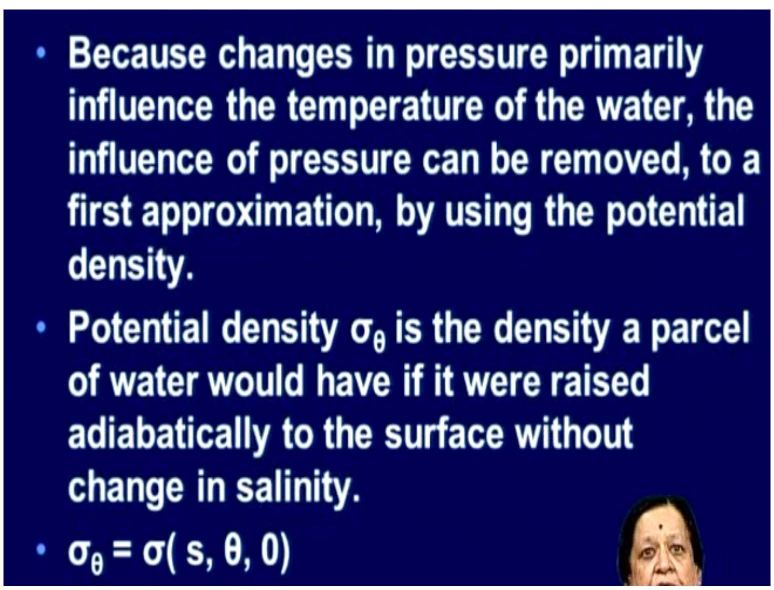

And just like in the atmosphere we talk of potential temperature, we can think of potential density here this is because the changes in pressure primarily influence the temperature of the water, so the influence of the pressure can be removed to a first approximation by using the potential density. Now potential density is sigma theta is the density parcel of water would have if it were raised adiabatically to the surface without change in salinity okay.

So you take a parcel of water in the ocean and rise it adiabatically means without giving any extra energy or without taking away the energy from the parcel, and rising to the surface at that point the density would be sigma theta which will be a function of s, theta and 0, theta being the temperature potential temperature in this case, theta is the temperature of the parcel which has been adiabatically raised to the surface. So sigma theta is sigma of s theta and 0 and that is what is plotted.

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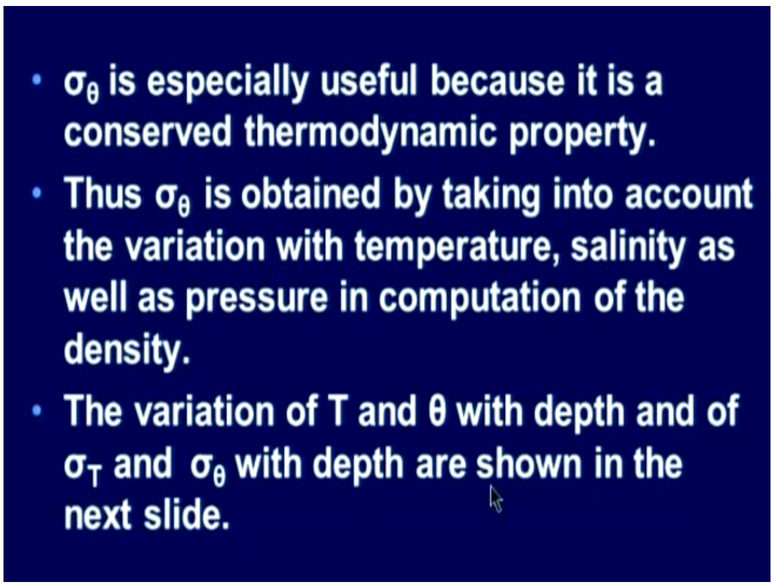

Now why do we do all this acrobatics? Because it is very useful because it is a conserved thermodynamic property is conserved as the parcel moves around, and thus sigma theta is obtained by taking into account the variation of temperature, salinity as well as the pressure in computation of the density. The variation of T and theta with depth and sigma T and sigma theta with the depth.

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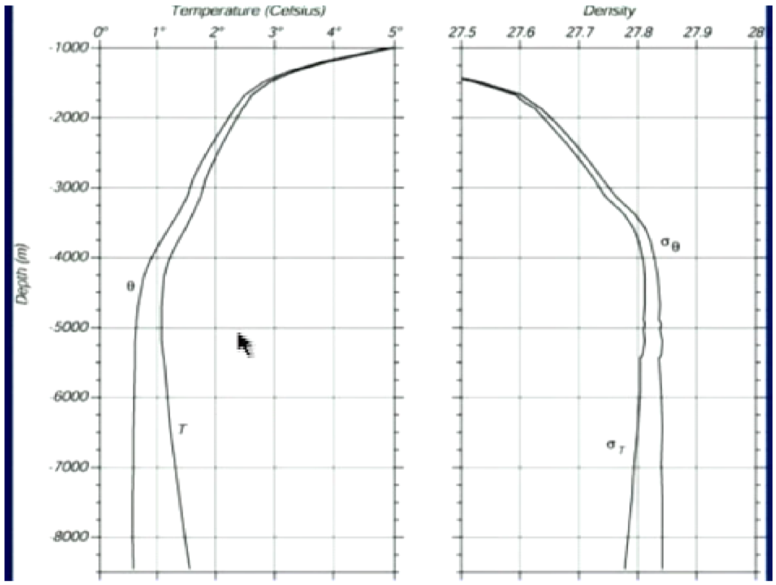

Again from the BOBMEX results are shown here this is theta, this is T, I am sorry these are not BOBMEX results, these are from another part of the oceans. So this is the temperature and you can see temperature and theta very close here, because there is hardly any change in temperature when you raise a parcel from this level to the surface. But as you go further deep naturally theta is different from the T and sigma theta is different from sigma T.

So you see here that density actually increases very shortly in this pycnocline, and then becomes constant this is the density of the ocean.

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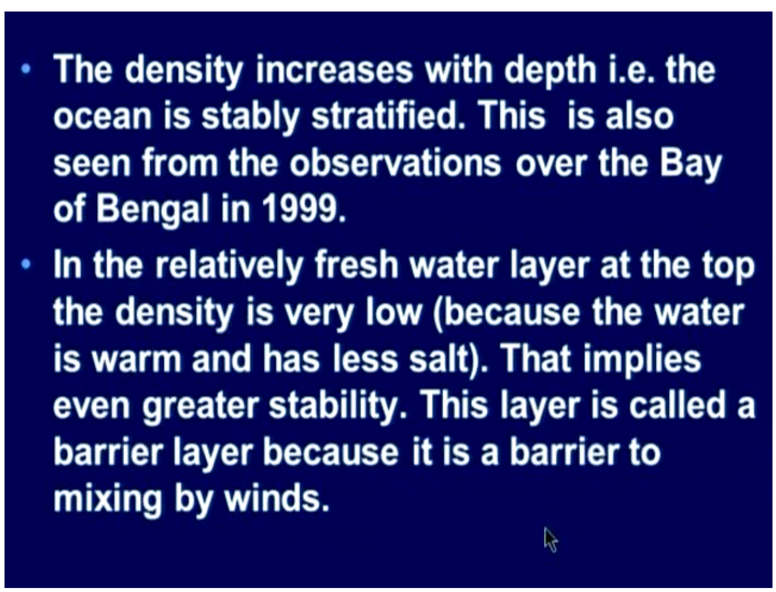

So the density increases with depth and the ocean is stably stratified, this is also seen from the observation for the Bay of Bengal. In the relatively freshwater at the top the density is very low right as it is typically you see that the density is lowest near the top, but if you have that is for a temperature profile like this, but if on top of this temperature profile you had a flat salinity profile, rather salinity profile in which the salinity is much lower than the water below.

Then what you would find is you have a freshwater layer at the top of the density, so that makes the fluid even more stably stratified right, because if the fresh water was not there anyway the density at the top layer is less than the density of the fluid below it, so it is stably stratified. Now the density of the top layer is further reduced because it does not have salt, because it is fresh water, and so the stability increases and so such a layer is called barrier layer.

Because it is a barrier to mixing by winds right, the stable fluid of a greater resistance to mixing by winds, so this is called a barrier layer the freshwater layer that you see in some places. And this is the barrier layer now that we saw earlier, this is the barrier layer because of the low salinity here, the salinity is given here and the temperature is given here. So the salinity actually this is the freshwater layer and the salinity actually increases below the freshwater layer okay.

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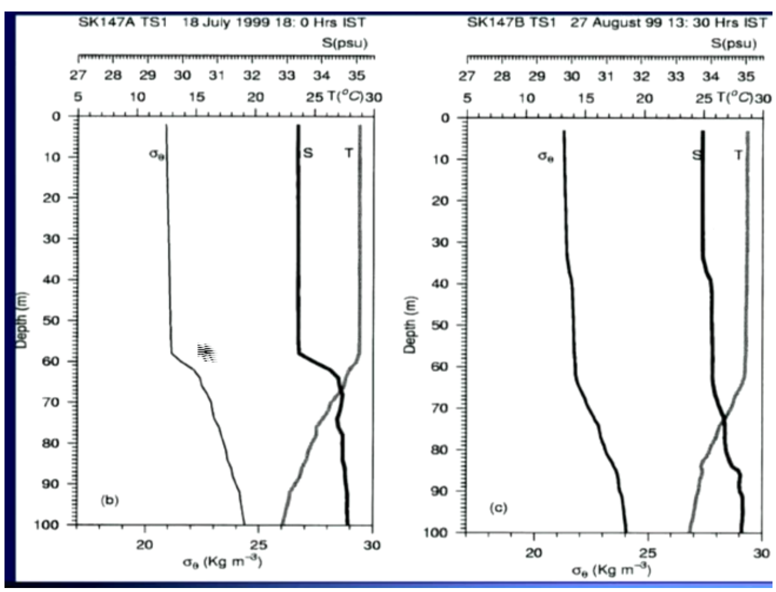

Now in the next slide which is over central Bay, now this is over central Bay and what you find is that the still salinity is somewhat less than what it is here, but actually the water is not fresh you see the salinity is not 33 parts whereas in the earlier slide in the head Bay salinity had reached 29 parts okay. So this is not as fresh, and furthermore you see that the salt mixed player and the temperature mixed player are the same and are much deeper than the barrier layer that was there.

Now actually this profile also changes from time to time, so over central Bay itself this was 18th July and this was 27th August and you find that the mixed player has become much deeper in August than it was in July, here it was around 60 and now you see it has become about 70 or so, and salinity is more or less fixed even up to 80 okay.

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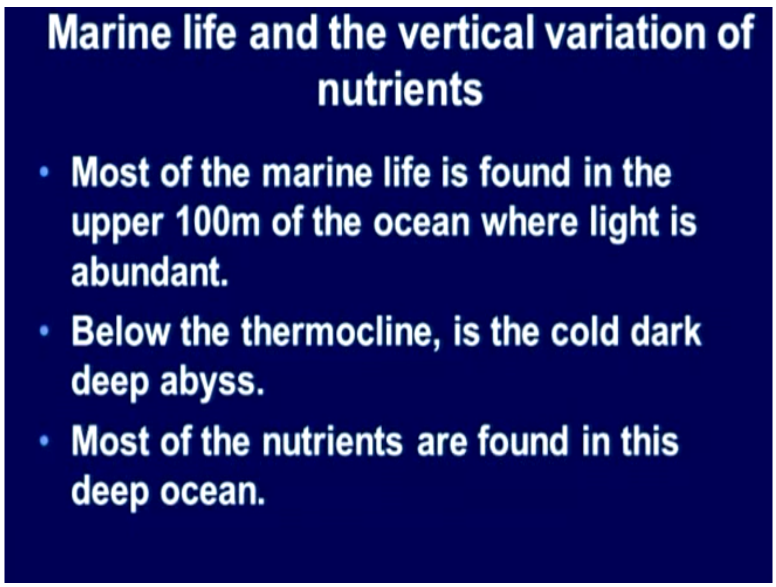

So this is so far we have talked about some facts of life about how temperature, salinity and density change in the ocean okay. Now marine life in the ocean is also very important, and how does marine life vary with the depth of the ocean okay? Now in fact most of the marine life is found in the upper 100 meters of the ocean where light is abundant, below the thermocline is the cold dark deep abyss. Most of the nutrients are found in this deep ocean okay.

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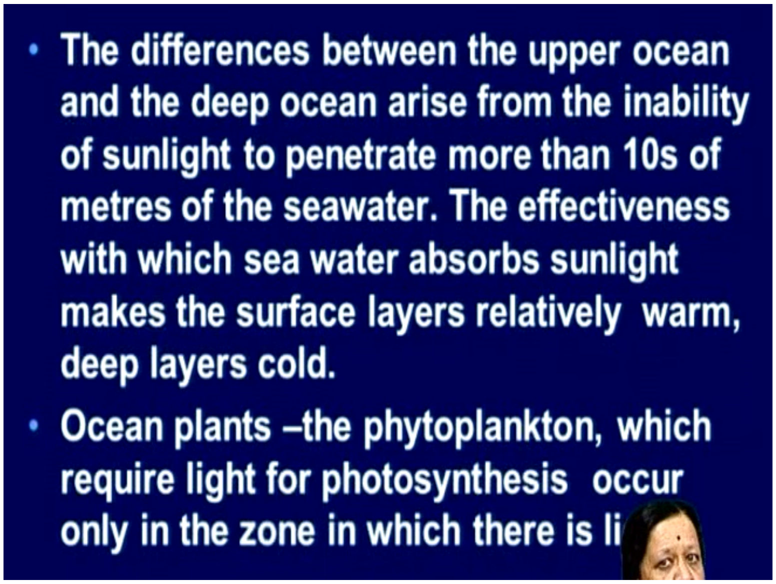

So now you will wonder why? Now the differences between the upper ocean and the deep ocean arise from the inability of sunlight to penetrate more than 10s of meters of the sea water okay, the sun light is incident on the surface of the sea does not penetrate beyond few 10s of meters okay. The effectiveness with which the sea water absorbs sunlight makes the surface layer relatively warm and deep layers cold.

So the sunlight penetrates only up to a few 10s of meters and until that point because it is observed the ocean becomes warm okay, and the deeper layers are cold because the sunlight does not reach it. Now the ocean plants -the phytoplankton which require light for photosynthesis occur only in the zone in which there is light okay.

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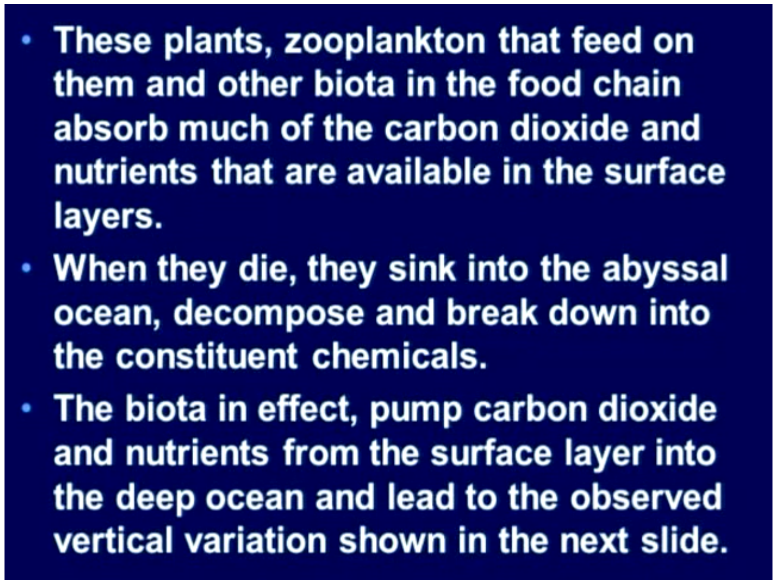

So because they require photosynthesis they cannot occur below the layer in which the sunlight is observed. So these plants which are phytoplankton as well as zooplankton or small animals which feed on the phytoplankton on this plants, and then other life in the food chain observe much of the carbon dioxide and nutrients that are available in the surface layers okay. But when they die they sink in to the abyssal ocean decompose and break down into the constituent chemicals.

This is how lot of nutrients actually are stored in the deeper waters of the ocean, this is because of these animals which are animals and plants which grow in the surface layer when they died they sink and actually enrich the deep water okay. So the biota in effect, pump carbon dioxide and nutrient from the surface layer into the deep ocean and lead to the observed vertical variation of the nutrients.

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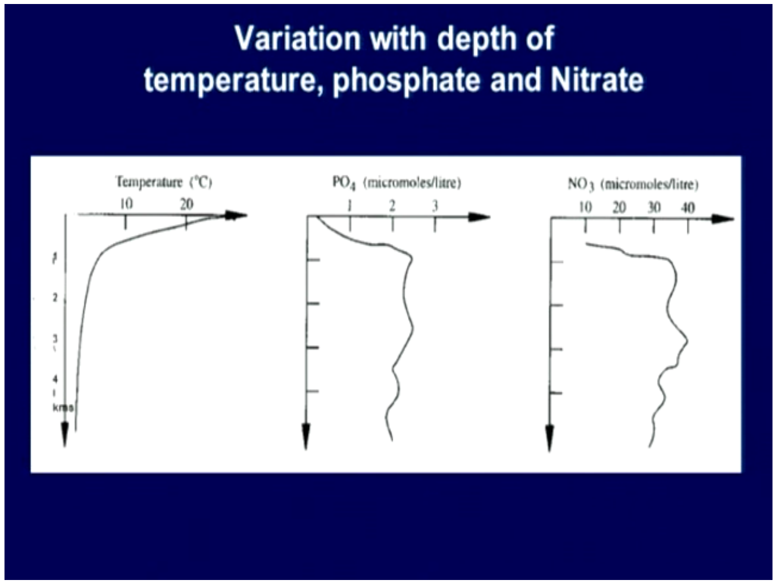

And this is important to remember because later on we will see that wherever cold water from deeper levels comes to the surface of the ocean you will get a lot of abundance of phytoplankton, and zooplankton and fish and so on and so forth. So these regions where this deep water comes up because very very important from the biological perspective, and so what you see here this is the variation of the temperature right temperature decreasing here and it is only up to this point the sunlight gets absorbed.

Now this is the phosphate and this is the nitrate concentration, and you can see that it is below the layer in which all this phytoplankton, zooplankton etc. live that the phosphate becomes maximum and the nitrate also becomes maximum. So the nutrients are below the layer in which these plants and animals live okay.

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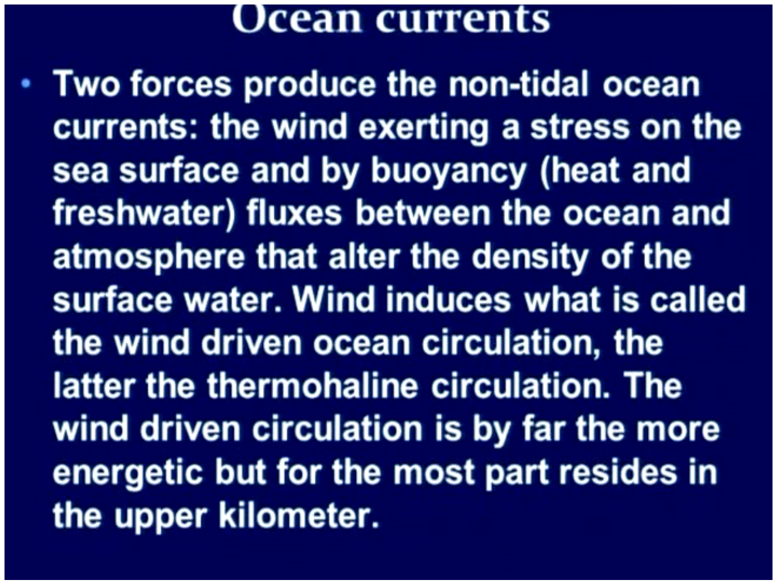

Now this is an important thing to remember because when we talk of and so we will talk of what El Nino does to the cold water coming from below. Now ocean currents this is another facet of the ocean very interesting facet, and which of course Sailors known for a long time, but now we know a great deal more about ocean currents because of systematic observations with ships. Now how do ocean currents occur?

So 2 forces produce the non-tidal ocean currents, when we talk of ocean currents we are talking of ocean currents which are steady over time scales of month and so on okay, we are not talking of tides which are of a much shorter time, so we do not talk of tides. So non-tidal ocean currents 2 forces are responsible for one is the wind exerting a stress on the sea surface, that is to say wind by blowing over the sea surface actually exerts the stress tries to push the ocean and generates current by that okay.

And the other is by buoyancy that is if you have heating from the top or if you have flux of freshwater, then that also can create ocean circulations or ocean currents okay. Now the wind induced currents are much stronger okay, and they induced what is called the wind driven ocean circulation, and the circulation which is driven by buoyancy that is heat and fresh water fluxes between the ocean and atmosphere is called thermohaline circulation.

Now wind driven circulation is by far the more energetic but for the most part resides in the upper kilometer right, because that is where the wind effect is felt more strongly. So I am going to actually discuss primarily the wind driven circulation.

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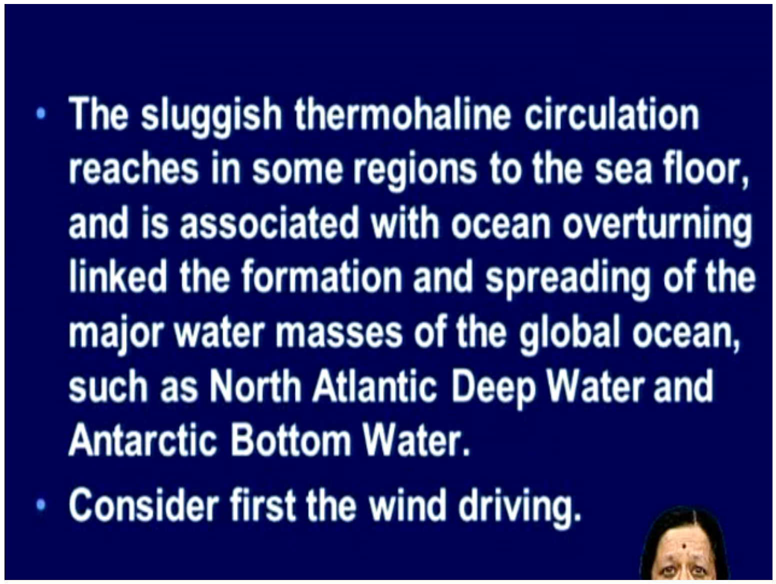

Now the sluggish thermohaline circulation reaches in some regions to the sea floor, and is associated with ocean overturning linked to the formation and spreading of the major water masses of the global ocean North Atlantic deep water, Antarctic bottom water and so on, but I will not talk about the thermohaline circulation in this set of lectures. So consider then the wind driving.

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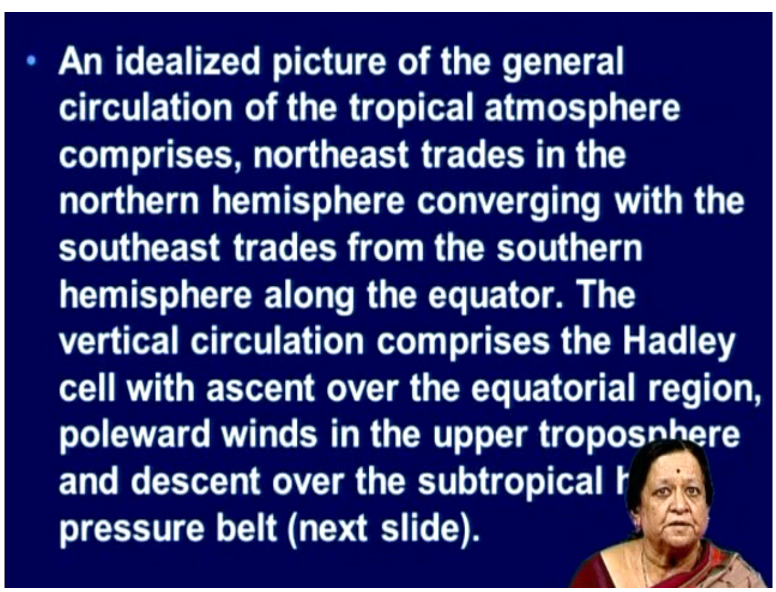

So an idealized picture of the general circulation of the tropical atmosphere which we have seen before comprises northeast trades in the northern hemisphere converging.

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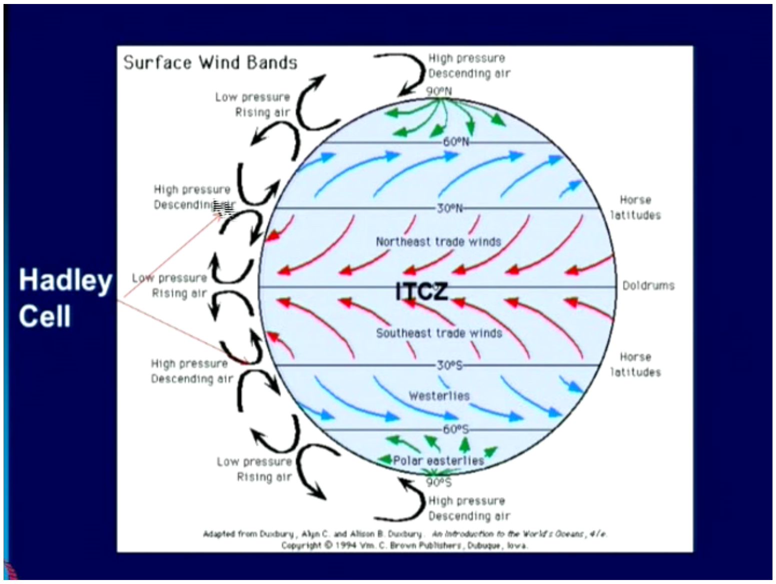

So let us see this is the idealized picture this is the picture in which we do not worry about variation with longitude right, it is if you wish zonally average circulation, and what you see here is that there is a low pressure belt here, and into the low pressure belt equatorial trough or ITCZ. You have northeast trades coming here, and southeast trades coming here, let me remind you that if the earth were not rotating then you would simply get winds from the north moving here and winds from the south moving here.

But because the earth is not rotating Coriolis force leads to very strong components along constant pressure that is to say zonal components and this is why we get easterly component here. And in both northern and southern hemispheres the northerly and southerly components is simply because near the surface of the earth there is friction becomes important. And therefore, you get some flow down the pressure gradient remember the pressure is lowest here.

So this is an idealized picture then you have the northeast trade winds coming from the north, and southeast trading means coming from the south. Now in the middle lat this is the tropical thing in mid latitude what you have is the belt of westerlies, this is all a belt where the wind is primarily going coming from the west to east, here the zonal component is the easterly, here the zonal component is westerly okay.

So you have essentially the winds pushing the currents in a clockwise manner here okay. And so an idealized picture of the general circulation of the tropical atmosphere comprises northeast trades in the northern hemisphere converging with the southeast trades from the southern hemisphere along the equator. The vertical circulation comprises the Hadley cell with ascent over the equatorial region poleward winds in the upper troposphere and descent over the subtropical high.

See this is the vertical circulation here, we saw the horizontal circulation here, the vertical circulation is the Hadley cell here in the tropics with air rising here there is convergence at low levels and the air divergence at higher level and descends here. So this is the Hadley cell which we have seen before, this is the idealized circulation of the zonally averaged atmosphere.

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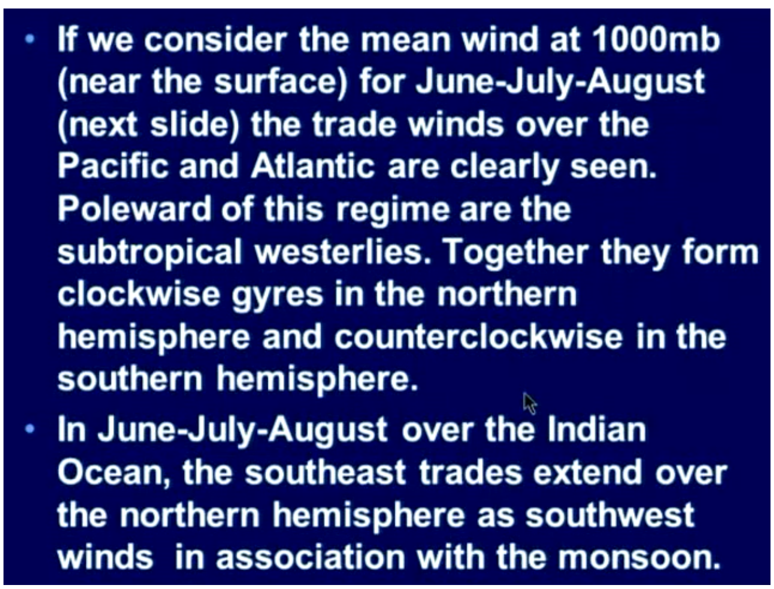

Now if we consider the mean wind at 1000 millibar near the surface for June-July-August, then what do we see? Okay.

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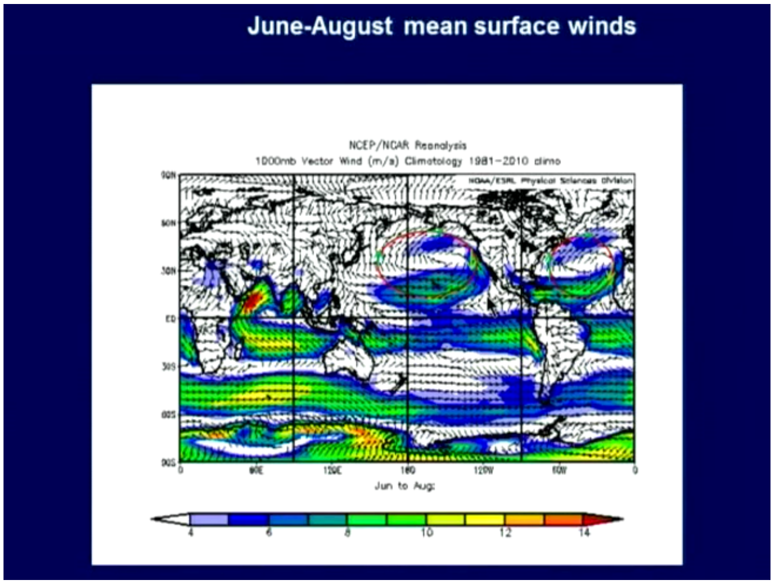

These are the mean winds and what you see here in terms of arrows see this is where you have winds from the east and this is where winds are from the west, I am not sure that this is very clear but you see these are all winds from the east, these are all winds from the west. So what I have drawn here as red is the kind of gyre that you expect the winds to drive right, winds are pushing the water towards the west here, and they are pushing the wash water towards east here.

Because they have an easterly component or from the east here and westerly component here, so the kind of things you get to this is gyre here. And perhaps in the Atlantic it is even more clear you see these are the easterlies of the trades, and these are the westerlies, and what you see here is the clockwise gyre that is being made.

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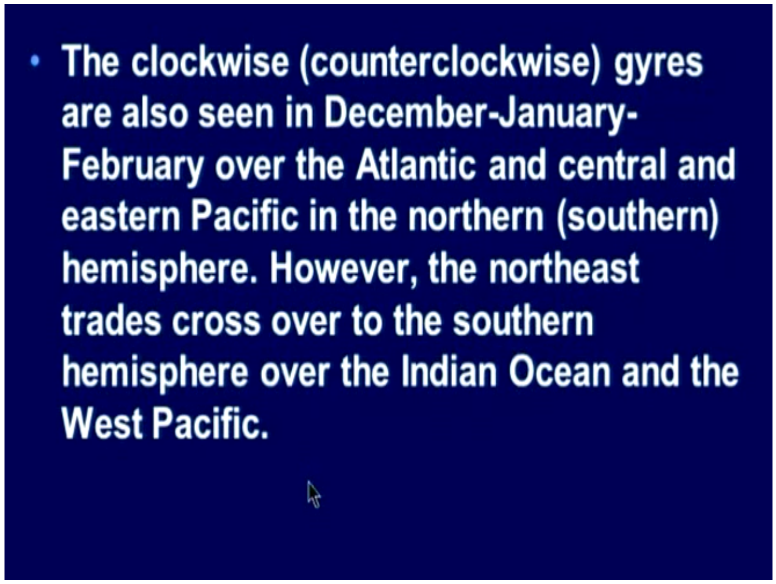

So the clockwise okay, so we see this trade winds and mid latitude winds which are westerly winds and together they form clockwise gyres in the northern hemisphere and counter-clockwise in the southern hemisphere okay. So what you see here is in the southern hemisphere you have easterlies here in the tropical belt and westerlies here, so the gyre will go this way which would be counterclockwise right, it is going this way which is counter clockwise.

Whereas in the northern hemisphere it is going this way so it is clockwise, so you have counter clockwise or anticlockwise gyres in the southern hemisphere and clockwise gyres in the northern hemisphere both of the Atlantic and the Pacific. Now in June-July-August over the Indian region you have a different story, I was talking more on the Atlantic and Pacific but what you see here is June-July-August is our monsoon season.

And we have seen this picture before what we get during the monsoon season? Is that the trades from the southern hemisphere actually cross over here and you get very very strong winds from the southwest here during what is the summer monsoon, which is also called the southwest monsoon. So in this case this is the very difficult circulation from the typical one over the Atlantic and Pacific because over the Atlantic and Pacific over the tropics we get easterlies, but here we get westerlies.

So Indian Ocean is a different story which we will come to later. So the clockwise or counterclockwise gyres are also seen in December-January-February over the Atlantic.

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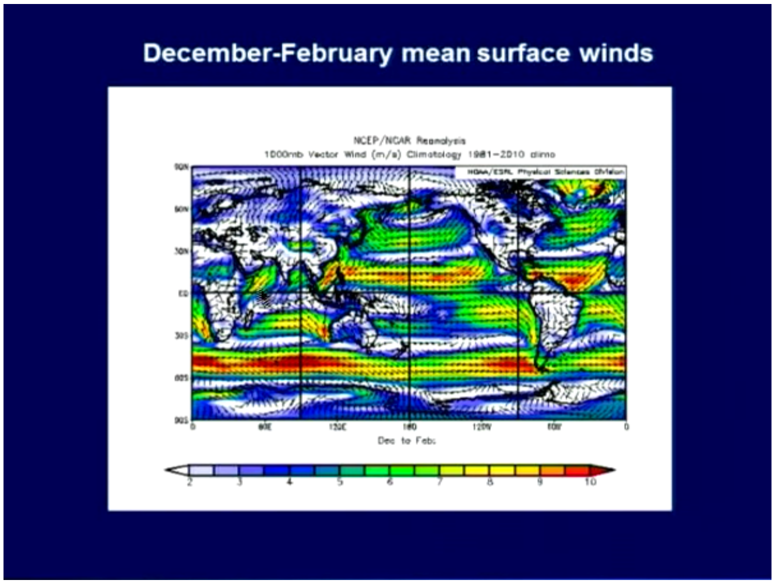

So this is the feature that does not vary with season in December-January-February also you have a clockwise gyre here, a clockwise gyre here and anticlockwise here and anticlockwise here. Now monsoon is somewhat different because now you get winds from the northern hemisphere penetrating the southern hemisphere, and so again the monsoon region is somewhat different okay.

So northeast trades cross over the southern hemisphere over the Indian ocean, and the west Pacific so as I mentioned Indian ocean and west Pacific is more complicated because they cross the equator the northeast trades cross the equator in winter also, and the southeast trades cross the equator in summer this is the June-July-August mean and this is the December-January-February.

So you see again the northeast trades are crossing the equator, over west Pacific here also you see west Pacific as well as Indian Ocean, Indian Ocean is somewhat different but Atlantic and Pacific are typical ones which always have clockwise gyres of the wind in the northern hemisphere and anticlockwise in the southern hemisphere.

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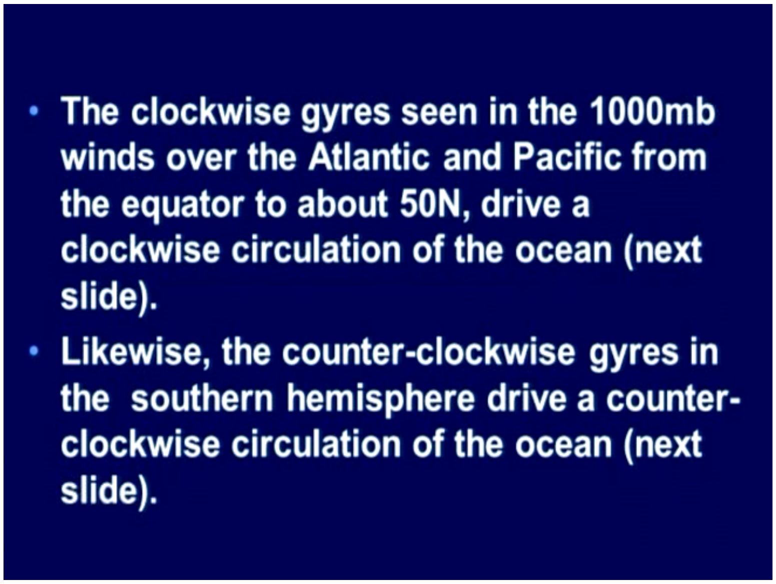

So the clockwise gyres seen in the 1000 millibar winds over the Atlantic and Pacific from the equator to about 50 north drive, now you have seen that see it goes all the way this clockwise gyre goes all the way from the equator to about 50 north that is what is seen here. So to about 50 north drive a clockwise circulation of the ocean, so because of this clockwise gyres what is the kind of circulation of ocean begin we get, and similarly, counterclockwise gyres will get counterclockwise.

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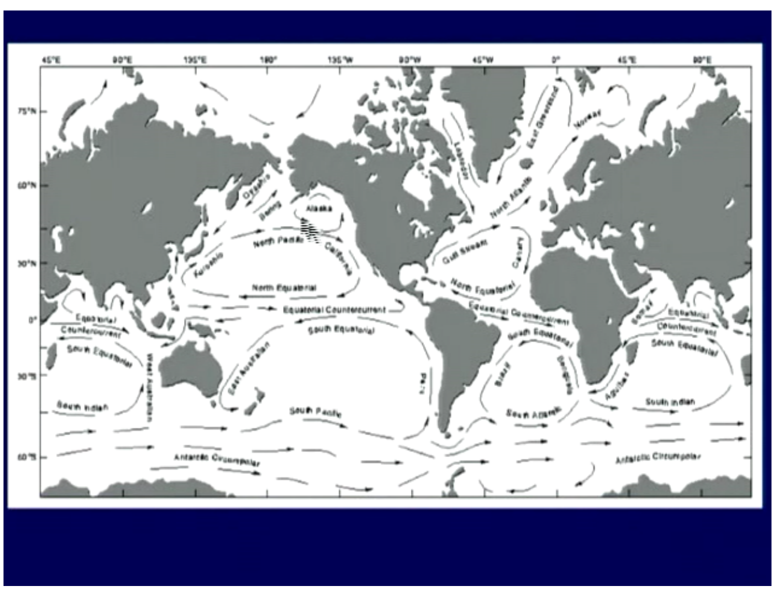

So let us look at the Pacific first, remember you had clockwise gyres driving it, so what you get in terms of ocean currents with also a clockwise gyre, this is the north equatorial current going from the east to the west, then this is the Kuroshio current which is going along this coast of

Japan, and then this is the north Pacific current, and then there is California current which goes parallel to the coast of United States and goes this way.

So you have a gyre which is very similar to the gyre driven by the wind except in this gyre, we find that the currents on the west here are much stronger than the currents on the east, now that again is the very very interesting part of wind driven ocean circulation theory, why is the west different from east? Unfortunately, in this set of lectures I will not have the time to talk about this, so for now we do not worry too much about the asymmetry in the currents.

But just say that we have a clockwise gyre in here, this is the clockwise gyre over the Atlantic where we have not equatorial current here, the Gulf Stream which brings warm water and makes the weather much better than it would have been without gulfstream, and again we have a clockwise gyre here. In the southern hemisphere we have counterclockwise gyre we have south equatorial current, the east Australian current, the south Pacific current and the Peru current.

Now this Peru current just see it, it comes from south to north and flows along the coast of south America, now similarly, you have gyre here as well and a gyre in the Indian ocean as well you know which is similar to these in the southern hemisphere. Now we will have reason to discuss these particular systems here in the context of El Nino southern oscillation.

So as this should not be a big surprise that we have clockwise gyres of winds driving clockwise gyres of ocean currents in the northern hemisphere and anticlockwise gyre of winds driving anticlockwise ocean currents in the southern hemisphere okay.

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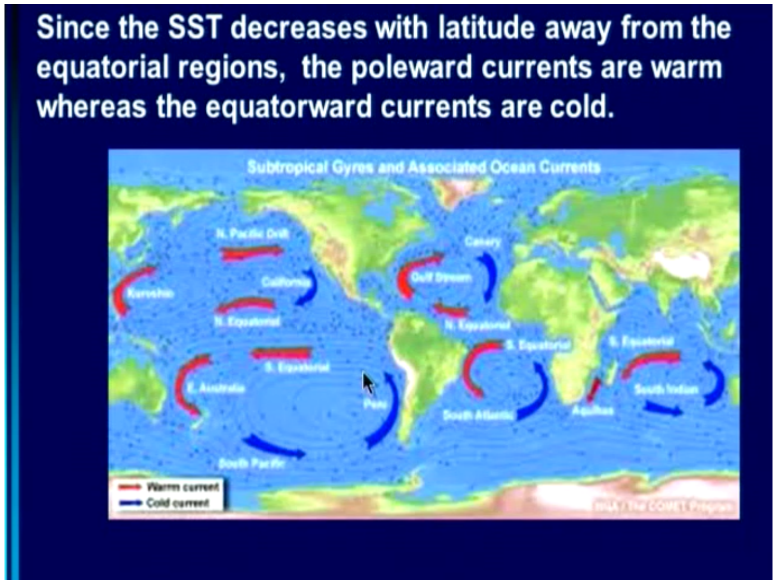

Now what is interesting is one thing remember the surface temperature of the ocean is maximum in the tropics and decreases as you go towards north or south right, so what does that mean? That means if you take this region for example Kuroshio the water will be warm, the Gulf Stream as I said the water is warm. Whereas current which come from the polar regions here like Peru for example, Peru current is coming from the polar region here so this will be a cold current.

And this will be a warm current because it comes from the tropics okay, so because sea surfaces temperature decreases on either side of the tropics towards the pole, currents that comes from the poleward side are cold and current that go from the tropics towards the pole are warm okay, and that is what you will see here. Now in fact the red are warm currents and the blue are cold currents okay, and obviously tropical currents are warm.

So you have in the Atlantic you have north equatorial current and the Gulf Stream being warm, whereas this current is actually cold. Now similarly, here we have Kuroshio is warm, north equatorial current is warm and the Gulf Stream actually sorry this is the Kuroshio Gulf stream is here and north Pacific current is here, and the real cold current is the California current because it comes from very high latitude, so it is low SST okay.

So we have cold currents coming from here, along the coast of America here, west coast of America, along the west coast of South America also Peru current, along the west coast of Africa also there is a cold current and of course Indian ocean things get complicated. So these gyres look very symmetric but the point is that on this side cold currents are there, on this side warm currents are there.

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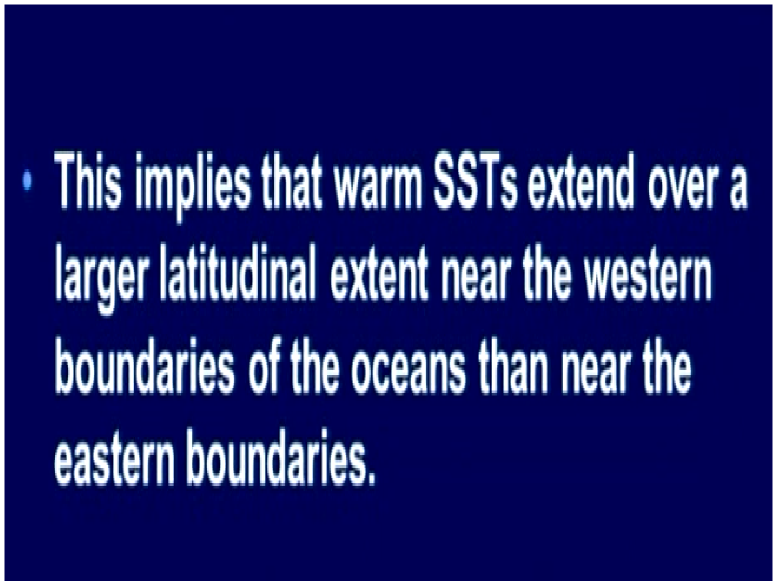

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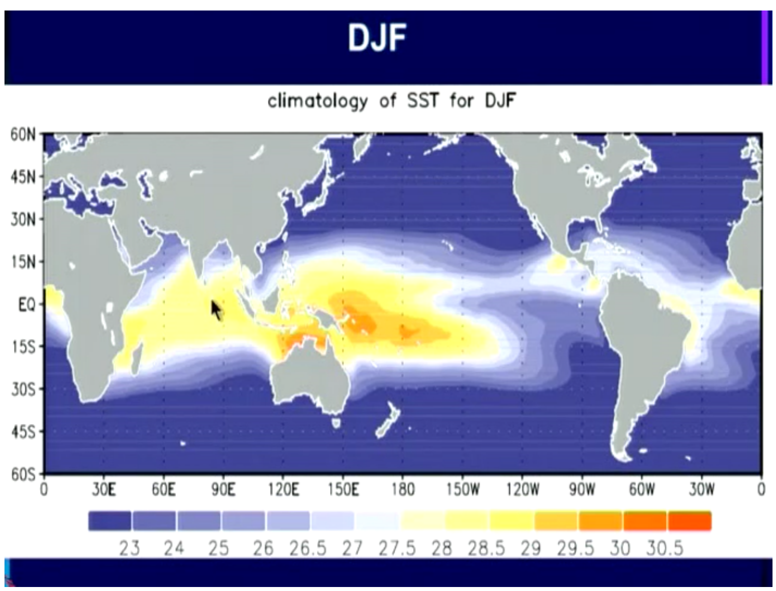

And because of that the SST warm SST that extent over a larger latitude in this west than east. So if you look at now the December-January-February okay and what you find is that the warm water of course here is extending much more than over the west then over the east.

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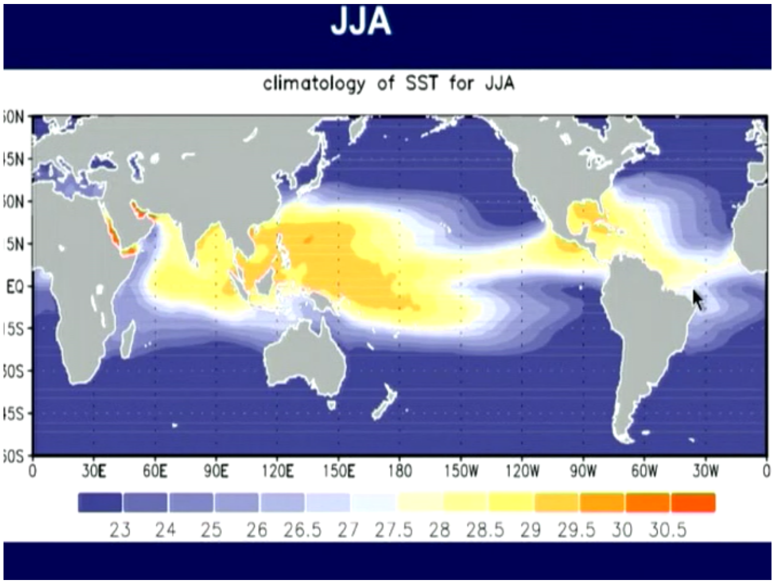

And the same thing you see over June-July-August, June-July-August also you see warm water extending over a large region here of the Atlantic over the western part as compared to the eastern part where it is much narrower, remember all the yellows are about 27.5 and these the darker blues are very cold is 23 and 24 and so on. So you have a huge expands of warm water towards the west of the ocean and relatively less towards the east.

Because remember the circulation is like this, so the cold current is coming from here and the cold current is coming from here that makes the warm water tongue makes much narrower here, whereas here it is the warm water going either way, so here the warm water is very broad. So this is something that is also going to play an important role, the fact that you have much larger extent of warm water in the west relative to the east.

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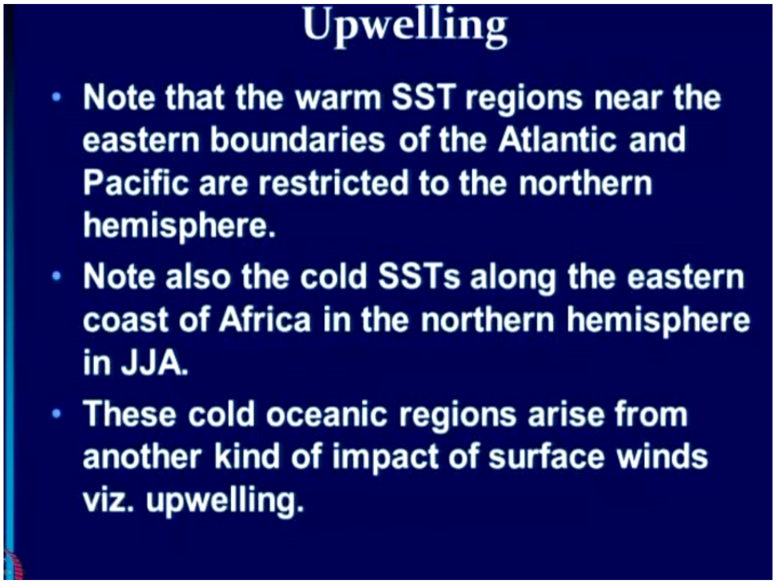

Now there is another phenomenon which is extremely important in understanding the sea surface temperature in fact here itself you could see that here the water is very warm, whereas in the same latitude here the water is very, very cold, and you can see that actually it is cold along a tongue like this. Now why should the water be so cold? Because the radiation from the sun is the same at all the longitudes irrespective of the longitude, yet, why is this water is so cold?

Now to understand this, we need to understand a little bit about ocean dynamics and that is upwelling. Now note that the warm SST regions near the eastern boundaries of the Atlantic and Pacific are restricted to the northern hemisphere, in fact this is another point to make that here of course this JJA is the northern hemispheric summer, so it is not surprising that in fact the warm water regions here are in the northern hemisphere.

But in DJF also even in December-January-February which is the austral summer or northern hemispheric winter even then in the southern hemisphere there are no warm regions at all, little bit of warm regions is there only in the northern hemisphere okay. And we have to understand why that happens. And we have already noted that the cold SST is along the eastern coast of Africa in the northern hemisphere in JJA, I think we should see here okay.

So along the west coast of course you have cold but along the east coast also there is a band of somewhat cold SST although right next to it is very, very warm ocean here, so this is also an interesting region. Now these cold oceanic regions arise from another kind of impact of surface winds namely upwelling, under certain conditions winds can lead to actually water coming up from deep levels to the surface, and deep water is cold and that is why it is called upwelling of cold water.

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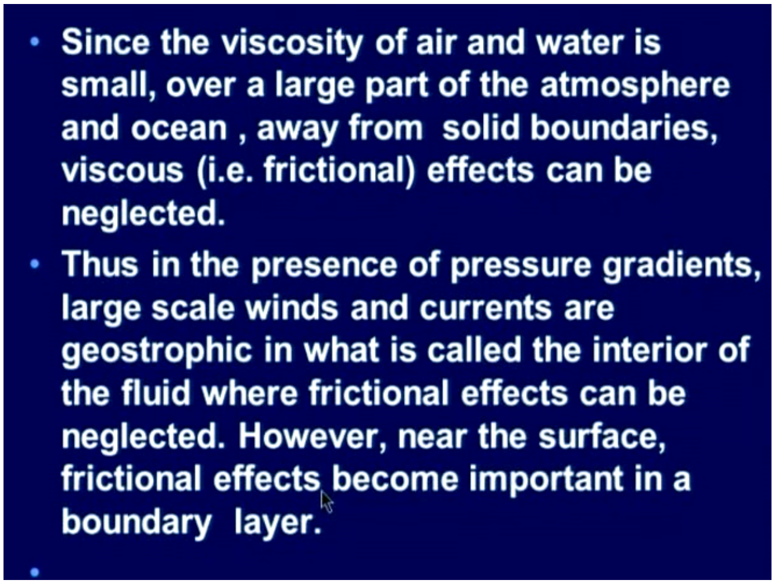

Since, the viscosity of air and water is small now to understand how does upwelling takes place to understand that we have to go back to the what we learnt a little bit earlier about rotating fluids and that applies both to the atmosphere and ocean, and in particular to the Ekman layer or the frictional boundary layer.

So let me just quickly recapitulate what we had learnt, since the viscosity of air and water is small over a large part of the atmosphere and ocean away from solid boundaries viscous that is to say frictional effect can be neglected okay. So in the presence of the pressure gradient large scale winds and currents are geostrophic, there is a balance between the Coriolis force and pressure gradient and we have geostrophic flow.

But near the surface frictional effects become important, and they become important in a layer which is called the boundary layer, because they occur near the boundaries of the fluid.

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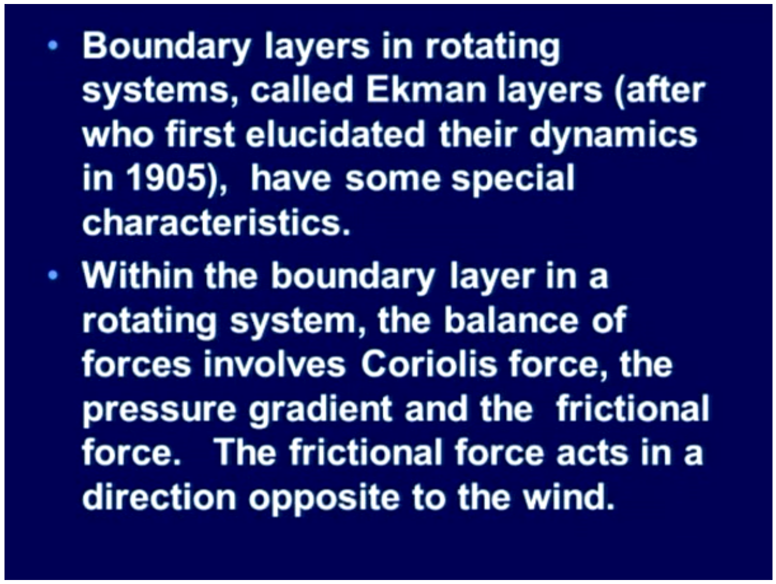

So boundary layers in rotating fluids just to remind you they are called Ekman layer after Ekman who first elucidated the dynamics, and we also showed that they have some very special characteristics, let me quickly revise them for you. Within the boundary layer in a rotating system the balance of force involves the Coriolis force, the pressure gradient and the frictional force. The frictional force acts in a direction opposite to the wind.

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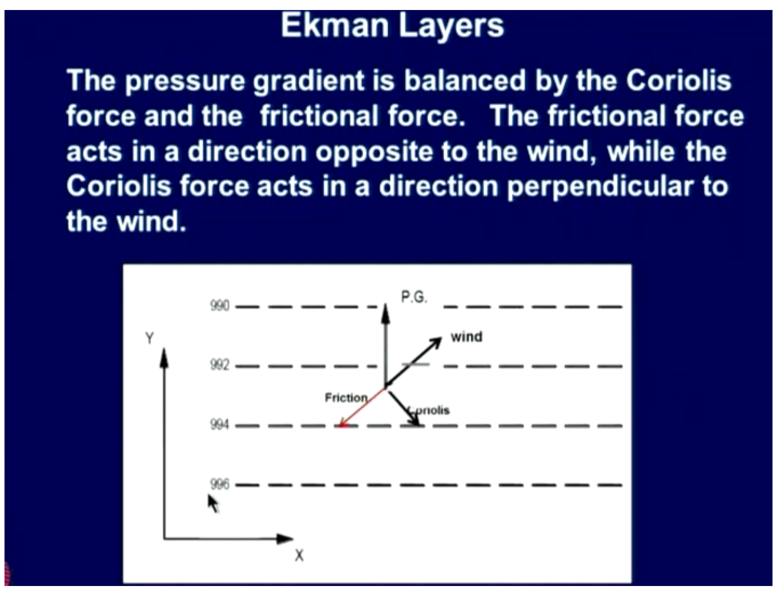

So let us now see what are the big balance of forces, suppose we have a simple case in which the pressure is actually decreasing as we go north, so these dash lines are lines of equal pressure or isobars and this is 996, 994, 992, 990, so there is high pressure here and low pressure here okay.

So the pressure gradient force is always of course down the pressure gradient, this is the pressure gradient force okay.

Now the wind in the boundary layer will be not geostrophic, because if it were geostrophic it would be along the lines of the constant pressure it would be just zonal okay, so above the boundary layer the wind is just zonal but in the boundary layer friction is also important. Now friction acts opposite to the wind, so suppose you have been like this, then friction will act opposite and how does the Coriolis force act?

If the wind is blowing this way then the Coriolis force in the northern hemisphere acts at right angles to the winds to its right okay, so this is the Coriolis force so the wind has to be in this directions, so that between the friction and the Coriolis force the pressure gradient is balanced okay. So this is why the wind actually has a component which is like it would have without friction that is to say which is along the isobars or along the lines of constant pressure and it has another component in the frictional boundary layer which is down the pressure gradient.

So you get down the pressure gradient flow and not that as the wind decreases, then it will change direction okay.

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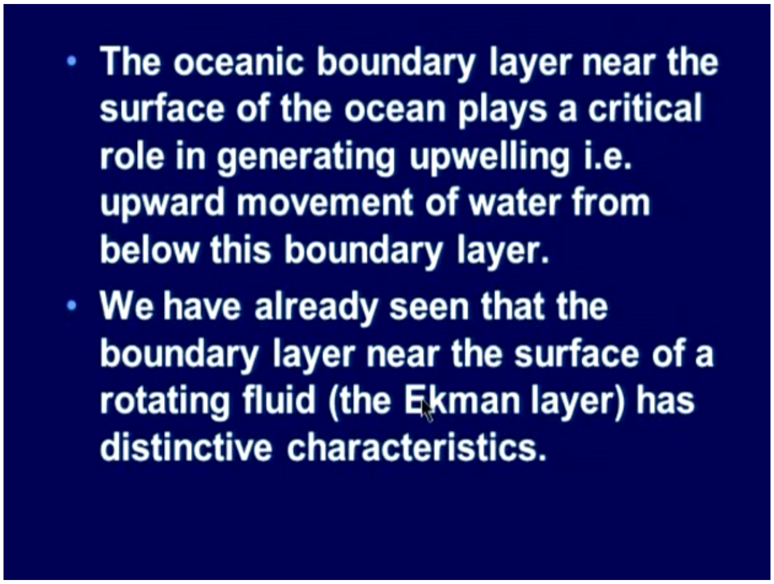

The oceanic boundary layer near the surface of the ocean place a very critical role in generating of upwelling that is the upward moment of water from the below this layer we have already seen that the boundary layer near the surface of rotating fluid has very distinctive characteristics.

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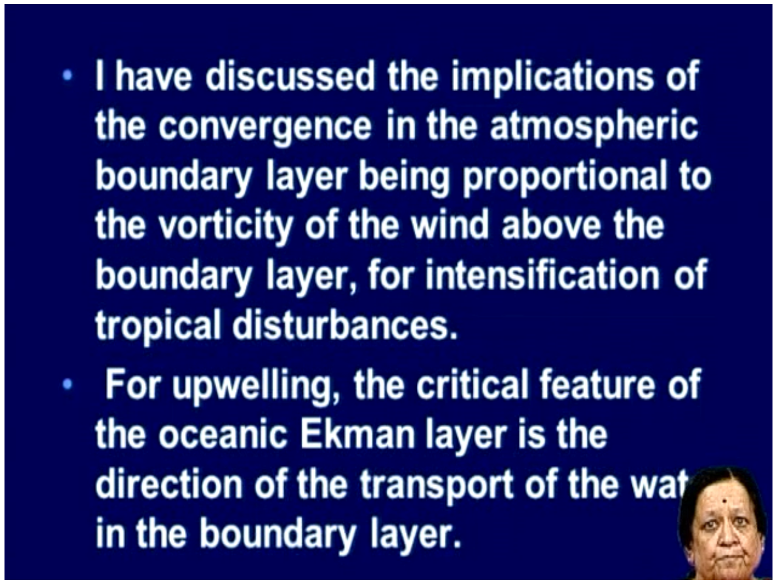

And in fact if you remember while discussing in the atmosphere I had shown that the ascent of air at the edge of the boundary layers is proportional to the vorticity above the boundary layer. And how that can lead to intensification of tropical disturbances such as cyclones and so on and so forth, the feedback between ascent driven by the cyclonic vortex from the boundary layer and the vortex itself.

Now, so for the oceanic upwelling the critical features of the oceanic Ekman layer if the direction of transport of water in the boundary layer okay.

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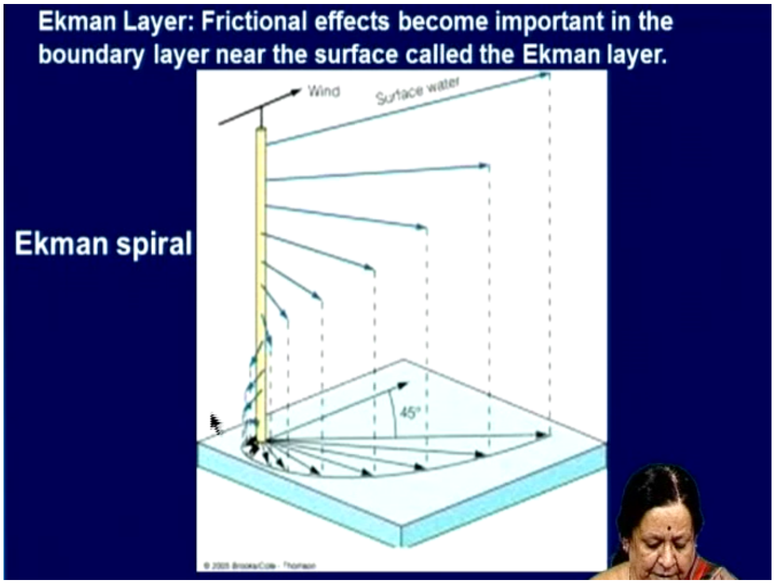

Now what is the direction as I said before this is the wind then the surface water moves like this, but as you go deeper and deeper the wind direction has to change because the wind becomes weaker and weaker until it becomes 0 at the bottom right, so the wind direction changes and this is the Ekman spiral okay. Now what we want to know is if we integrate over the depth of the Ekman layer, how is the water moving? What is the transport like?

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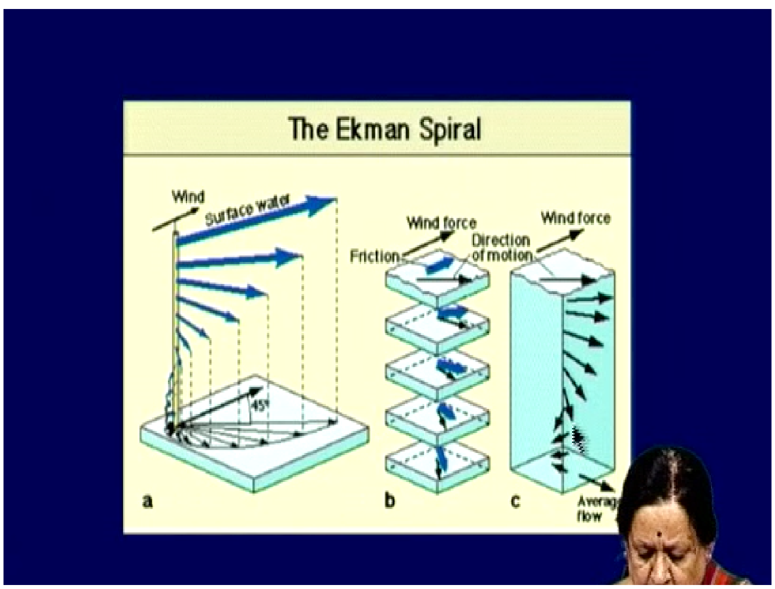

And that in fact this is the wind and this is the surface wind, and so we have actually this Ekman spiral here and when we integrate over the whole layer.

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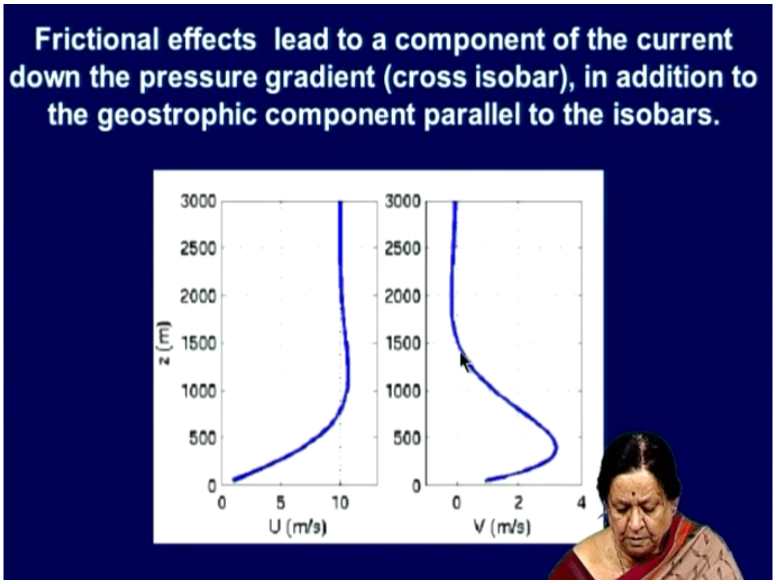

What we get is so frictional effect lead to a component of the current down the pressure gradient cross isobar in addition to geostrophic component current, so we have this is geostrophic current going to 0, and this is the V velocity which is down the pressure gradient in this case.

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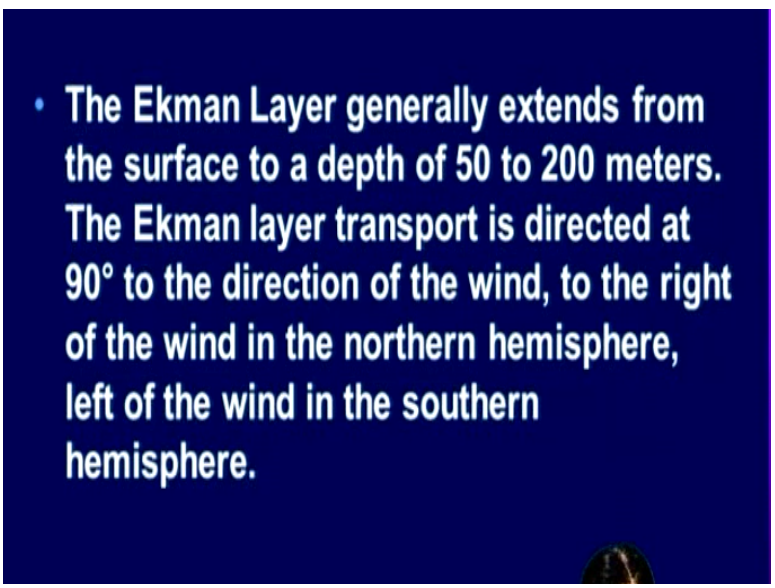

The Ekman layer generally extends from the surface to a depth of 50 to 200 meter, and Ekman transport is directed at 90 degrees to the direction of the wind to the right of the wind in the northern hemisphere. So for us what is important to remember is that if we are in the northern hemisphere then if this is the surface wind then the total transport of the Ekman layer will be in a direction at 90 degrees to the wind okay, and to the right in the northern hemisphere and to the left in the southern hemisphere.

Now this is an important thing that we need to remember to derive the upwelling.

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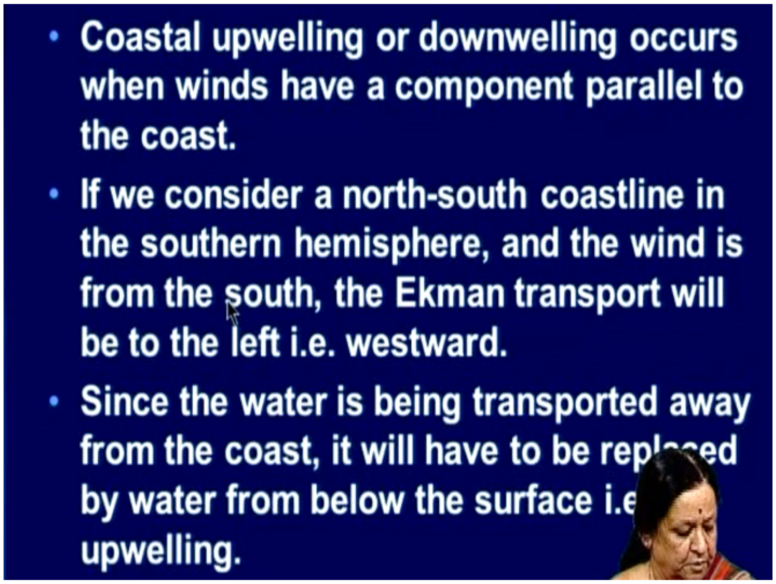

So coastal upwelling or downwelling occurs when winds have a component which is parallel to the coast.

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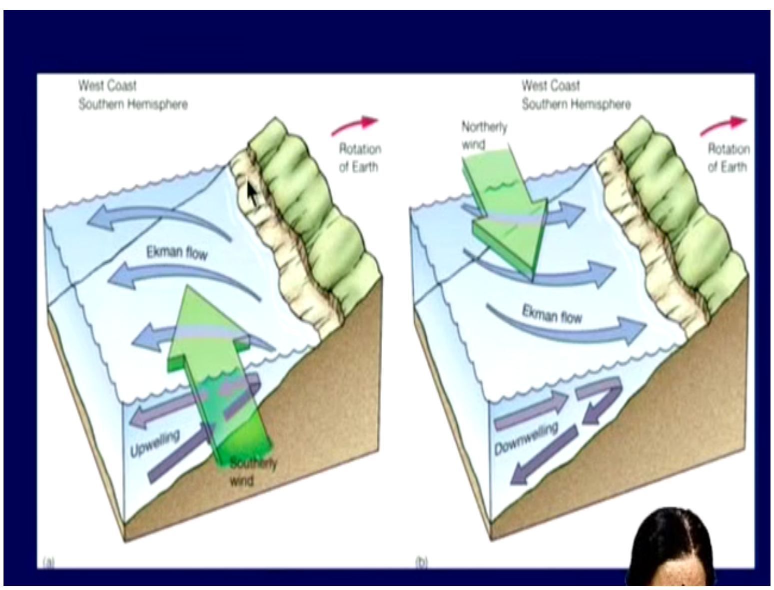

And what we can do is considered here suppose this is a coastline okay, which is north south, and suppose we are in the southern hemisphere and suppose wind is blowing parallel to be coast, then because we are in the southern hemisphere the Ekman flow is going to be away from the coast okay. So Ekman flow is going to be 90 degrees to the left, so it is going to be away from the coast, whereas if the wind was from the north then the Ekman flow in the southern hemisphere is going to be towards the coast.

So what happens if we consider the north and south coast line in the southern hemisphere and the wind is from the south the Ekman transport will be to the left that is away from the coast, and since the water is being transported away from the coast it will have to be replaced by water from below the surface that is upwelling. So now if the water is being driven away then along the coast deep water has to rise to take the place of this water.

So wind is constantly pushing water away from the coast and this water is replaced by deeper water coming to the surface this is the upwelling. And in this case you get downwelling.

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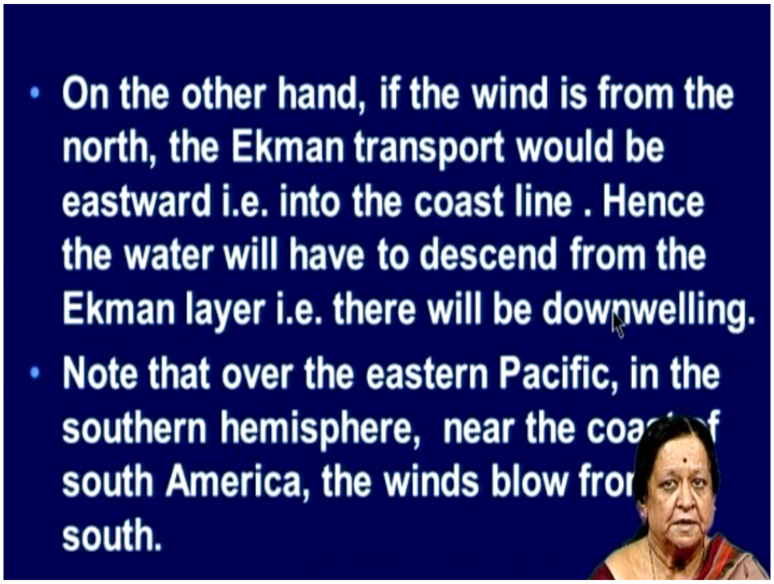

So on the other hand, if the wind is from the north then the flow would be into the coastline and hence the water will have to descent from the Ekman layer, so it will be downwelling. So over the eastern Pacific in the southern hemisphere, now let me just remind you again, see these are the winds June to August and over the eastern Pacific you see the winds are all going parallel to this coast Peru is here.

All the winds are going parallel to the coast which means that the Ekman transport is going to be driven away from the coast and you should get upwelling here okay. Similar, story in the Atlantic also again the winds are parallel to the coast here and Ekman transport is going to be away from the coast and therefore you will get upwelling. So same thing happens irrespective of the season.

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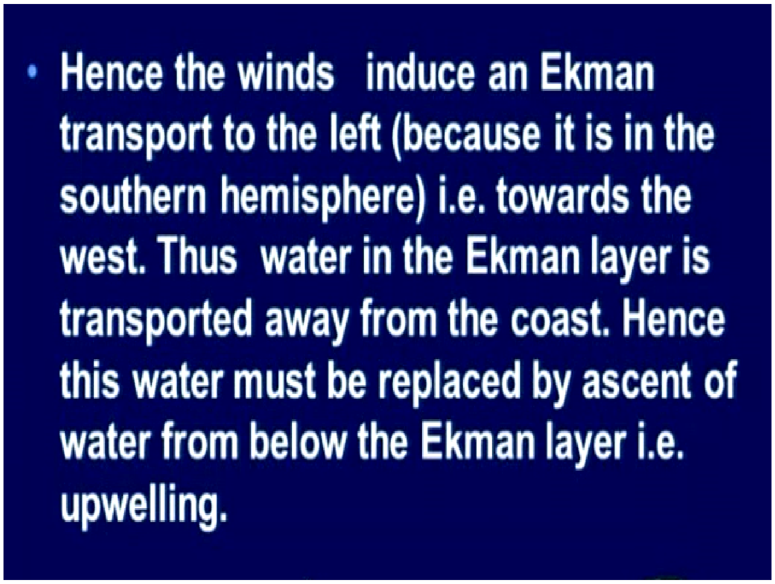

And hence the winds induced an Ekman transport to the left that is towards the west, thus water in the Ekman layer is transported away from the coast hence this water must be replaced by ascent of water from below that is upwelling.

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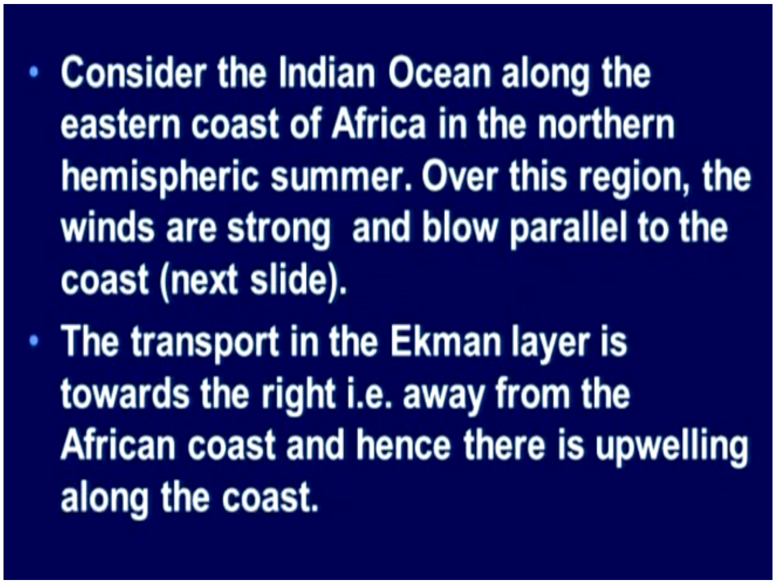

So the winds are such that over the southern hemisphere along the coast of the South America and along the Pacific which means along the western coast of South America as well as Atlantic along the western coast of Africa and this leads to upwelling along those coastlines. So transport in the Ekman layer is a way and so you get upwelling.

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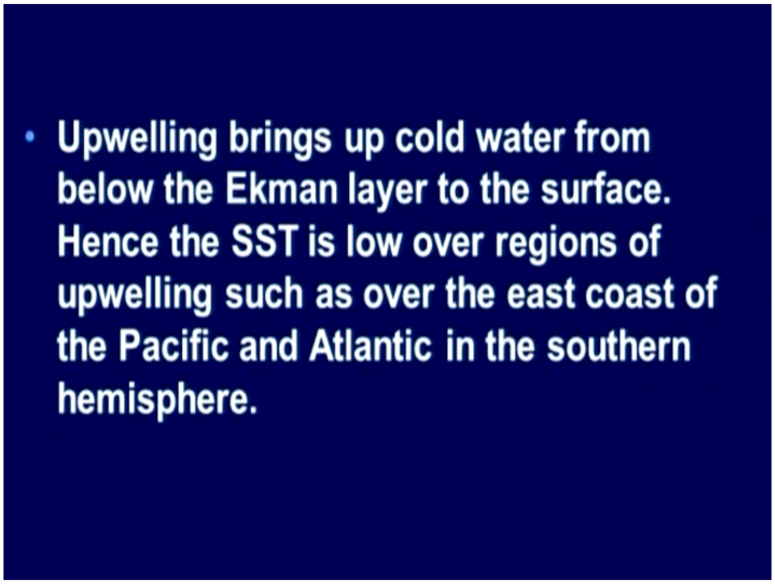

So upwelling brings up cold water from below and hence the SSTs low over regions of upwelling such as Atlantic and Pacific, so now you see this is the region, it is so cold here relative to what it is here, because there is upwelling all along this coast here, because the wind blows this way, and same story here as well. And in JJA also you see so much upwelling here and actually you see a cold tongue along the equator also okay.

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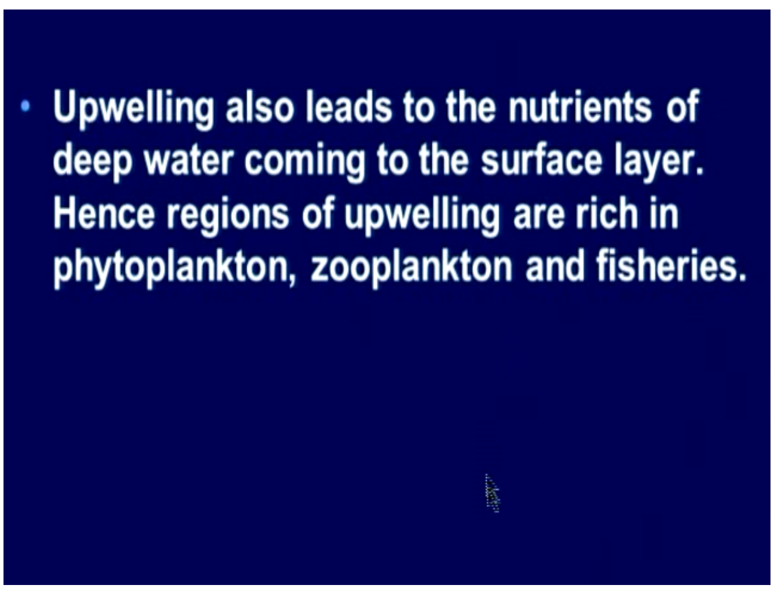

So upwelling also leads to nutrients of the deep water coming to the surface layer, hence regions of upwelling are rich in phytoplankton and zooplankton and fisheries. So this is a very important phenomena and as you will see this upwelling which is a response of the ocean to certain kinds of wind, when they have a component parallel to a coast which is north south, then you get upwelling along the coast if the Ekman transport is such that it is surface water is being driven away from the coast.

So this is the very, very important feature and we will see how this upwelling affects the coupled ocean atmosphere system, because remember this is the part of coupling it is the winds that are leading to upwelling, upwelling which is leading to cold sea surface temperatures, which will again have an impact on the atmosphere.

So this is a phenomenon which is also going to play a very important role in the coupled ocean atmosphere system, which we will start looking at from the next lecture, thank you.