The Monsoon and Its Variability

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Lecture – 30
Indian Ocean and the Monsoon - Part 1

Today I am going to talk about the Indian Ocean and the monsoon.

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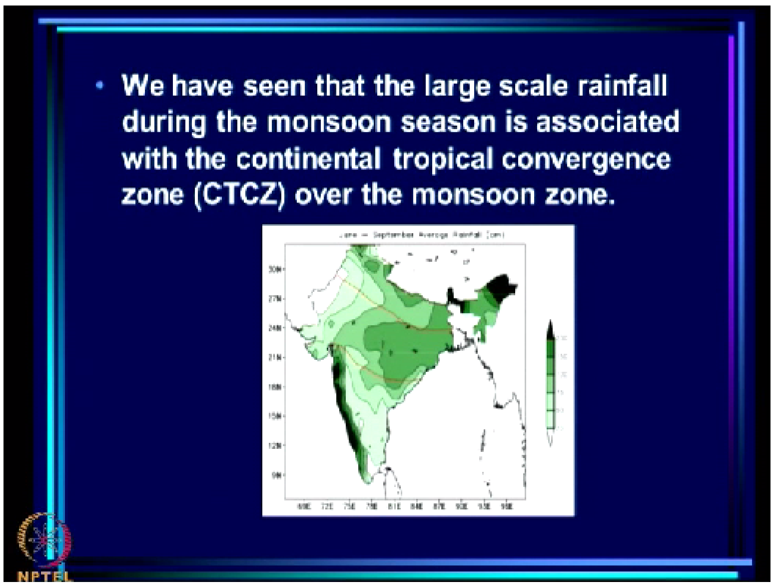

As you know that the large-scale rainfall during the monsoon season is associated with the continental tropical convergence zone, that is the CTCZ, over the monsoon zone. So we get an organized system over the monsoon zone which leads to the large-scale rainfall.

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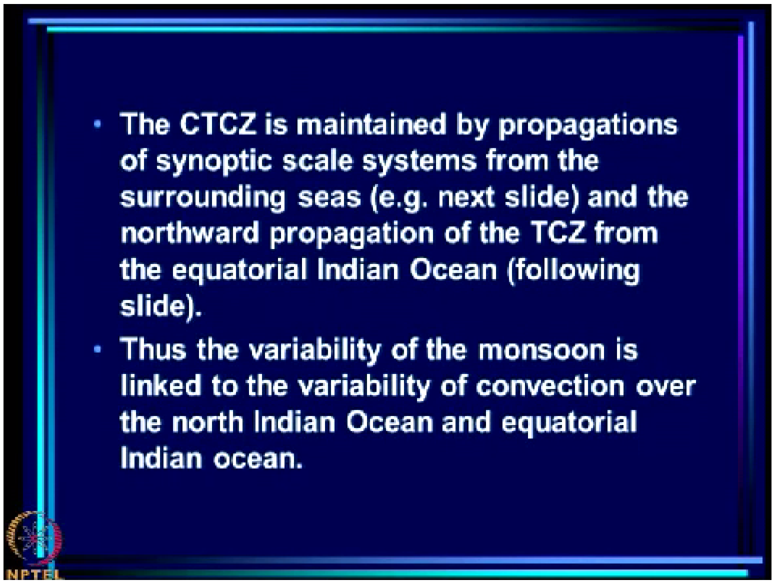

Now the CTCZ itself is maintained by propagations of synoptic scale systems from the surrounding seas.

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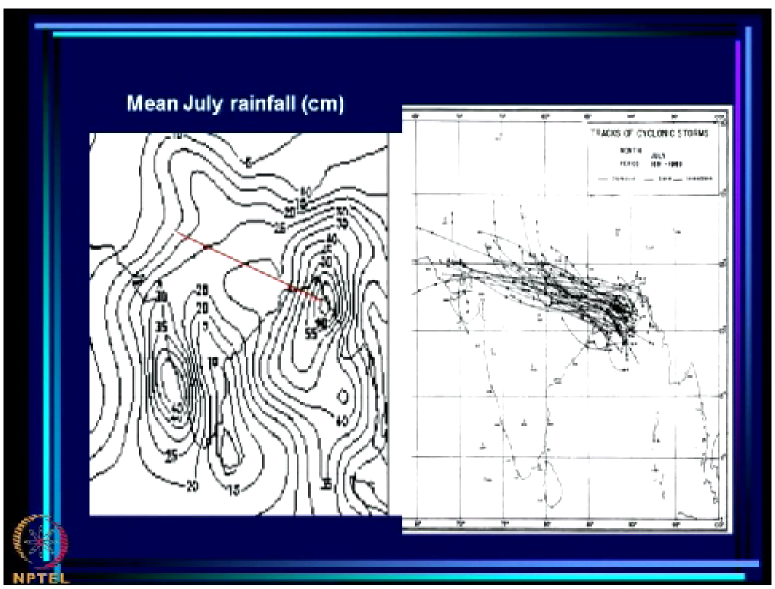

And you see an example of this here. What you see here are tracks of tropical storms in July, these are all the storms in July and you can see that all of them travel from the head Bay across the monsoon zone and this is the rainfall for July and you can see that the 2 are related. So these are the tracks of the storm and this is the monsoon zone.

So the CTCZ is maintained by propagations of synoptic scale systems from the surrounding seas, such as the one shown in the next slide which we already saw and northward propagation of the

TCZ from the equatorial Indian Ocean which we have also seen.

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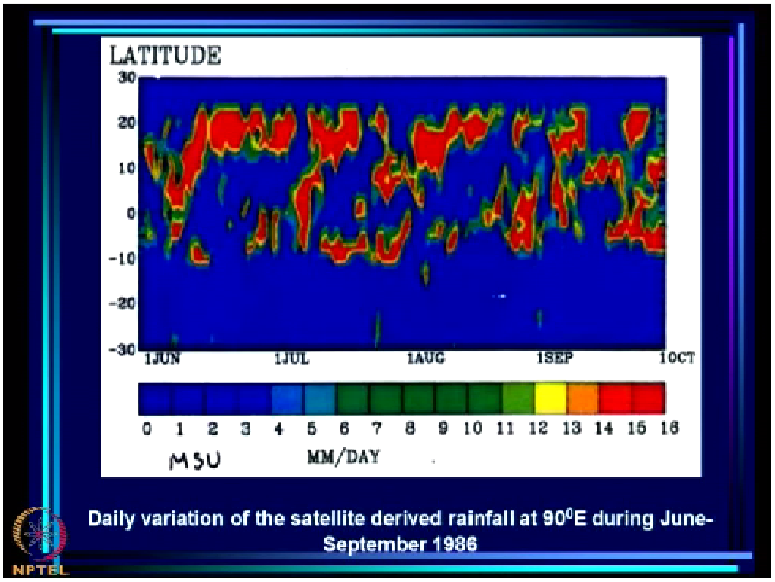

So the band gets, cloud band gets generated in the equatorial Indian Ocean and it moves northward. So the cloud band or the organized convection system over the monsoon zone is maintained by genesis and propagation of systems over the surrounding seas, both the Bay of Bengal, Arabian Sea and the equatorial Indian Ocean. This means that the variability of the monsoon is linked to the variability of convection over the north Indian Ocean which comprises Bay of Bengal and the Arabian Sea and the equatorial Indian Ocean.

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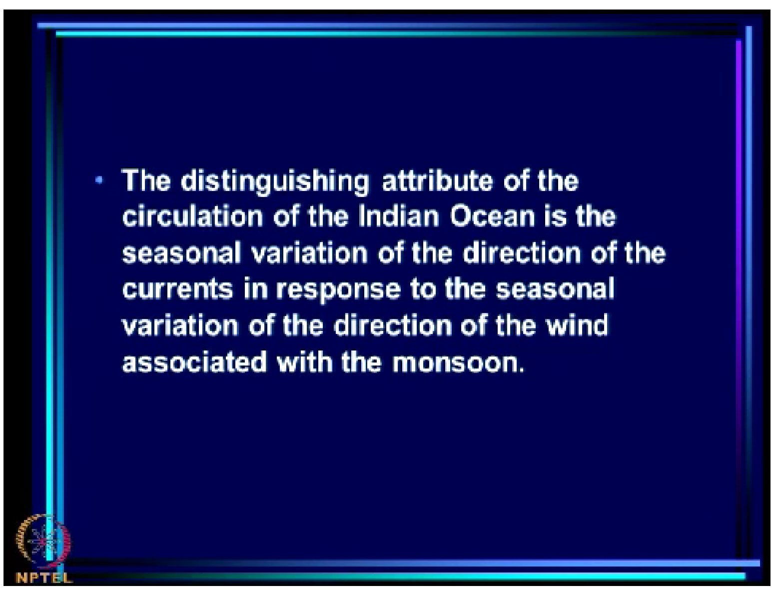

The distinguishing attribute of the circulation of the Indian Ocean is the seasonal variation of the direction of the currents in response to the seasonal variation of the direction of the wind associated with the monsoon. Now you remember that monsoon is defined by seasonal variation of the wind traditionally.

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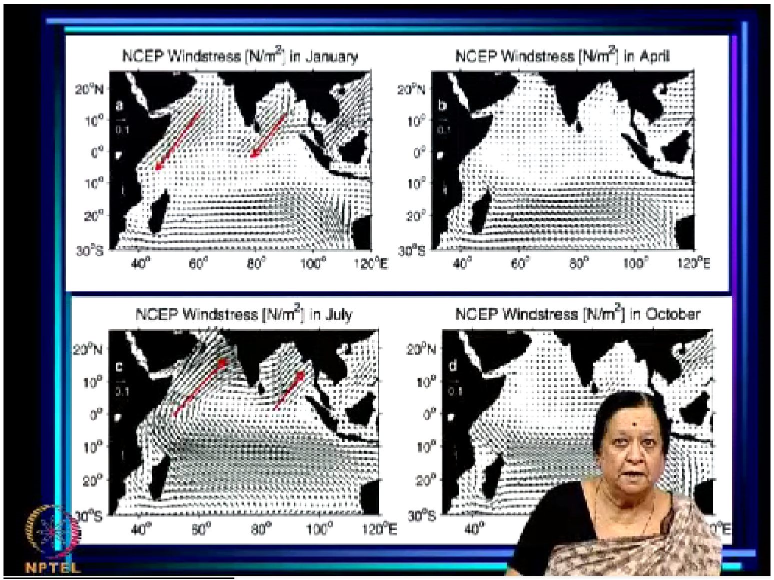

And you see here, the seasonal variation of the wind stress, this is January and this is July and you see a reversal of winds from January to July. So the distinguishing attribute of the circulation of the Indian Ocean is the response to the seasonally varying wind and that is what oceanographers were first excited by.

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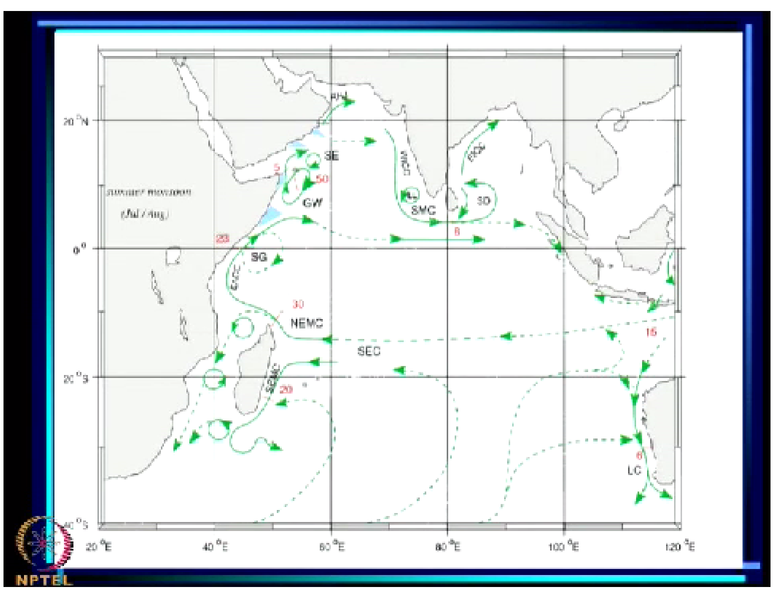

And what you see is these are the currents of the Indian Ocean and this is the Somali current and this is the current that goes along the equator and you see a whirl here and this is the situation in July-August. So when you have a Somali current going from the south of the equator, crossing the equator going northward.

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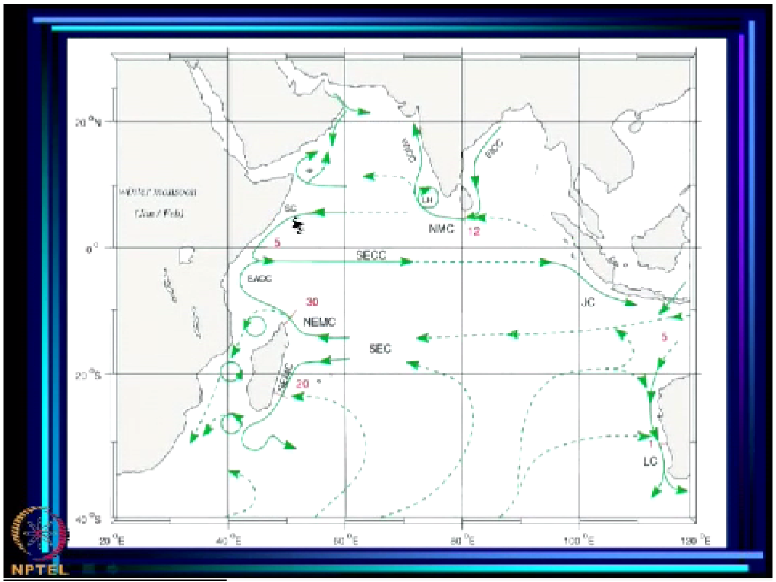

And you see what is happening in the northeast, in the winter season, January-February, there is a reversal in direction and there is a reversal in direction of currents here as well. So in other oceans of the world of Atlantic and Pacific, the winds do not have seasonal variation. It is over the Indian Ocean that we have the monsoon and therefore the seasonal variation of the winds and therefore most people got very excited about seeing the response of the ocean to seasonal variation of the wind.

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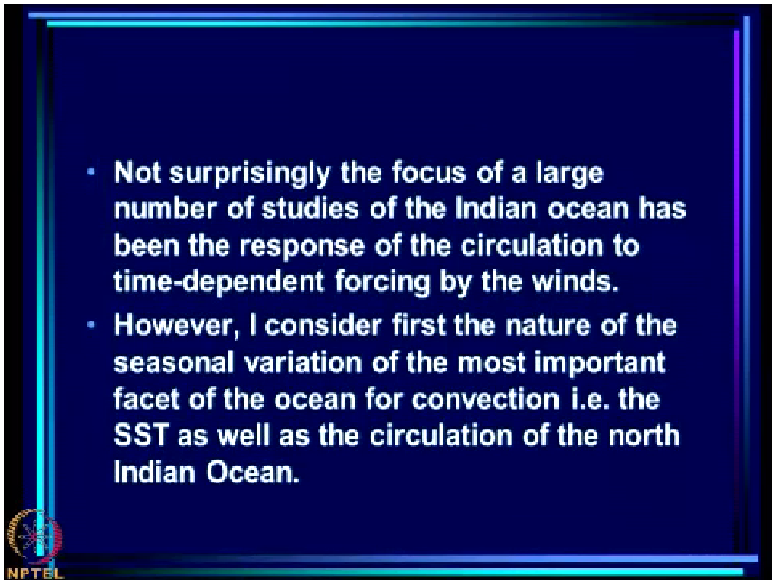

So not surprisingly the focus of a large number of studies of the Indian Ocean has been the response of the circulation to time-dependent forcing by the winds. However, we are not going to focus too much on the winds here because what I consider more important is the nature of the seasonal variation of the most important facet of the ocean for convection, only the sea surface temperature and the circulation of the north Indian Ocean.

So let us consider the seasonal variation of sea surface temperature over the Indian Ocean.

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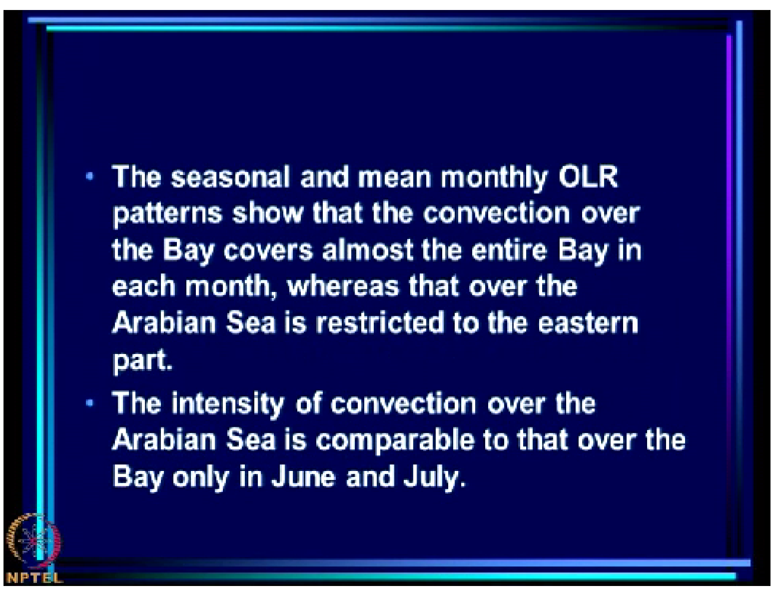

Now the seasonal and mean monthly OLR patterns, what did they show?

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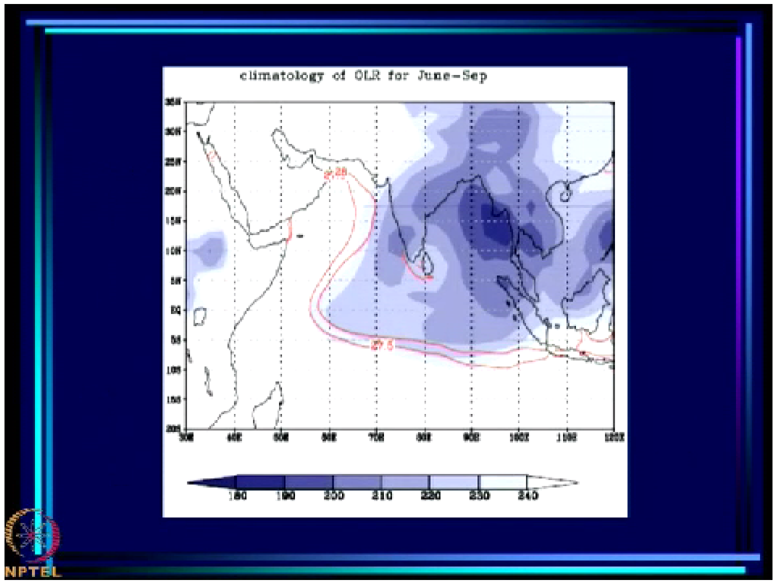

This is the seasonal pattern and this is June to September seasonal pattern and what you see is almost entire Bay is covered with deep convection, this is the OLR and the entire Bay is covered with deep convection whereas and also part of the east Arabian Sea is also covered. This is the June to September. Notice these are the SST isotherms. So the region inside the redline is warmer than 28 degrees Centigrade and this is 27.5.

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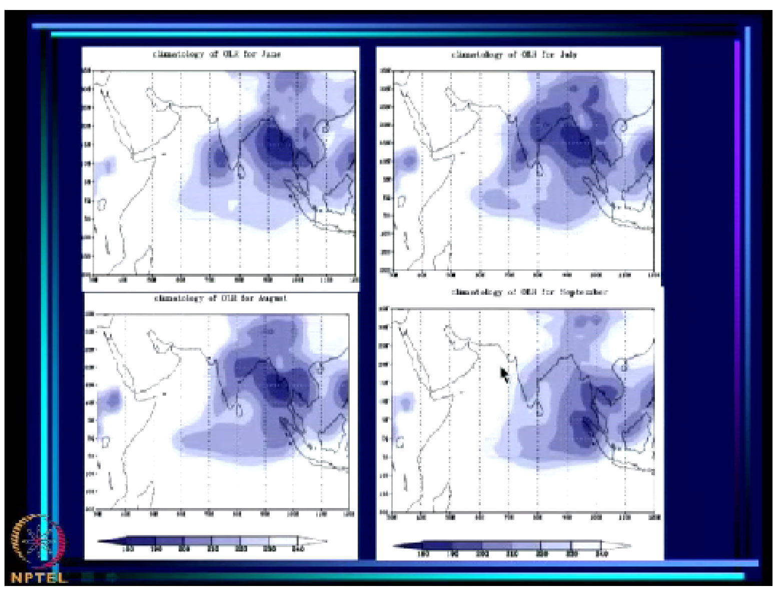

Now what do the monthly pattern show? Monthly patterns also show that almost the entire Bay is covered with deep convection, part of the Arabian Sea is but much more so in June and July than in August and September when there is hardly anything over the eastern Arabian Sea. But in June and July, we have a prominent clouding over the eastern Arabian Sea and in June, it is of intensity comparable to that over Bay and in July also.

So what is the nature of convection over the Indian Ocean then? The seasonal and mean monthly OLR patterns show that the convection over the Bay covers almost the entire Bay in each month, whereas that over the Arabian Sea is restricted to the eastern part. The intensity of convection over the Arabian Sea is comparable to that over the Bay only in June and July. This is something we have seen.

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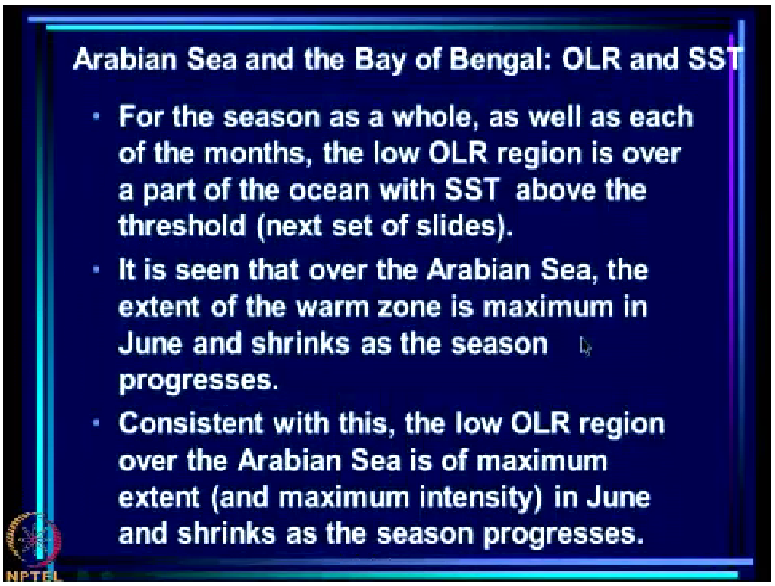

So within the north Indian Ocean, there seems to the considerable difference between Arabian Sea and Bay of Bengal. Let me just point out to you here, okay. There seems to be considerable difference between the Arabian Sea and Bay of Bengal for the season as a whole as well as each of the months, the low OLR region is over a part of the ocean with SST above the threshold.

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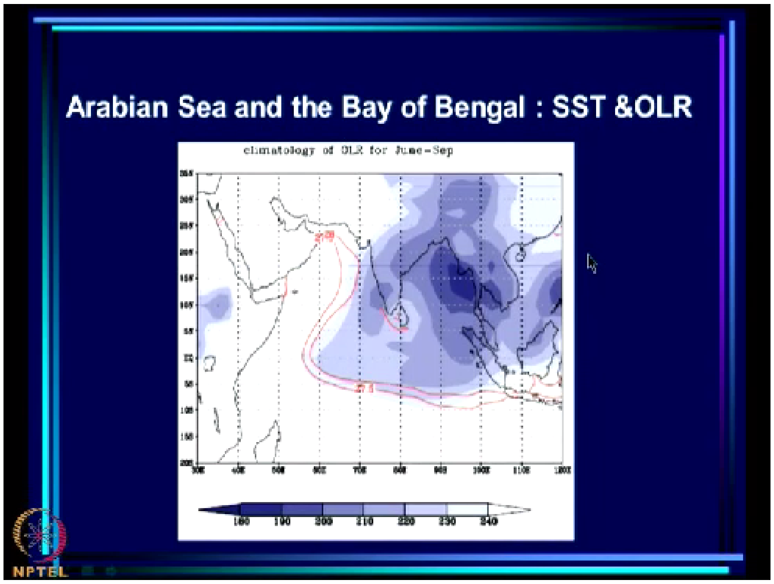

So what we have is, this is what you have seen here, this is the SST OLR and the low OLR region is entirely over the warm ocean with SST above the threshold.

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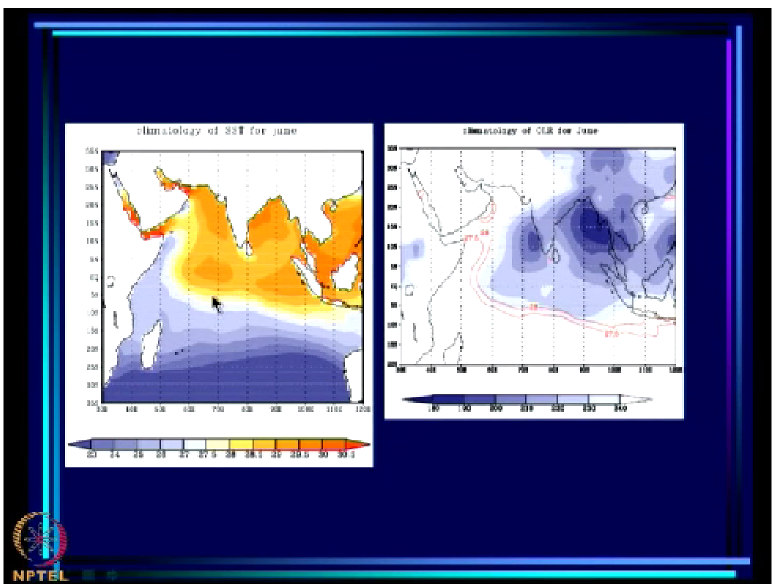

Now this is the case of June and again all the yellows, the light yellow is SST about 27.5 and all the darker shades including this orange and so on correspond to SST about 28. So you see and that is again drawn here for you, this is 28 degrees isotherm and you can see that the convective region is entirely over the warm oceans. This is for the month of June.

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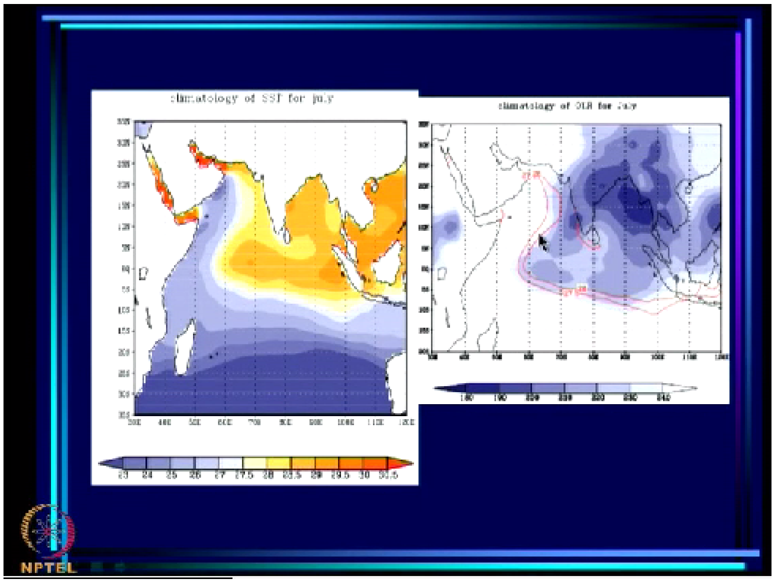

This is for the month of July and you see again it is restricted to that. Notice that the warm region over the Arabian Sea is shrinking from June to July.

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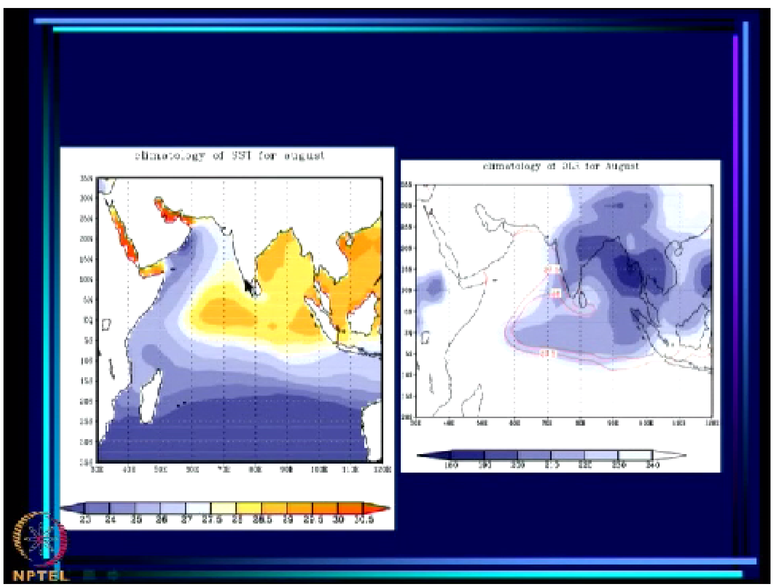

And August just shrunk further and so has the convection over the Arabian Sea.

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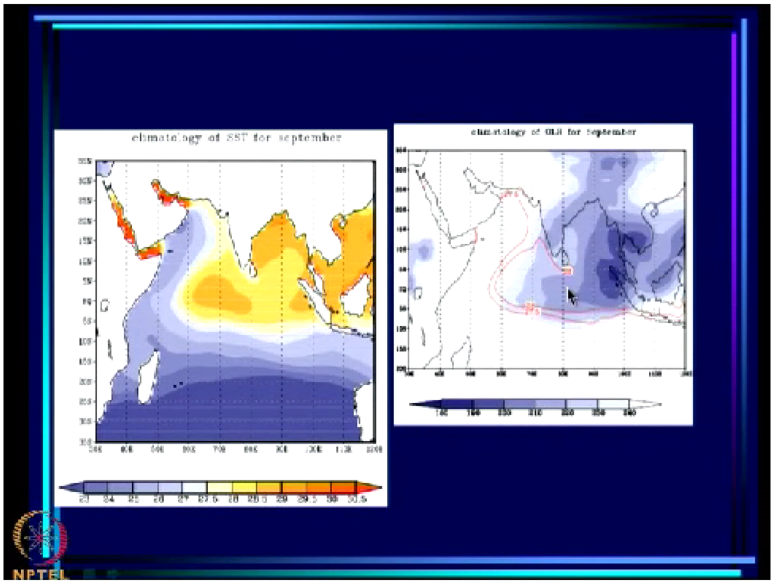

And in September also, there is hardly any convection over the Arabian Sea. So these are the mean pictures then and what you see is that for the season as a whole as well as each of the months, the low OLR region is over a part of the ocean with SST above the threshold. It is seen that over the Arabian Sea, the extent of warm zone is maximum in June and shrinks as the zone progresses.

Consistent with this, the low OLR region over the Arabian Sea is of maximum extent and maximum intensity in June and shrinks as the season progresses. Now this is what we have seen, okay.

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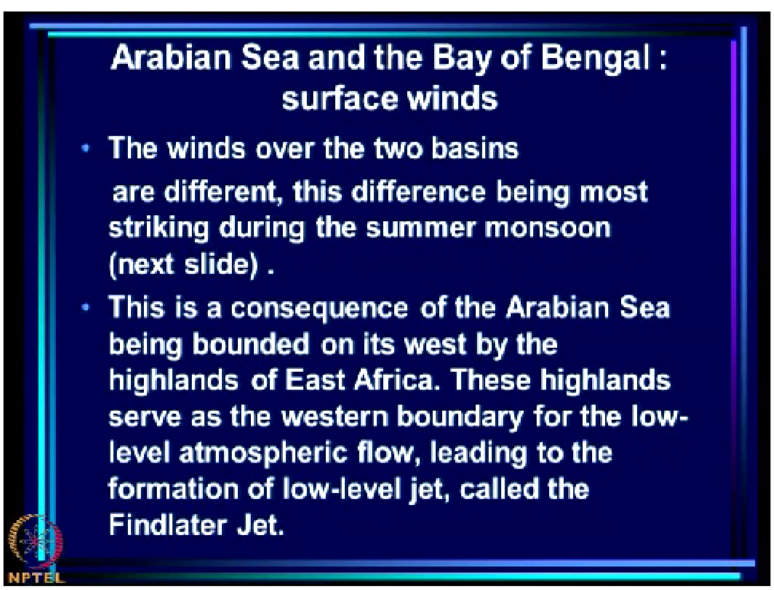

So it is, if you want to understand the variability of the mean pattern, convection pattern over the Arabian Sea and Bay of Bengal, it is clearly important to understand why the SST varies as it does, because the variation of convection is definitely linked to the variation of the region over which SST is above the threshold. Now Arabian Sea and the Bay of Bengal, now we consider the differences in the surface winds.

The winds over the 2 basins are different. Note that the direction of the wind is not different but the wind speed is different. This difference being more striking during the summer monsoon.

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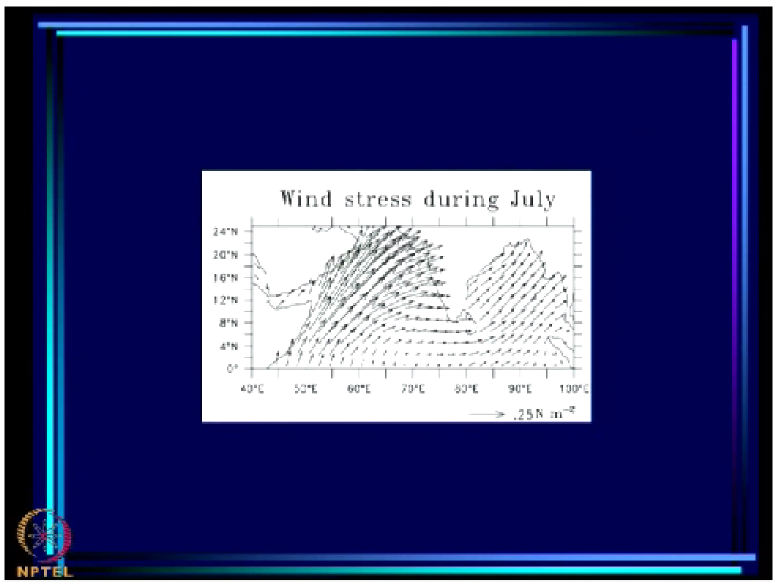

So what we see here is the wind stress during July and you see that the wind stress is much much higher over the Arabian Sea than it is over the Bay of Bengal. So the winds over the 2 basins are different and this difference is more striking during the summer monsoon. Now why does this occur? This is the consequence of the Arabian Sea being bounded on its west by highlands of west Africa.

Now here Arabian Sea is bounded here in Somalia and other region by highlands of east Africa and because of that, it acts like a boundary to the lower atmosphere and that generates a strong jet in the atmosphere known as the Findlater Jet. So why do we have such strong winds over the Arabian Sea? It is because it is bounded on its west by the highlands of east Africa.

These highlands serve as the western boundary for the low-level atmospheric flow leading to the formation of low-level jet, called the Findlater Jet.

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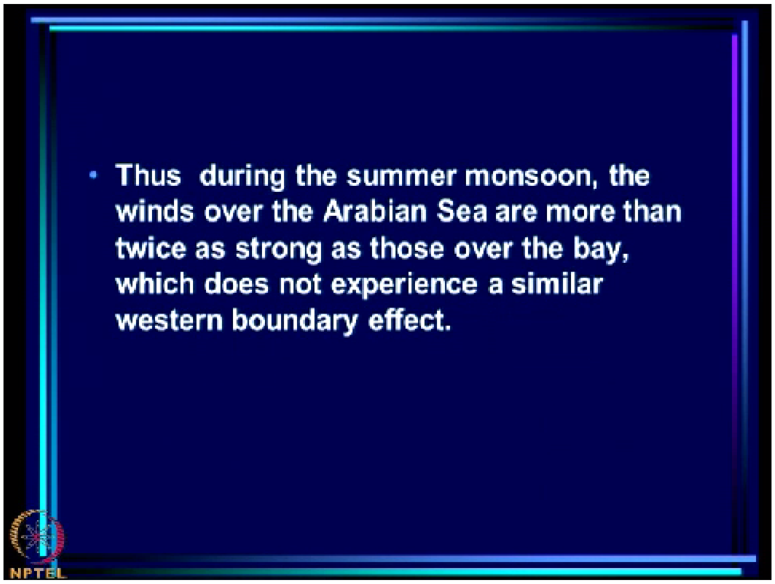

Now thus is during the summer monsoon, the winds over the Arabian Sea are more than twice as strong as those over the Bay which does not experience a similar western boundary effects. There are no big highlands that are over east India that gives the similar effect.

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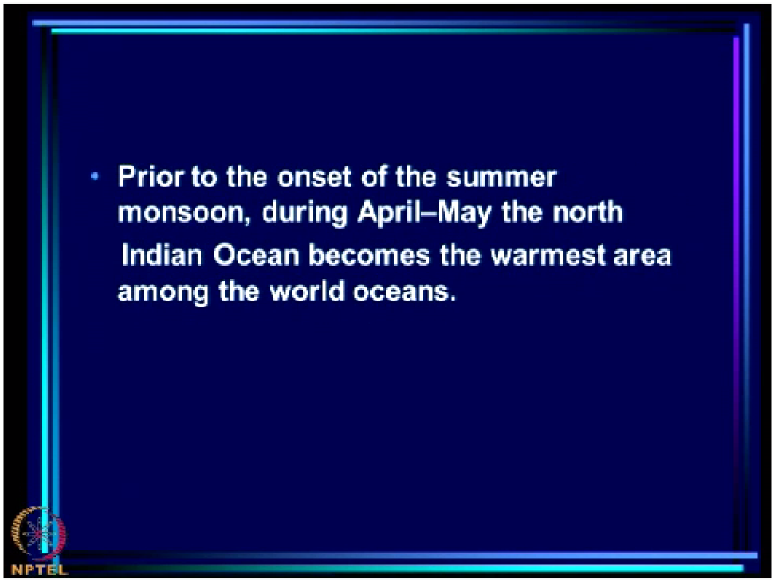

Now what is happening? Prior to the onset of the summer monsoon, during April-May, the north Indian Ocean becomes the warmest area among the world oceans.

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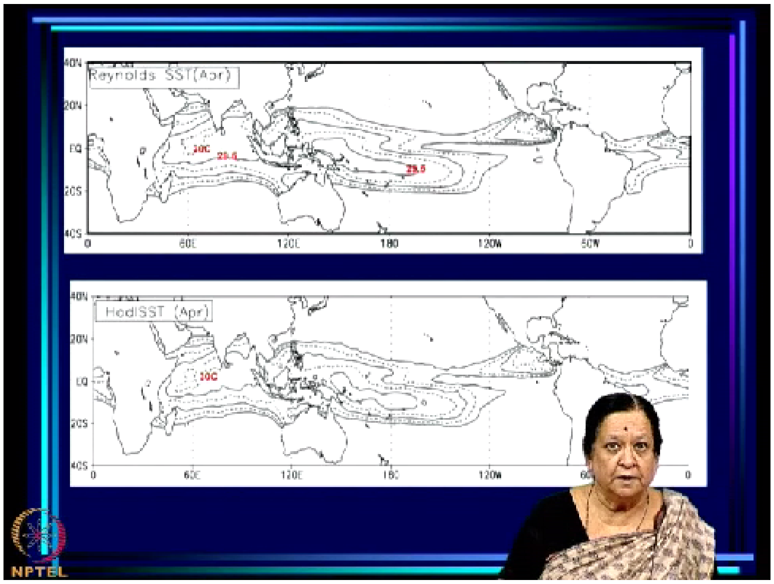

And you see that here. What I have done is again only contours of 27.5 and above are plotted and this is the contour of 29.5. So none of the oceans, other oceans go beyond 30 degrees, whereas you see here, this is from Reynolds SST, this is from Had SST and you see here, there is a contour, so temperatures are higher, sea surface temperatures are higher than 30 degree centigrade irrespective of which data you take over this part of the north Indian Ocean, north Indian and equatorial ocean.

So this is the hottest region in the world oceans in April and also in May. In fact you see in May, the contour of 30 degrees centigrade has become very very large here, occupying a large region. So all along here the temperatures are over 30 irrespective again of which dataset you take and it is certainly the hottest region in the world.

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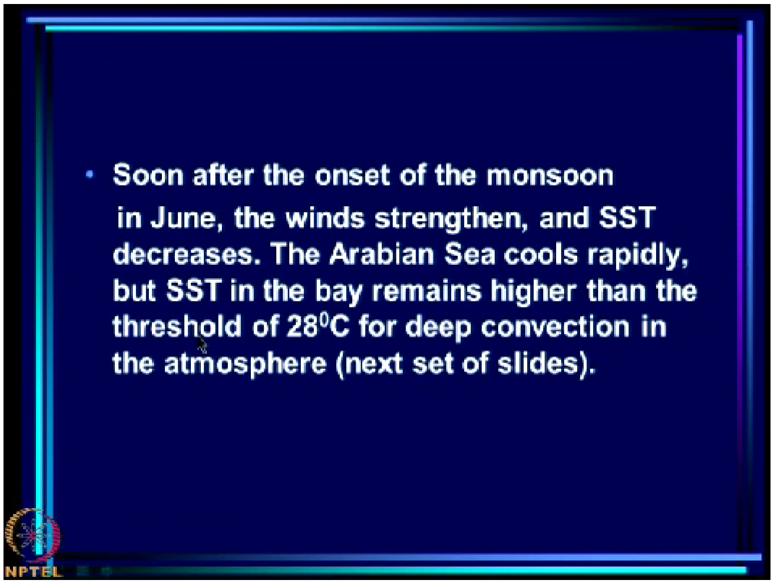

Soon after the onset of the monsoon in June, the wind strengthens and SST decreases. The Arabian Sea cools rapidly but SST in the Bay remains higher than the threshold of 28 degree centigrade for deep convection in the atmosphere.

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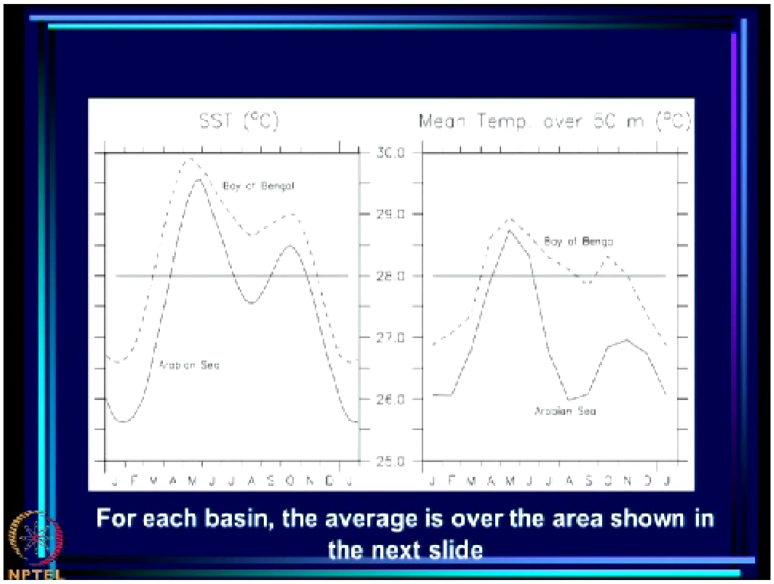

So now what has been done is averages are taken over the dash region.

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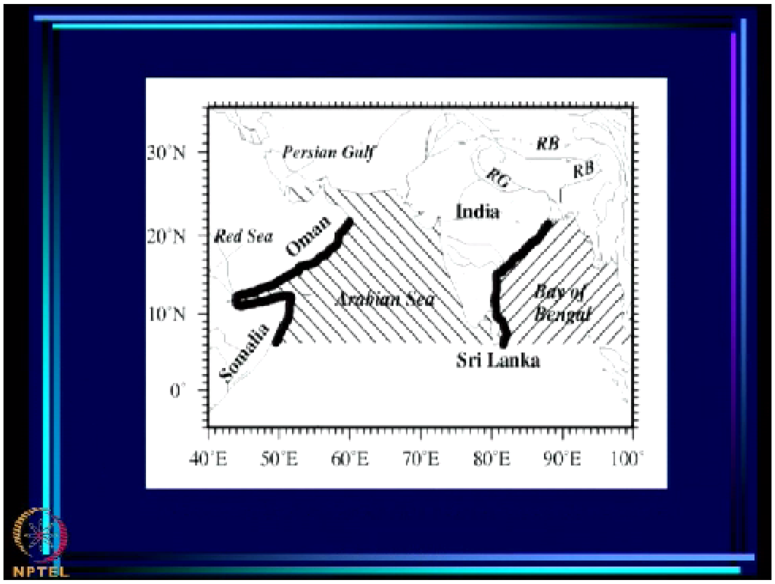

So this is the Arabian Sea and this is the Bay of Bengal. Then we look at averages over that region. What we see is, this is the sea surface temperature, this is the Bay of Bengal and this is Arabian Sea. You can see that right from April onwards up to November, the Bay of Bengal is warmer than 28 degrees but Arabian Sea starts cooling right from June onwards and reaches below the threshold in August.

So you can see that the distribution is bimodal, the distribution is similar for the 2 seas but while Bay remains always above the threshold for a large part of the year, Arabian Sea goes below the threshold. Now the mean temperature over 50 metres is shown in the right-hand part here and what you see again that mean temperature over 50 metres is also much lower for the Arabian Sea than the Bay of Bengal and for the Bay, it remains again even over the layer of depth 50 metres, the temperature is above 28 for most of the year, okay.

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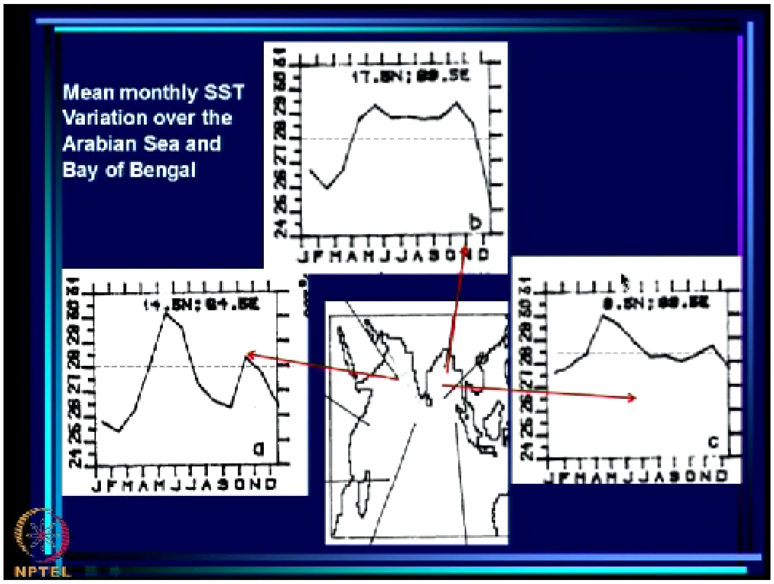

Now one could just take a look at some points and see how the variation of SST is and this is a point in the central Arabian Sea, not eastern Arabian Sea and central Arabian Sea, you can see that it goes way above the threshold in May and June, it is maintained but from July onwards, it cools very much and then there is another minor peak around October.

If you go to the head Bay, you see that head Bay is consistently maintained above 28 from April till November, consistently above, this is the head Bay region. If we go to central Bay, now we find that for a large part of the year, it is in fact higher than 28 but that is before the monsoon, then in the beginning of the monsoon, again it is higher than 28 and then it hovers around 28 or so.

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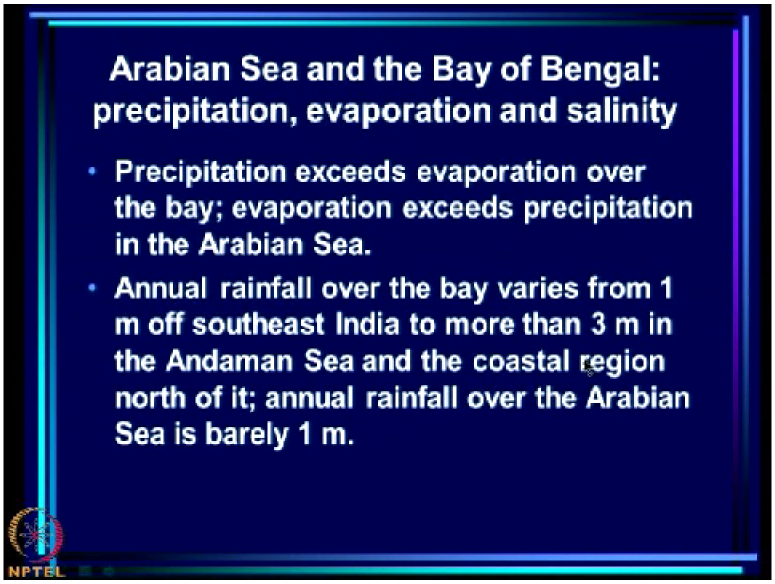

Now Arabian Sea and the Bay of Bengal, so now so far we have seen how the sea surface temperature varies, the mean monthly patterns over the Arabian Sea and over the Bay of Bengal and you have seen that by and large, the SST over the Bay of Bengal is above the threshold for a large part of the year, whereas Arabian Sea, it is above the threshold only over the eastern Arabian Sea for a few months of the year.

Now let us look at other facets, mainly precipitation, evaporation and salinity. Precipitation exceeds evaporation over the Bay and evaporation exceeds precipitation in the Arabian Sea. So annual rainfall over the Bay is huge, it varies from 1 metre off southeast India to more than 3 metres, that is to say more than 300 centimetres in the Andaman Sea and the coastal region north of it. Annual rainfall over the Arabian Sea is barely 1 metre.

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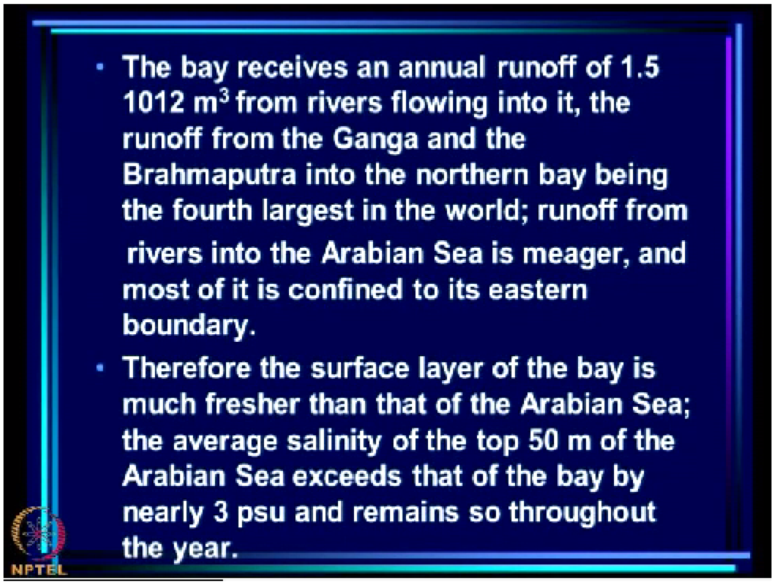

Now the Bay in addition to getting so much rain, the Bay receives an annual runoff of 1.5*10 raise to 12 metre cube from rivers flowing into it, the runoff from the Ganga and the Brahmaputra into the northern Bay being the 4th largest in the world. Runoff from the rivers into the Arabian Sea is meager and most of it is confined to its eastern boundary. So the Bay is flooded with river runoff as well as with rain.

And therefore, the surface layer of the Bay is much fresher than that of the Arabian Sea. The average salinity of the top 50 metres of the Arabian Sea exceeds that of the Bay by nearly 3 psu and remains so throughout the year.

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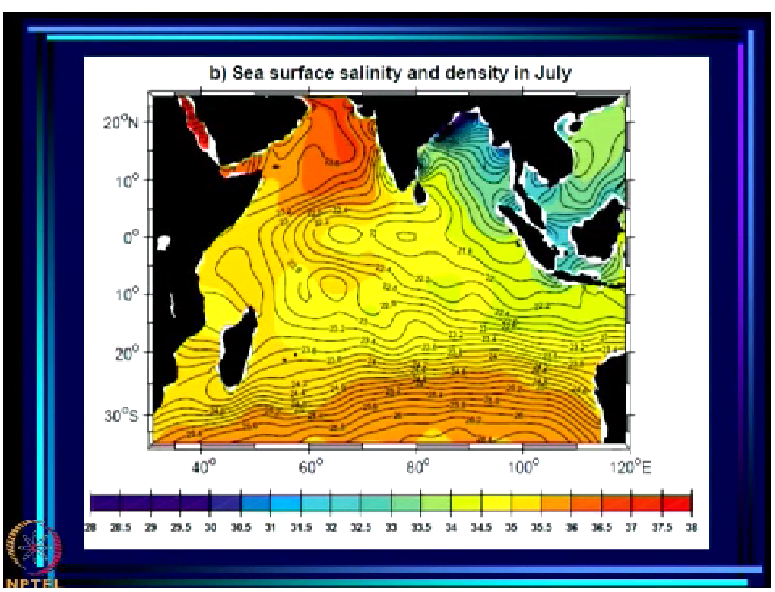

And you see that here. Now what is shown here is the salinity and the density and the colour shows the salinity and you know this green and shades of blue mean very low salinity and you can see how low the salinity is over the Bay and low saline water actually extends to the eastern part of the equatorial Indian Ocean as well, whereas over the Arabian Sea you see, the salinity is extremely high.

So these 2 basins if you look at, Arabian Sea and Bay of Bengal, they provide a contrasting picture in the salinity. Water being highly fresh over the Bay and very very salty over the Arabian Sea. So there is a major difference in the salinity pattern.

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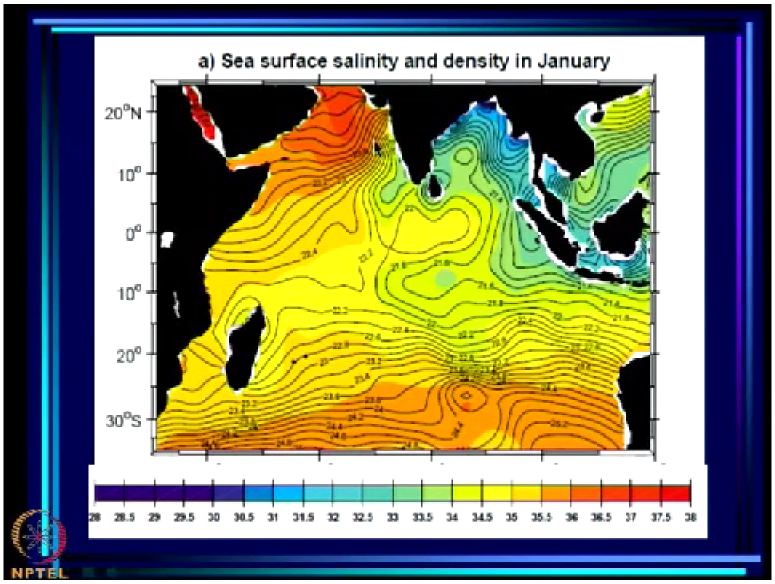

And interestingly that was for July but similar difference remains in January as well. So throughout the year, Bay is very much fresher than the Arabian Sea.

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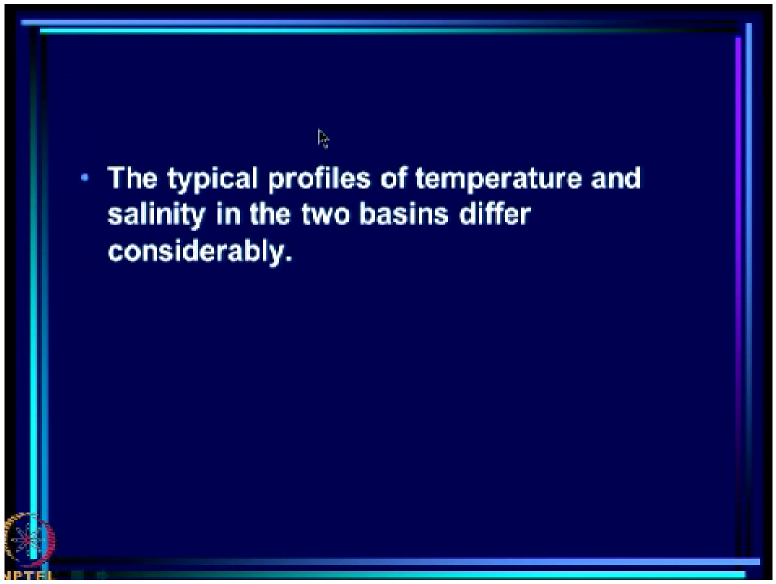

Now typical profiles of temperature and salinity in the 2 basins also differ considerably.

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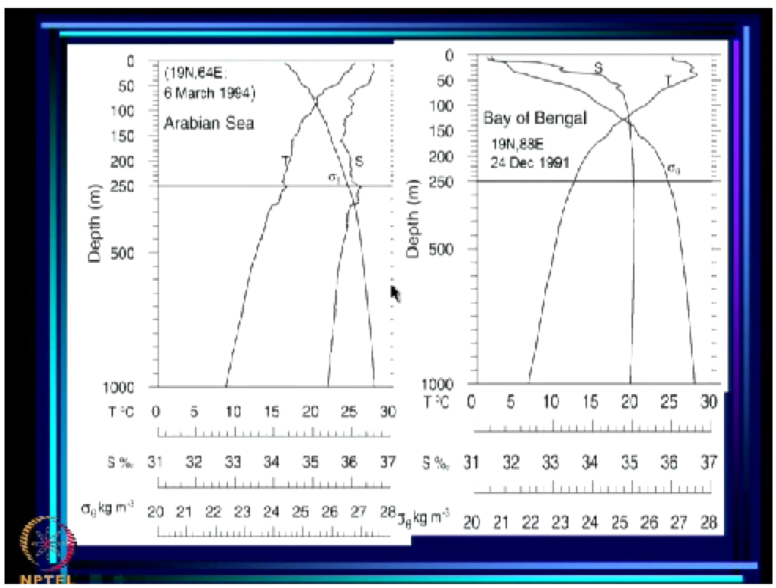

So you have here, now this is taken in March and this is the temperature decreasing and this is the salinity. This is the Arabian Sea. Both temperature and salinity decrease in the Arabian Sea and if you go to the Bay on the other hand, you find that the salinity shows a sharp decline as you go to the surface, that is to say as you go away from the surface, whereas here, the salinity decreases as you go away from the surface.

Here salinity increases as you go away from the surface and then flattens out. The temperature has a mixed layer here, thinner one and then decreases.

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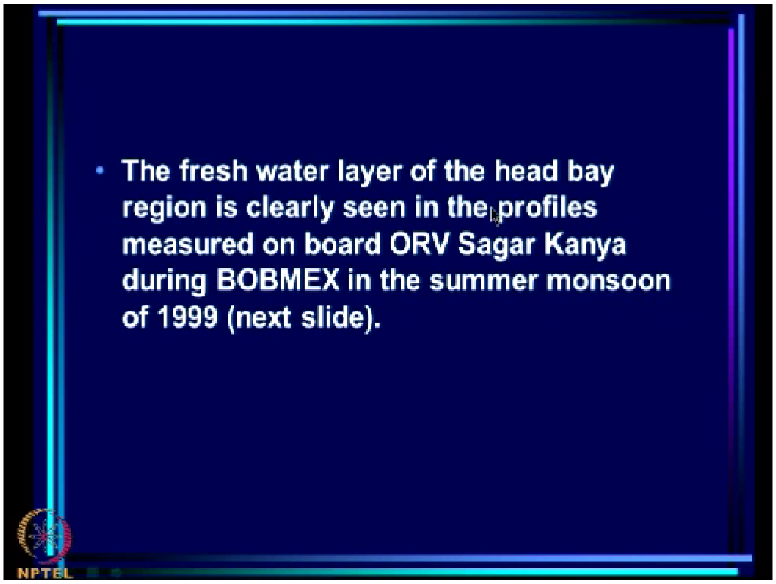

The fresh water layer of the head Bay region is clearly seen in the profiles measured on board of ORV Sagar Kanya during BOBMEX in the summer monsoon of 1999.

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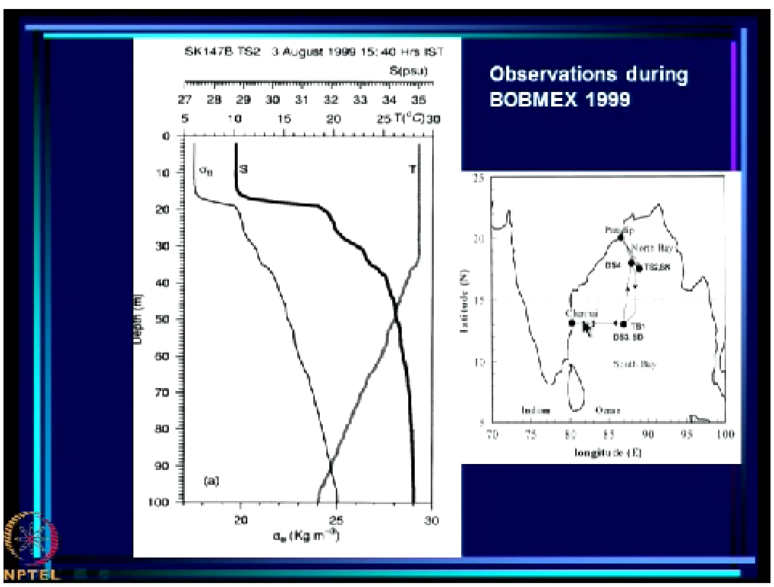

So we have here, this is the BOBMEX measurement, we have seen this before and this is done by from Sagar Kanya which was stationed somewhere here and what you see is a fresh water layer which is relatively shallow. Salinity is well mixed in a relatively shallow layer compared to the temperature.

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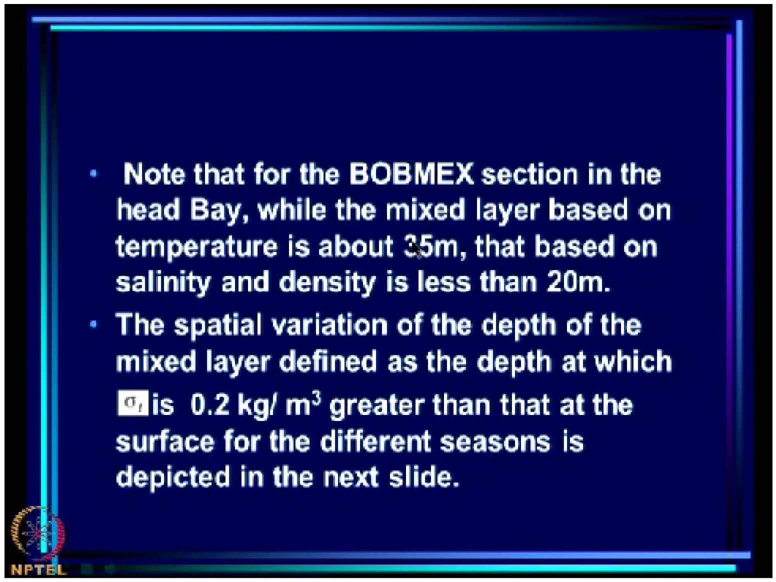

So what you find is that while the mixed layer based on temperature is about 35 metres, that based on salinity and density is < 20 metres, the spatial variation of the depth of the mixed layer defined as the depth at which the density is 0.2 kilogram per metre cube greater than that at the surface. See one has to define mixed layer somehow. In the old days, it used to be defined by temperature alone.

But now it is defined on the basis of density which is particularly important for regions like the Bay where a large variation in the density occurs because of salinity.

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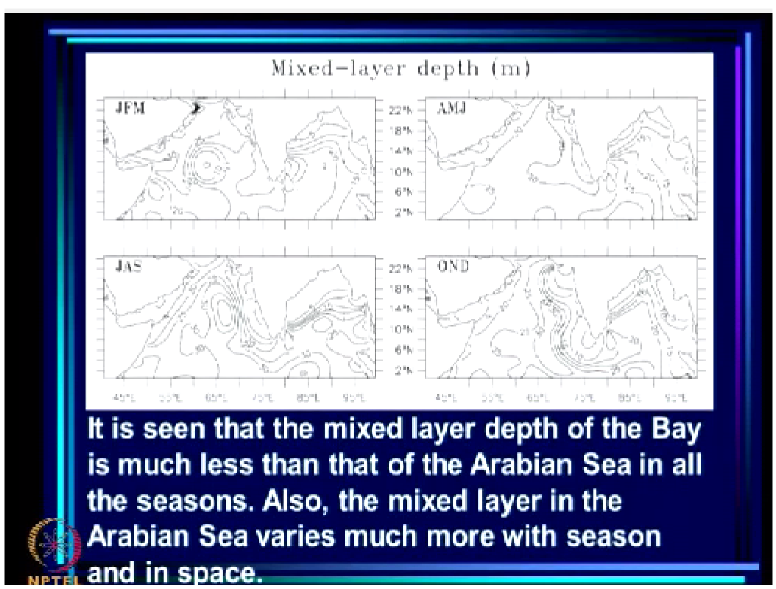

So if we look at mixed layer depth then, these are the mixed layer depths, this is January-

February-March, this is April-May-June, July-August-September and October-November-December. See the mixed layer right from April is deeper over the Arabian Sea, it is by and large more than 20 metres but over the Bay, it is very shallow. This is 15 and this is 10, extremely shallow and you see the same thing here in July-August-September. This is very very deep.

It has gone to beyond 30, 35 and so on, whereas it is of the order of 5 and 10 metres over the Bay. Maximum it gets to is about 20 metres here. So the mixed layer depth of the Bay is much less than that of the Arabian Sea in all the season and also the mixed layer of the Arabian Sea varies much more in space and with season than that over the Bay. Over the bay, it remains relatively shallow and not too much variation with season or space but the patterns change very much more over the Arabian Sea.

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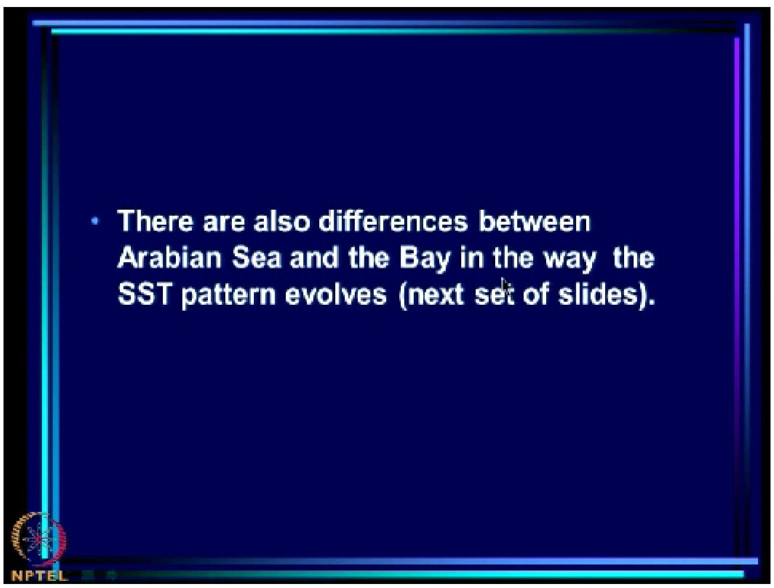

There are also differences between Arabian Sea and the Bay in the way the SST pattern evolves.

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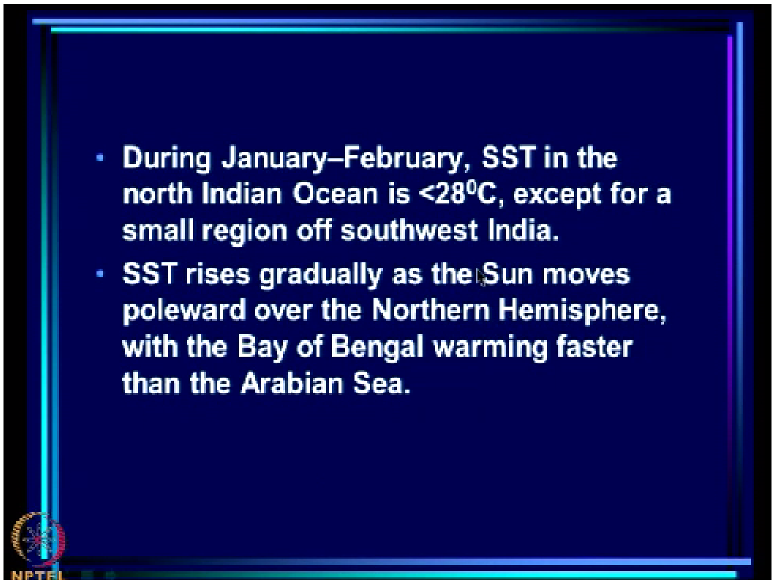

So what happens is the following: During January-February, SST in the north Indian Ocean is < 28 degrees centigrade except for a small region off southwest of India.

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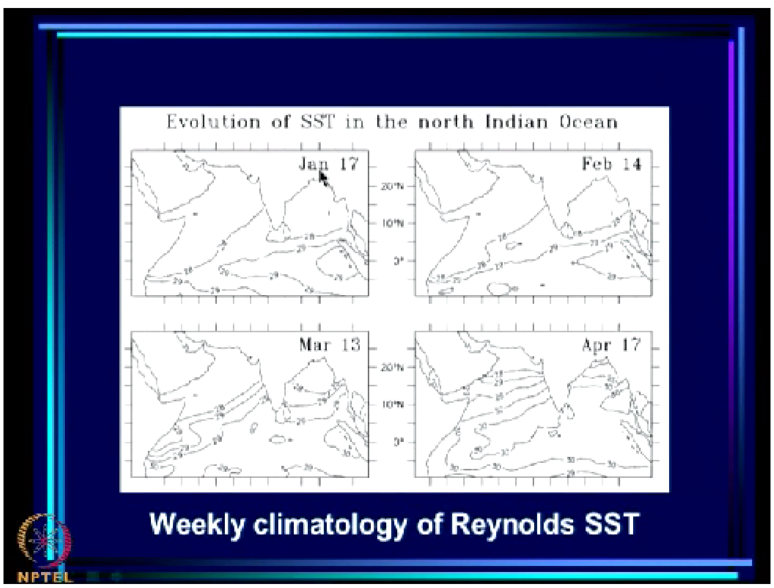

And what you will see here is weekly snapshots of climatology. So this is the climatology from Reynolds SST of January 17th and what you see is that there are SST in the north Indian Ocean is < 28 except for a small region of south-west India. So this is the 28 degrees contour here and except for this small region here, SST is below the threshold of 28 almost everywhere in the north Indian Ocean.

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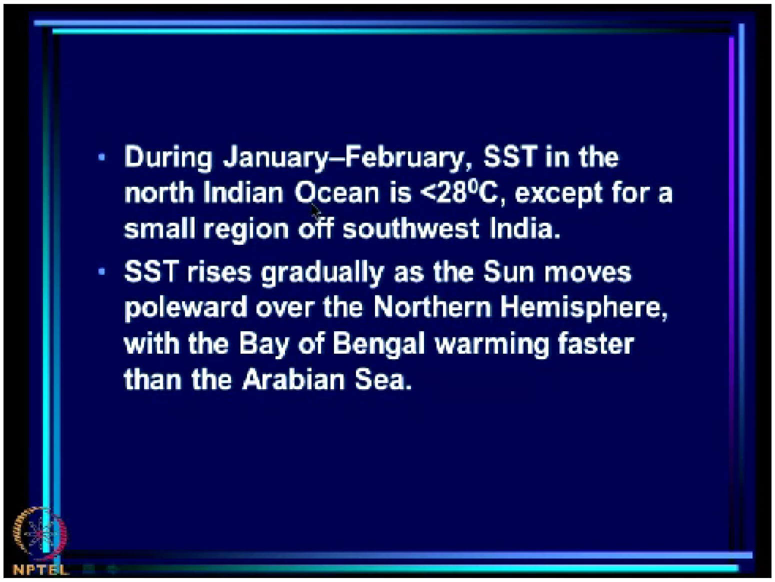

Now SST rises gradually as the Sun moves poleward over the Northern Hemisphere with the Bay of Bengal warming faster than the Arabian Sea. So here you are, now this is January, this is February middle and you can already see that SST is rising here, this has now become 29 and this is 28. So the warm region is expanding as the Sun is moving towards the north pole, northward and you see the same thing, warming up here and further warming here.

Now you can see, Arabian Sea has warmed up a great deal more than the Bay of Bengal. So Bay of Bengal warming faster than the Arabian Sea. So you see already here, in February, Bay is below 28 but it has begun to warm so that part of the central Bay is already above 28 and by April, a large part of it is above 28.

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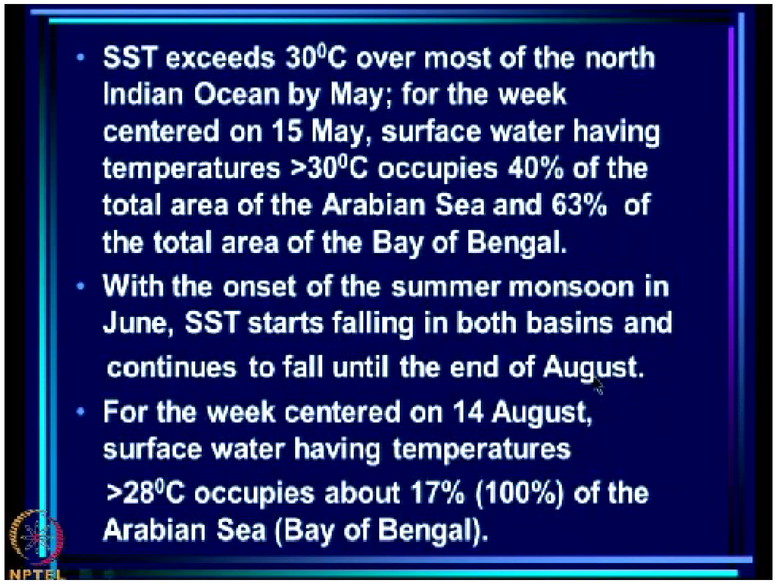

Now SST exceeds 30 degrees over most of the north Indian Ocean by May for the week centered on 15th May.

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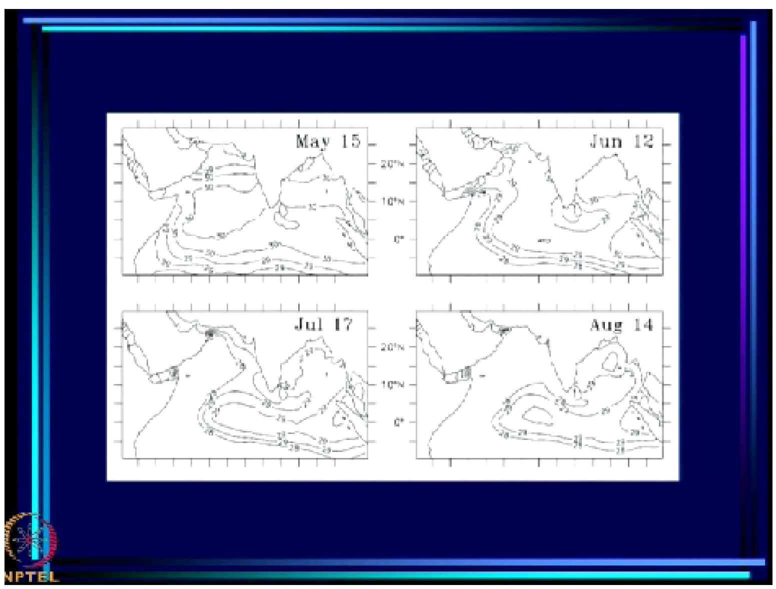

So we look at week center on 15th May, you see this huge region here which is over 30 degrees. So there is a huge tongue of warm SST over the north Indian Ocean in May. In fact, the surface water having temperatures > 30 degrees occupies 40% of the total area of the Arabian Sea and 63% of the total area of the Bay. So huge part of Bay is over 30 degrees and a huge part of the Arabian Sea is also over 30 degrees.

With the onset of the summer monsoon in June, SST starts falling in both the basins and continues to fall until the end of August and you see that. This is very warm. Now SST had begun to fall in both the basins. This is 29 here, this is 29, this is 30 here. So this is all now < 30, most of the Bay and most of the Arabian Sea is also colder and now it becomes even colder in July and even colder in August.

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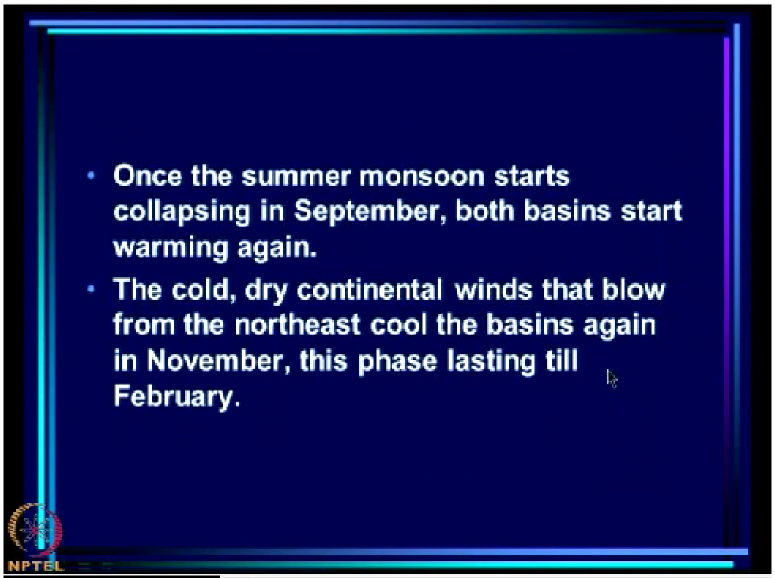

Once the summer monsoon starts collapsing in September, both basins start warming again.

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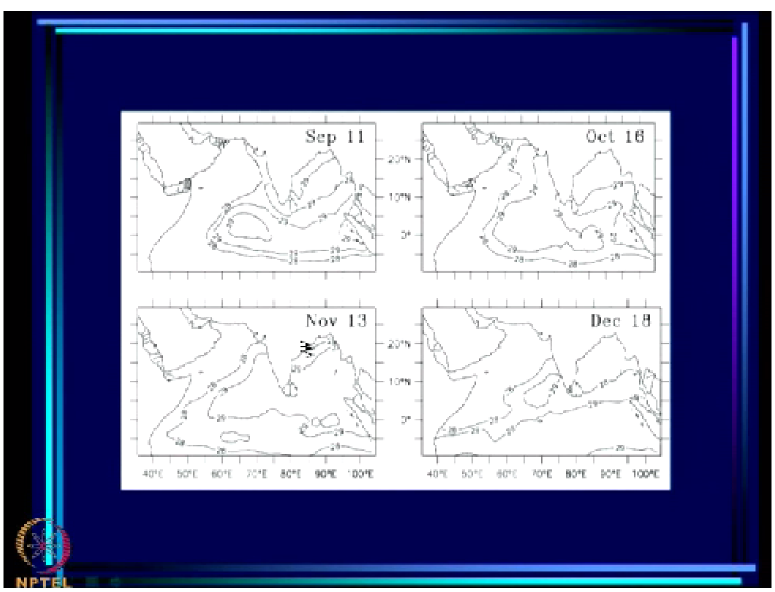

So you have here, they start warming again. Now it has gone above 29 in September and a large region is above 29 in October and also in November and then it starts cooling again.

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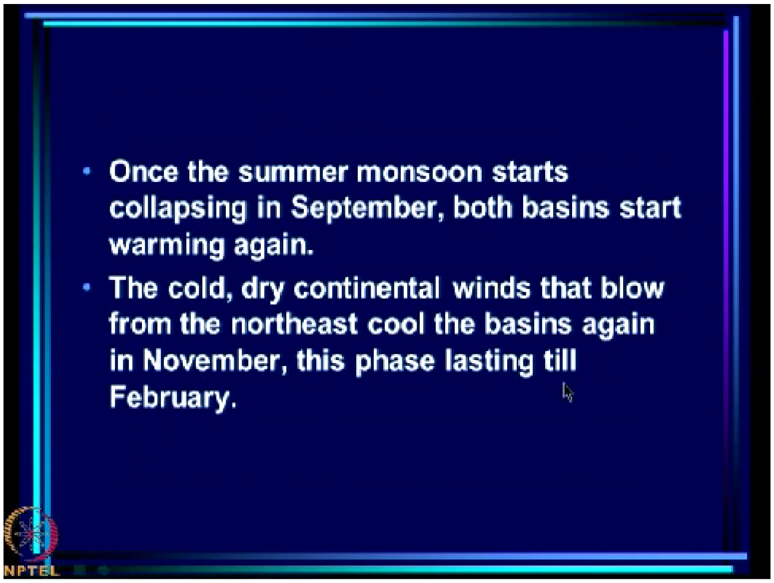

So the cold, dry continental winds that blow from the northeast cool the basins again in November and this phase last till February, okay.

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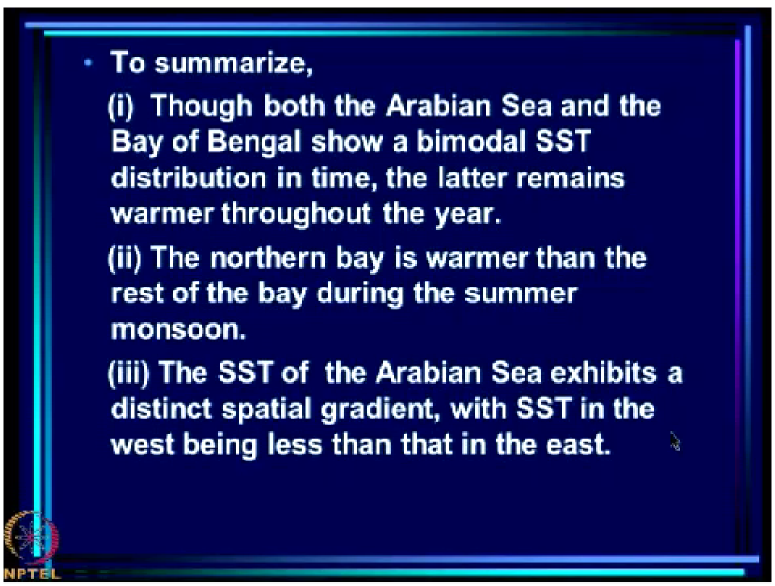

To summarize them, though both the Arabian Sea and the Bay of Bengal show a bimodal SST distribution in time, the latter remains warmer throughout the year. The northern Bay is warmer than the rest of the Bay during the summer monsoon. So the SST of the Arabian Sea exhibits a distinct spatial gradient with SST in the west being less than that in the east. So this is the nature of the SST of the north Indian Ocean.

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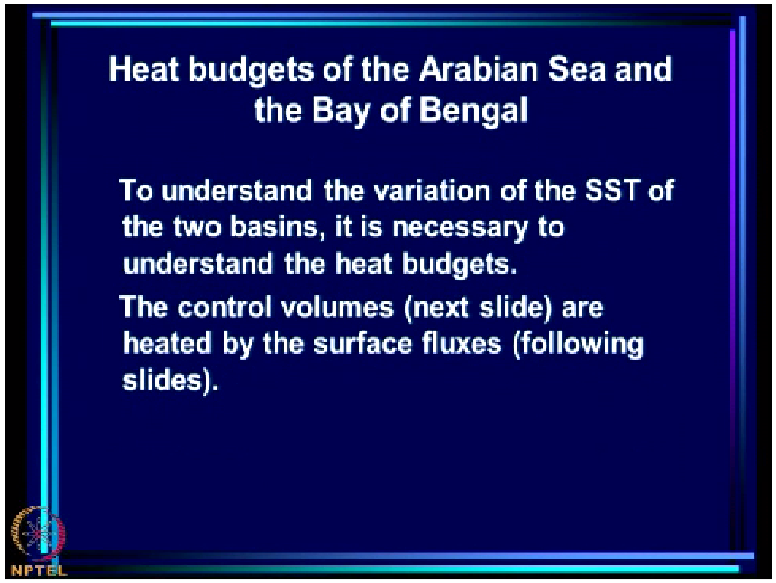

Now to understand the variation of the SST of the 2 basins, it is necessary to understand the heat budgets because what leads to the change in SST is determined by the heat budget. So now control volumes are heated by the surface fluxes.

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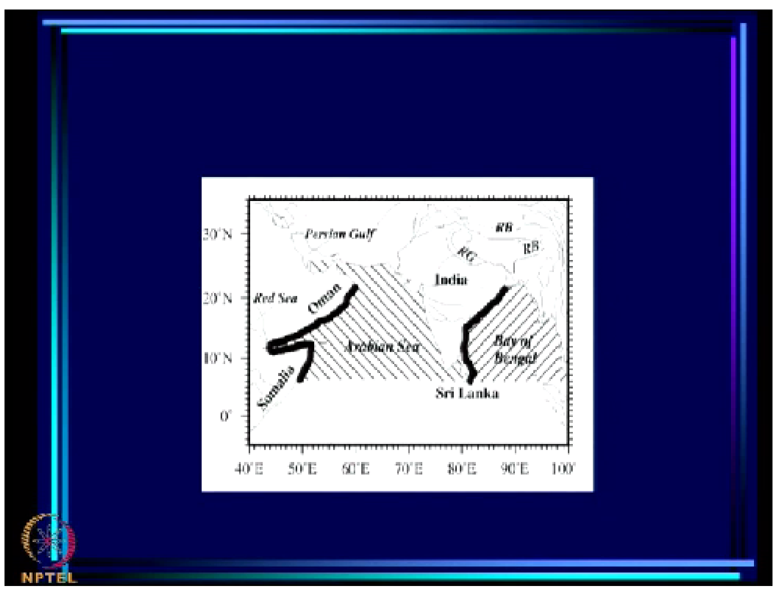

These are the control volumes. So when one talks about Arabian Sea, you are talking of the volume of water averaged over this region and Bay of Bengal is over this region.

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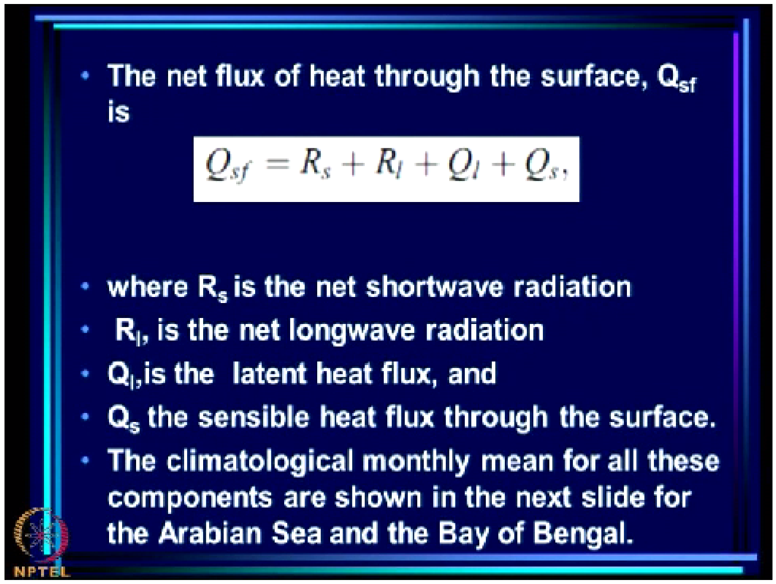

So those control volumes are heated by the surface fluxes. Now what are the surface fluxes involved. See the total surface flux includes the net shortwave radiation which is Rs, the net long wave radiation which is Rl, the latent heat flux and sensible heat flux. So add all these, we can calculate what is the net flux of heat through the surface. The climatological monthly mean for all these components are shown in the next slide for Arabian Sea and Bay of Bengal.

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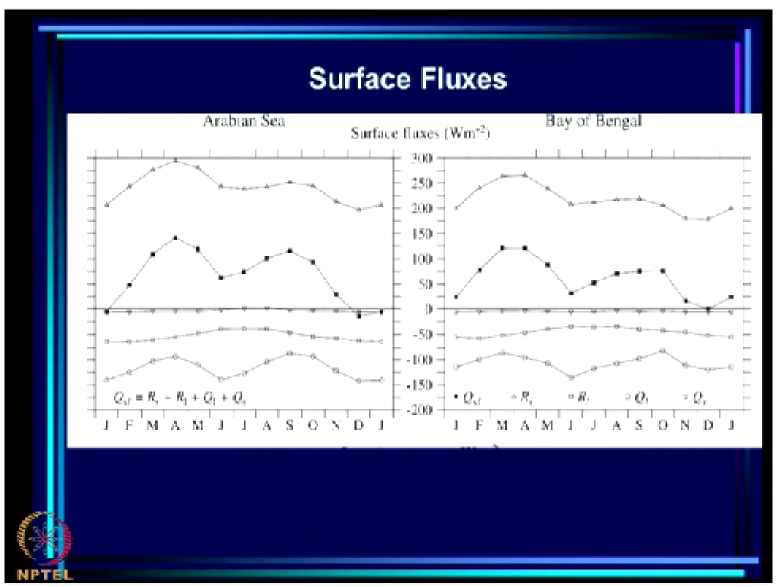

So now this is actually the shortwave radiation, is right here, this is the net shortwave and you can see that net shortwave is maximum in April and May and decreases because of the clouds as we proceed. So this is the net shortwave radiation. Then comes the longwave radiation. This is the longwave radiation and remember that the ocean is losing heat through the longwave radiation and you have this pattern for the longwave radiation.

Then there is the latent heat. This is the latent heat and these are rather similar actually. The latent heat variation is rather similar in both the basins and the sensible heat which is the direct heating, heat lost because of the temperature difference between air and sea is of very very small number as you can see and this is the total heat flux then. This is the total heating of the ocean. Remember both the oceans are actually being heated by the surface fluxes.

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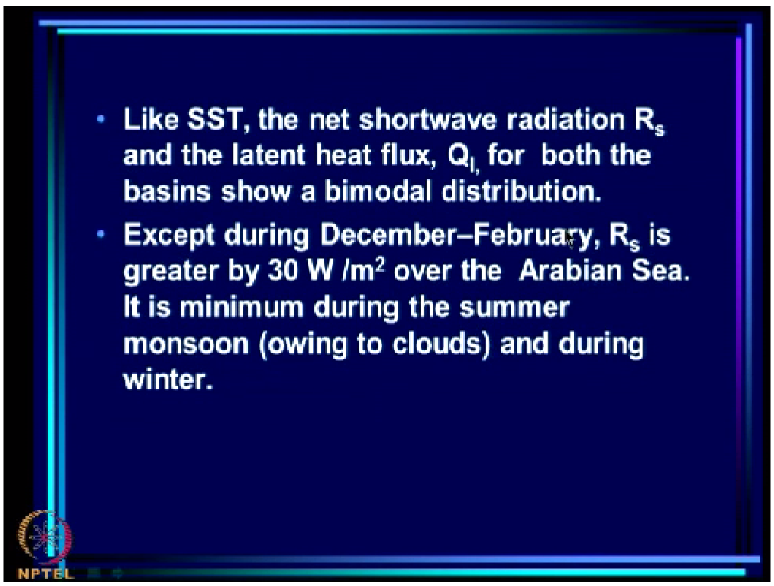

Like SST, the net shortwave radiation and the latent heat for both the basins show a bimodal distribution. See this is the net shortwave radiation and latent heat, both show a bimodal distribution. Except during December to February, Rs is greater over the Arabian Sea. This of course we have seen. This is the incoming radiation. This is greater except in this period. Rs here is of the order of 250 and here it is of the order of 200.

So the incoming shortwave radiation is greater over the Arabian Sea and it is minimum during the summer monsoon because of the clouds.

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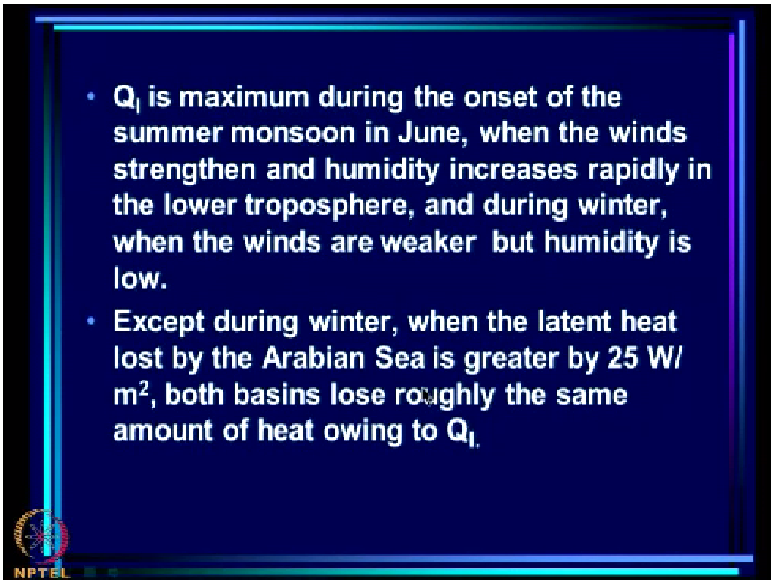

Now latent heat is maximum during the onset of the summer monsoon in June when the winds strengthen and humidity increases rapidly in the lower troposphere and during winter, when the winds are weaker but humidity is low. So latent heating is naturally maximum during the onset of the summer monsoon and when the winds are weaker but the humidity is low, again you get a lot of evaporation, so again you have high.

So that is why you get a bimodal distribution of latent heating also. This is the latent heating and you see a clear bimodal distribution here. So except during winter when the latent heat lost by the Arabian Sea is greater, both basins lose roughly the same amount of heat as latent heat.

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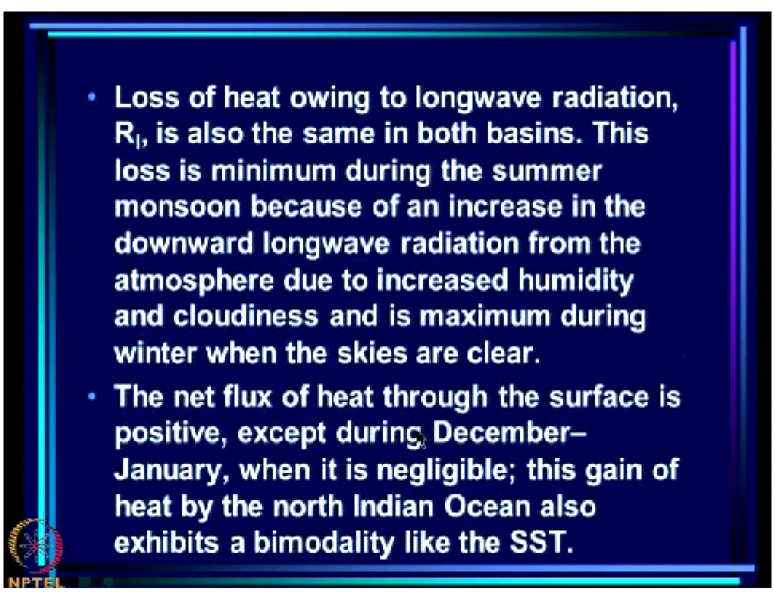

Loss of heat owing to longwave radiation is also very similar in both the basins, I have pointed this out. This loss is minimum during the summer monsoon because of an increase in the downward longwave radiation from the atmosphere due to increased humidity and cloudiness and is maximum during the winter when the skies are clear. The net flux of heat through the surface is positive, except during December-January when it is negligible.

This gain of heat by the north Indian Ocean also exhibits a bimodality like SST.

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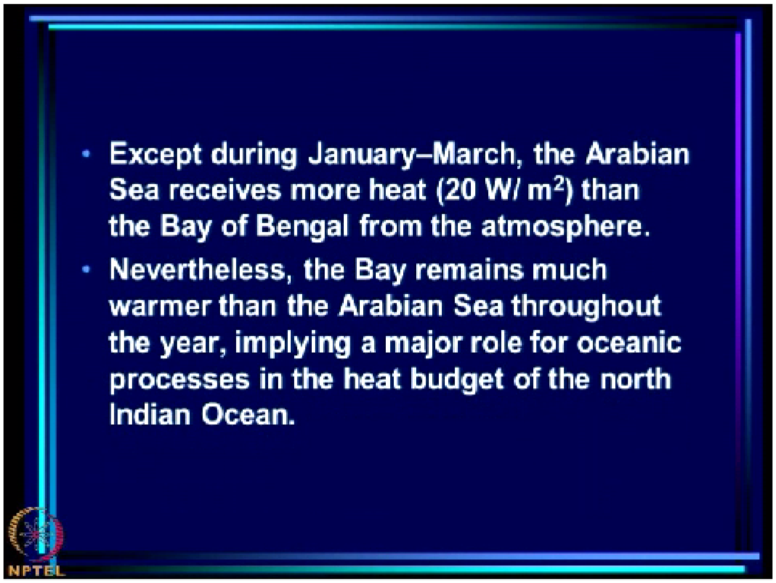

So except during January to March, the Arabian Sea receives more heat, about 20 Watts per metre square than the Bay of Bengal from the atmosphere. Nevertheless, the Bay remains much warmer than the Arabian Sea throughout the year, implying a major role for oceanic processes in the heat budget of the north Bay, of the north Indian Ocean.

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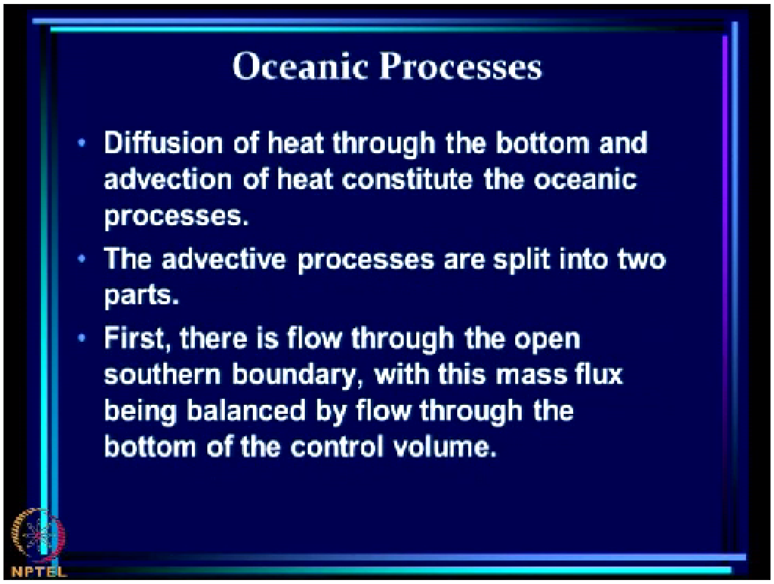

So now look at, consider what are the oceanic processes that one has to take into account in getting the heat budget for the Arabian Sea and Bay of Bengal. So the first is of course diffusion of heat through the bottom and advection of heat. So these are the 2 processes. The advective processes are split into 2 parts that is, first is there is a flow through the open southern boundary with this mass flux being balanced by flow through the bottom of the control volume.

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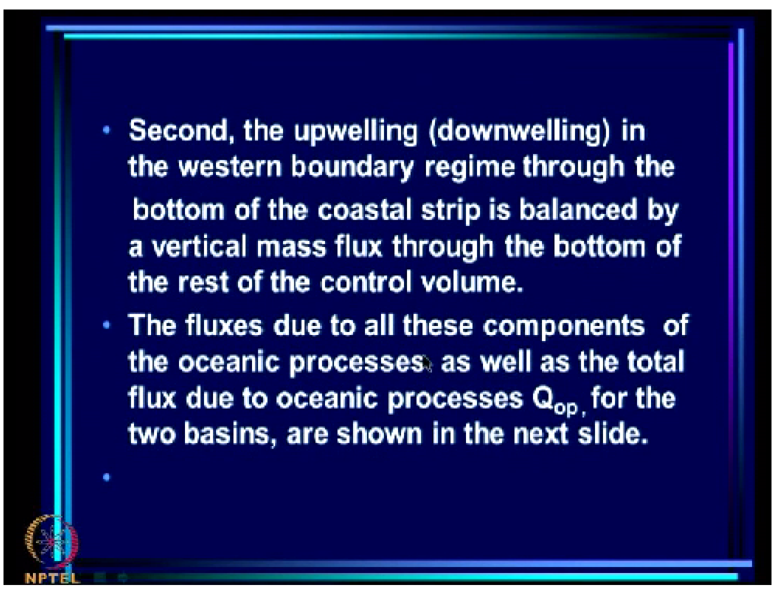

Then there is upwelling or downwelling in the western boundary regime through the bottom of the coastal strip and this has to be balanced by vertical mass flux through the bottom of the rest of the control volume. So there are 2 kinds of advective things that we have to look at. There is a flow through the open southern boundary which we have to see from the control. See there is an open southern boundary here.

So there is a flow from the open southern boundary and then the upwelling and downwelling on this region has to be balanced by opposite sign circulation, that is to say if there is upwelling here, there has to be downwelling over this strip here and that will also contribute to the heat budget, okay. So the fluxes due to all these components of the oceanic processes as well as the total flux due to the oceanic processes for the 2 basins are here.

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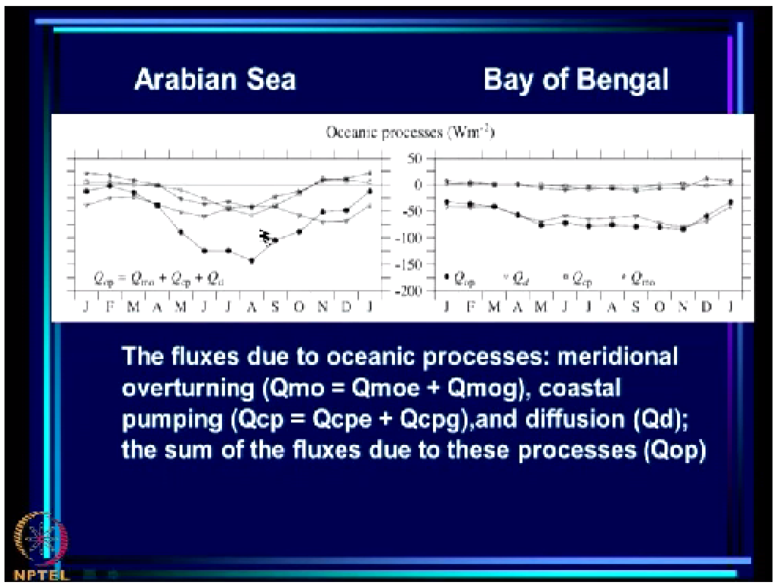

So these are all the oceanic processes, okay and I will not go into great detail here but this is really what is critical is, what is the total contribution of oceanic processes and you can see that the cooling in world or loss of it due to oceanic processes is rather large for the Arabian Sea relative to the Bay. The Bay it is much smaller than here.

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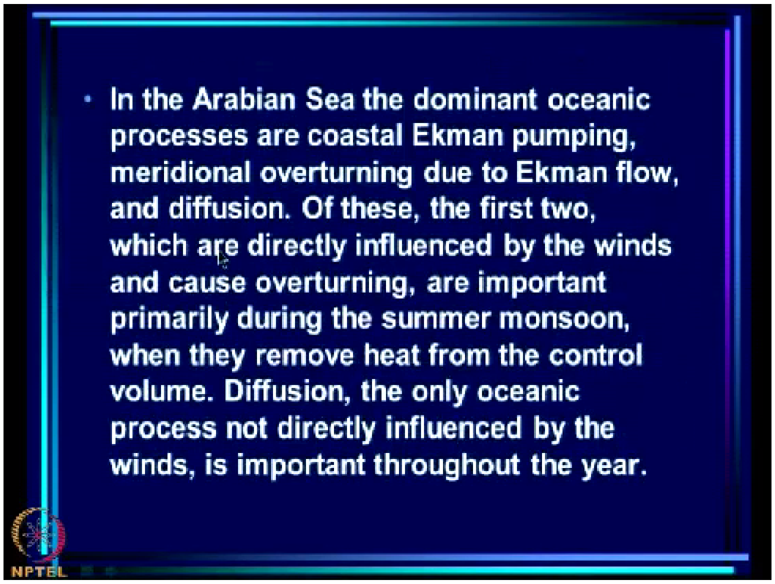

So in the Arabian Sea, the dominant oceanic processes are coastal Ekman pumping, meridional overturning, this is north-south overturning due to Ekman flow and diffusion. Of these, the first 2 which are directly influenced by the winds and cause overturning are important primarily during the summer monsoon when they remove heat from the control volume. Diffusion, the only oceanic process not directly influenced by the winds, is important throughout the year.

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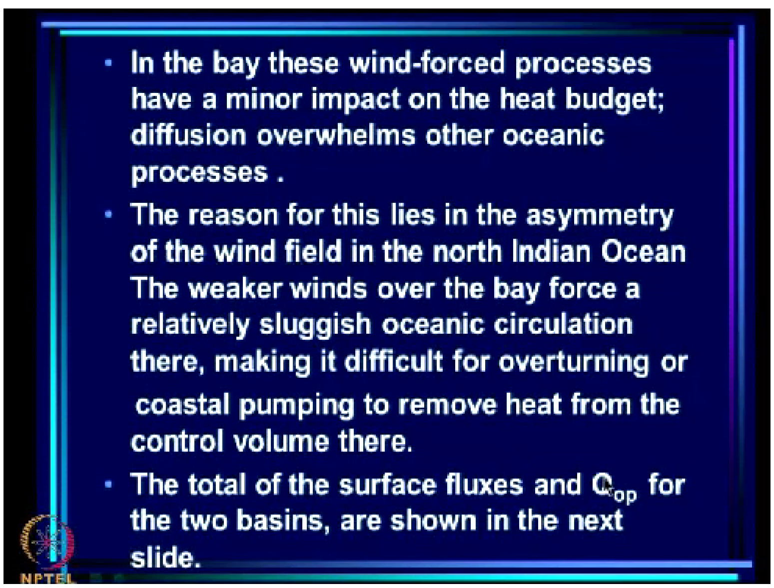

In the bay, these wind-forced processes have a minor impact on the heat budget, diffusion overwhelms other oceanic processes and you can see that here that the other processes are very very small here and it is this diffusion which is much larger in the Bay relative to the other processes and it is really diffusion that determines the impact of the ocean processes as far as the

Bay is concerned but in the Arabian Sea, you can see that all of them are very important.

All the ocean processes are very important. Now why is this asymmetry there? The reason for this lies in the asymmetry of the wind field in the north Indian Ocean, the weaker winds over the Bay force a relatively sluggish ocean circulation there, making it difficult for overturning or coastal pumping to remove heat from the control volume there.

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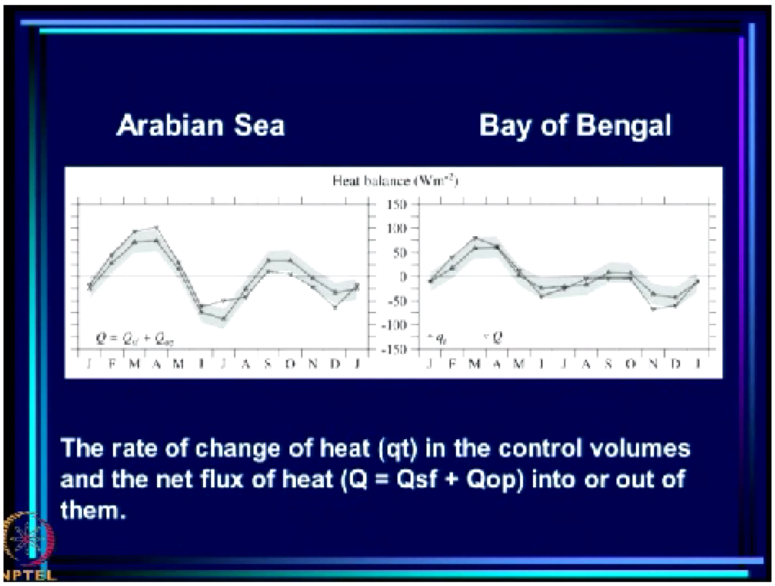

The total of the surface fluxes and the ocean, Qop for the 2 basins, we see here and what you see is that the Arabian Sea in total is being warmed up to May and is cooled during June-July-August, again slightly warmed here and on the other hand, the Bay is warmed in the early part of the year and more or less remains with no net heating till October and then losses a little bit in October-November.

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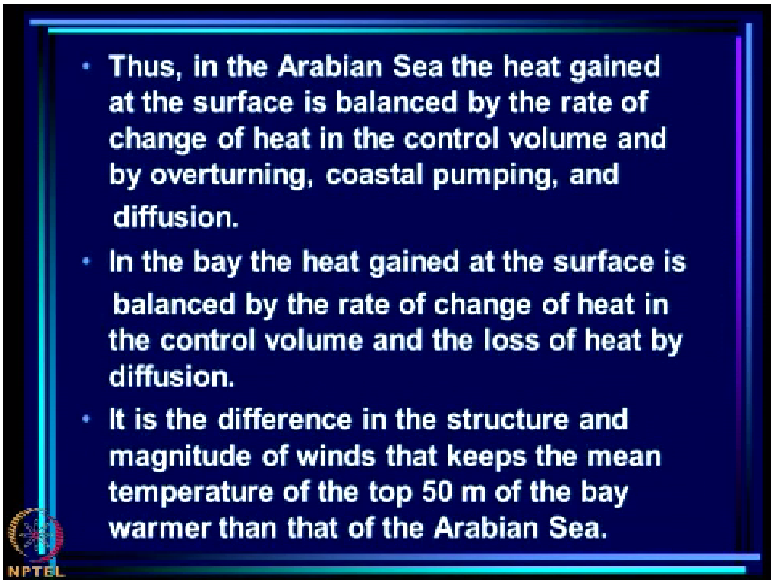

Thus in the Arabian Sea, the heat gained at the surface is balanced by the rate of change of heat in the control volume and by overturning, coastal pumping and diffusion. In the Bay, the heat gained at the surface is balanced by the rate of change of heat in the control volume and the loss of heat by diffusion. It is the difference in the structure and magnitude of winds that keeps the mean temperature of the top 50 metres of the Bay warmer than that of the Arabian Sea.

So we believe we have understood why is it that the Bay remains warmer than the Arabian Sea.

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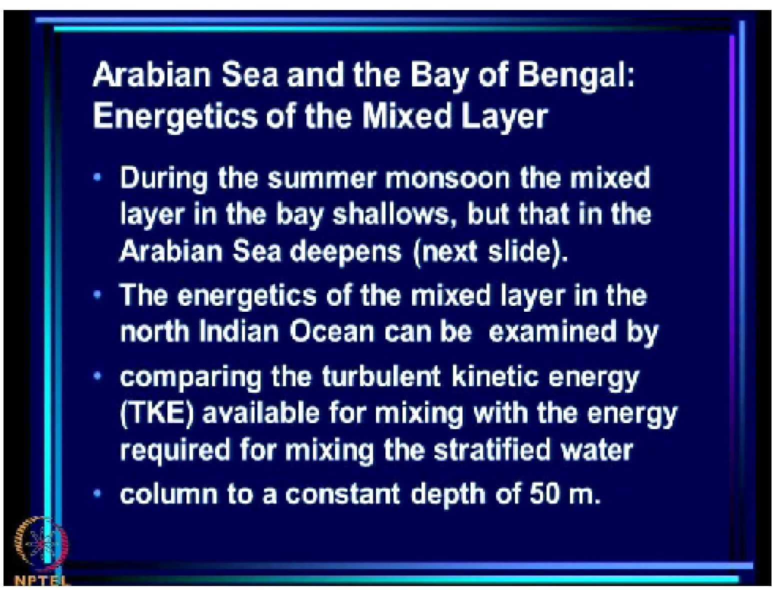

There is another factor that is also different between the 2 and that is the mixed layer. This is something we have seen earlier. So we should now look at the energetics of the mixed layer. So during the summer monsoon, the mixed layer in the Bay shallows, but that in the Arabian Sea deepens. So this is the mixed layer depth which we had seen earlier. So during the summer monsoon, the mixed layer in the Bay shallows but that in the Arabian Sea deepens.

And you can see that it is only about 20 here for April-May-June but it has become much more when 30 here by July-August-September but the Bay on the other hand, the mixed layer is shallowing because it is 5 only in the small region here but now it has become 5 in the much larger region. So you can see that the mixed layer is becoming shallower in the Bay and deeper in the Arabian Sea with the monsoon.

So during the summer monsoon, the mixed layer in the Bay shallows, but that in the Arabian Sea deepens. Now the energetics of the mixed layer in the north Indian Ocean can be examined by comparing the turbulent kinetic energy available for mixing with the energy required for mixing the stratified water column to a constant depth of 50 metres.

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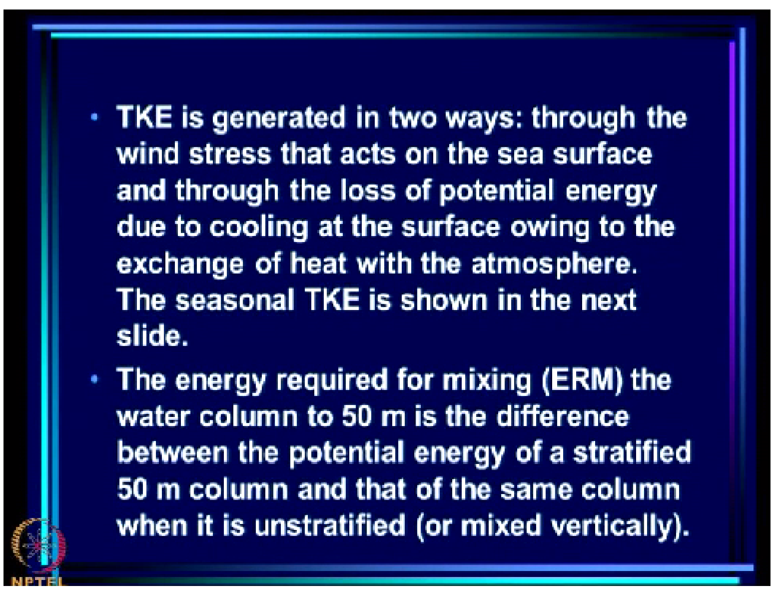

So what we are saying is first of all how much is the energy available for mixing and secondly, how much energy is required for mixing up to 50 metres given the nature of the mixed layer or given the nature of the temperature, salinity and hence density profiles in the 2 oceans. Now what is the kinetic energy available? See total kinetic energy generated in 2 ways. Through the wind stress that acts on the sea surface and through the loss of potential energy due to cooling at the surface owning to the exchange of heat with the atmosphere.

The seasonal TKE is shown in the next slide.

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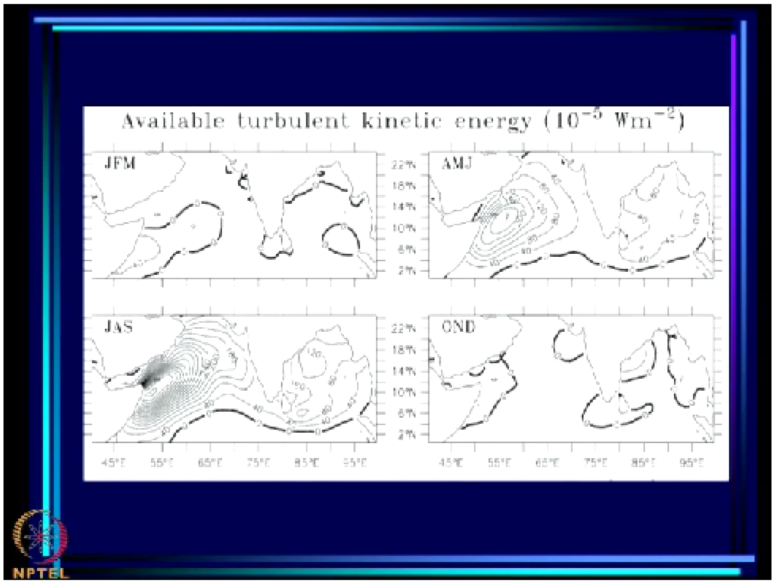

So this is the available turbulent kinetic energy in different seasons. This is JFM, this April-May-June and already quite a bit of turbulent kinetic energy is available over the Arabian Sea, much more so than over the Bay. In July-August-September, it is even more spectacular the difference in the 2. So much more turbulent kinetic energy is available over the Arabian Sea than over the Bay.

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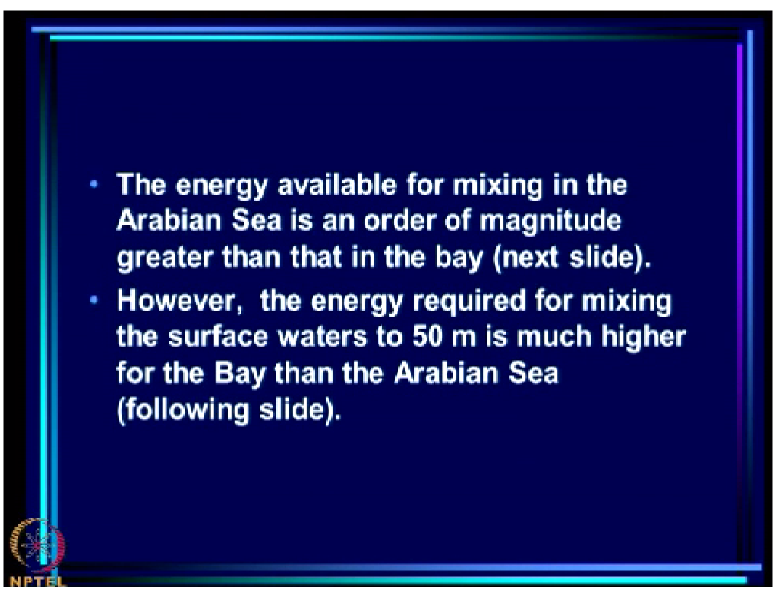

So the energy available for mixing in the Arabian Sea is an order of magnitude greater than that in the Bay. However, the energy required for mixing the surface waters to 50 metres is much higher for the Bay than the Arabian Sea.

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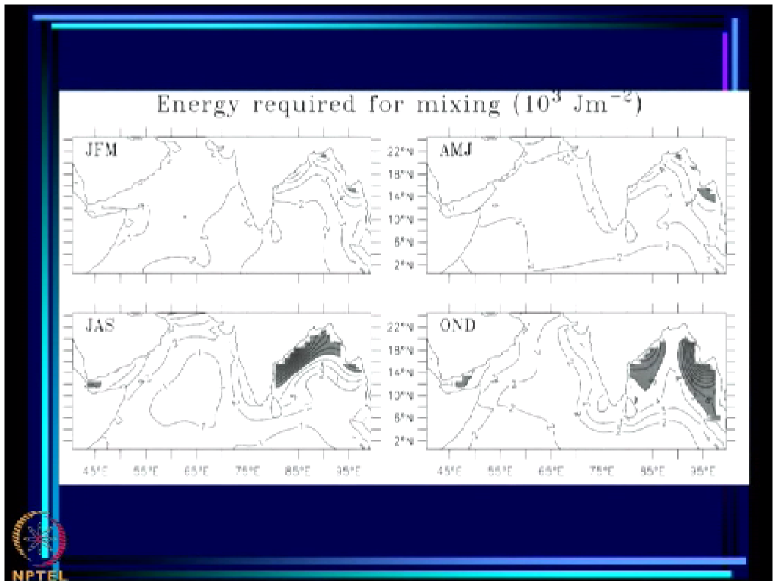

So what is happening is, this is the energy required for mixing and you know, this is determined by how stably stratified the ocean is. Now we know that the Bay is very much more stably stratified because of the salinity layer, thin fresh water layer over the Bay, whereas Arabian Sea is not so strongly stratified. So this means energy required for mixing is much larger over the Bay of Bengal.

You can see that typically it is 1 unit here whereas it is very much bigger in the Bay region here. Even here, this is between 2 and 3 and this is all above 3. So even in April-May-June, the energy required to mix a column, mix the top layer of the Bay is much higher but in July-August-September, it becomes even higher because of the build-up of the fresh water layer.

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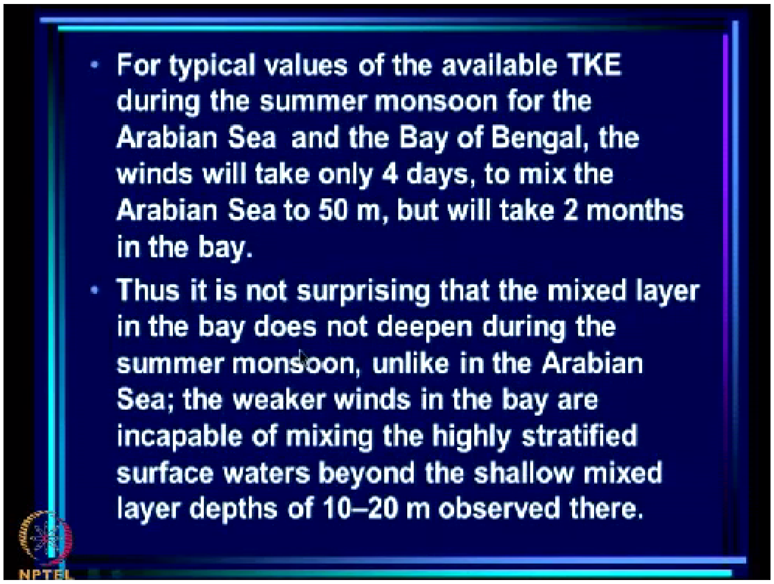

So for typical values of the available total kinetic energy during the summer monsoon for the Arabian Sea and the Bay of Bengal, the winds will take only 4 days to mix the Arabian Sea to 50 metres but will take 2 months in the Bay. So what is happening is that the available energy is more in the Arabian Sea and less is required for mixing. So it will happen very fast here and it will take typically only 4 days, whereas to mix the top 50 metres here.

It will take much longer because the available energy is less and the energy required for mixing is much much more. So this is why, whereas it takes only 4 days to mix up to 50 metres in the Arabian Sea, it will take 2 months to mix in the Bay. So it is not surprising that the mixed layer in the Bay does not deepen during the summer monsoon, unlike in the Arabian Sea. The weaker winds in the bay are incapable of mixing the highly stratified surface waters beyond the shallow mixed layer depths of 10 to 20 metres observed there.

So we have now understood why the Bay remains warm. Firstly it is warm because of the heat that it is gaining and secondly it does not allow any mixing because of this situation.

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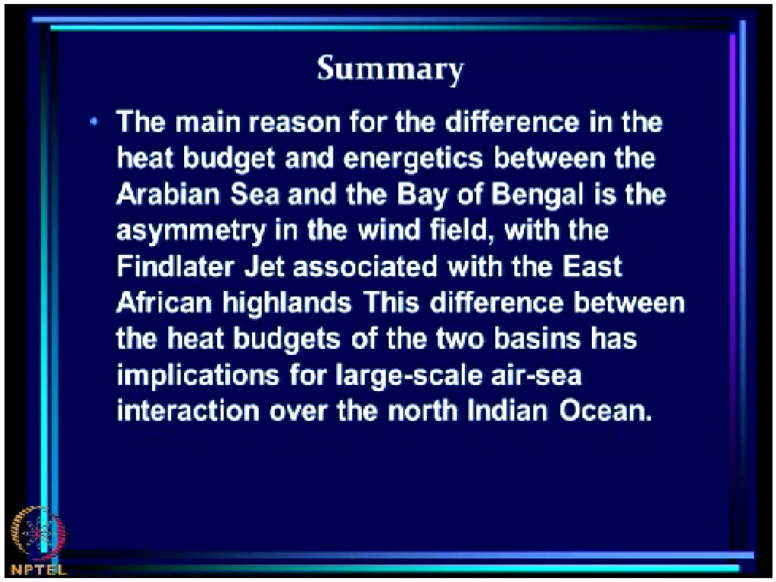

So what is the summary? The main reason for the difference in the heat budget and energetics between the Arabian Sea and the Bay of Bengal is the asymmetry in the wind field, with the Findlater jet associated with the East African highlands. This difference between the heat budgets of the 2 basins has implications for large scale air-sea interaction.

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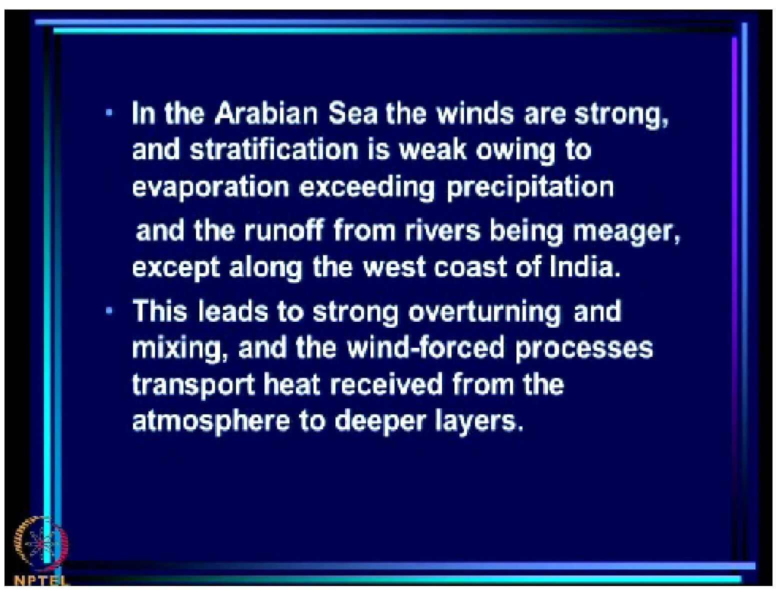

In the Arabian Sea, the winds are strong and stratification is weak owing to evaporation exceeding precipitation and the runoff from rivers being meager, except along the west coast of India. This leads to strong overturning and mixing and the wind-forced processes transport heat received from the atmosphere to deeper layers of the ocean. So this is what is happening in the Arabian Sea and therefore Arabian Sea is cooling.

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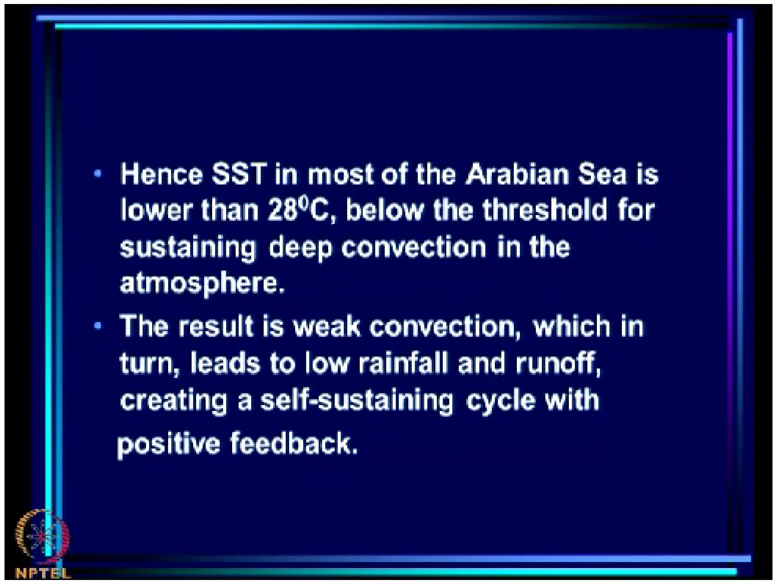

Hence SST in most of the Arabian Sea is lower than 39 degrees centigrade below the threshold for sustaining deep convection in the atmosphere. So the result is weak convection which in turn leads to low rainfall and runoff creating a self-sustaining cycle with a positive feedback.

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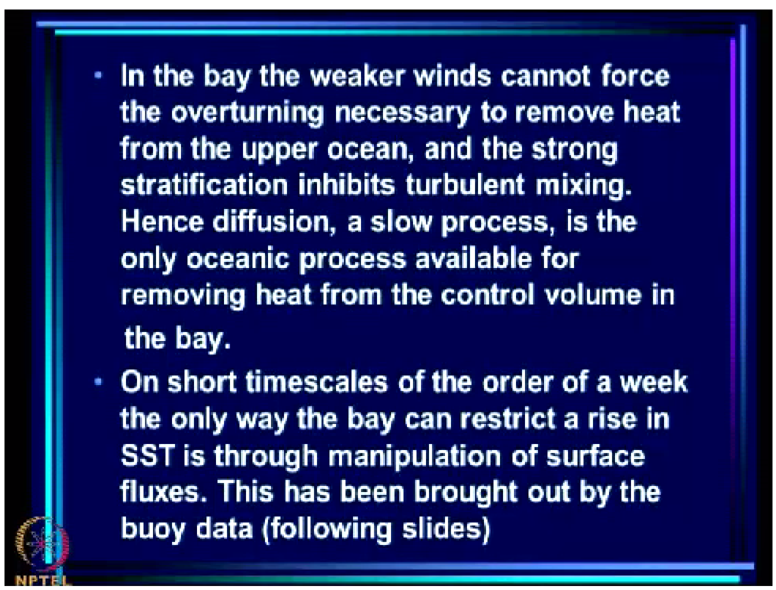

On the other hand, over the Bay, the weaker winds cannot force the overturning necessary to remove heat from the upper ocean and the strong stratification inhibits turbulent mixing. So we have weaker winds which cannot force the overturning and strong stratification which inhibits turbulent mixing. Hence diffusion, a slow process, is the only oceanic process available for removing heat from the control volume in the Bay.

On short timescales of the order of a week, the only way the Bay can restrict a rise in SST is through the manipulation of surface fluxes. Now the relationship between surface fluxes and SST over the Bay was first brought out very nicely when data became available from buoys which were stationed in the Bay.

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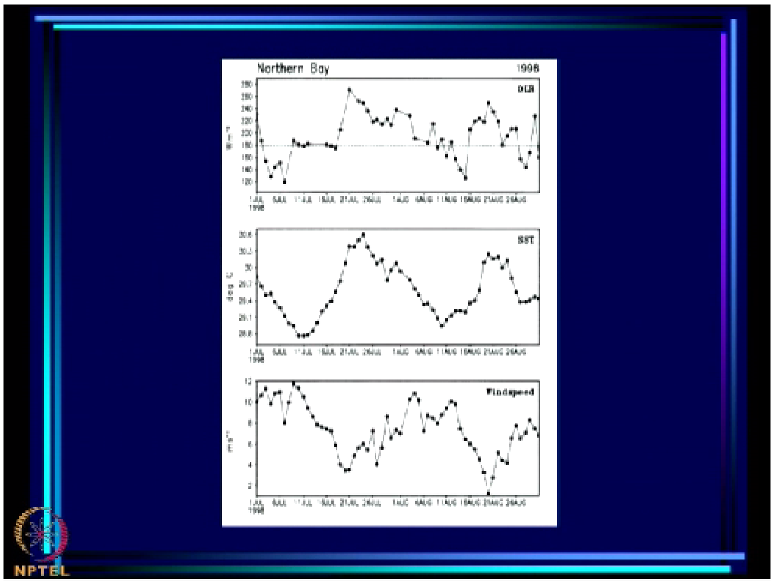

These buoys make measurements of sea surface temperature and also winds and what you see here is in the northern Bay, this is the sea surface temperature variation. Now I must point out that this variation is rather exaggerated because it is all above 28 anywhere. The Bay temperature in this case, now this is for the season of 1998 and this is 28.8 and this is 30.6, okay. So we are talking of very warm oceans, somewhat cooling and then warming again.

So that we have, this is from 1st July till 31st of August. These are the peak monsoon months of the year 1998 when the buoys were there and what you see is a definite variation in sea surface temperature here with SST decreasing up to 11 July, increasing here, again decreasing, again increasing and then decreasing and what is this related to? In fact, this is the outgoing longwave radiation that you see here and you see a one-to-one correspondence. See low outgoing longwave radiation occurred here which means there were deep clouds, right.

So the radiative fluxes were very much less and that is how sea surface temperature began to decrease. Then in fact, OLR has peaked up and become very high here. When OLR increases, that means the clouds have decreased and that means the sea surface temperature begins to heat and begins to warm and it warms up to this point at which the conditions have become, the sky has become cloud-free.

Again clouds start building up here, come to a maximum here and with the building up of clouds, the sea surface temperature has decreased. So you see a one-to-one correspondence almost between the outgoing longwave radiation and the sea surface temperature or between clouds and sea surface temperature. This is the relationship with winds but the relationship with winds is not that strong, okay.

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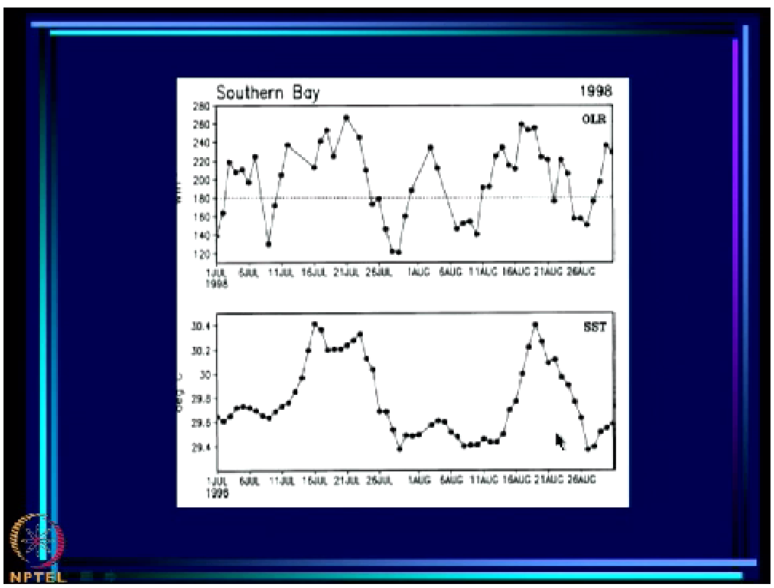

Now same thing you see in southern Bay also. Here also you had, these are clear conditions here most the days and we have sea surface temperature building up when there were clear conditions. As clouds began to form, sea surface temperature began to drop and we had very low temperatures when there were deep clouds. Then again the clouds disappeared but reappeared. So this was a minor change with that there was small change in SST.

But again as the sky became cloud free, then we got major change in SST. So there is a correspondence between the fluxes at the surface and the sea surface temperature of the Bay.

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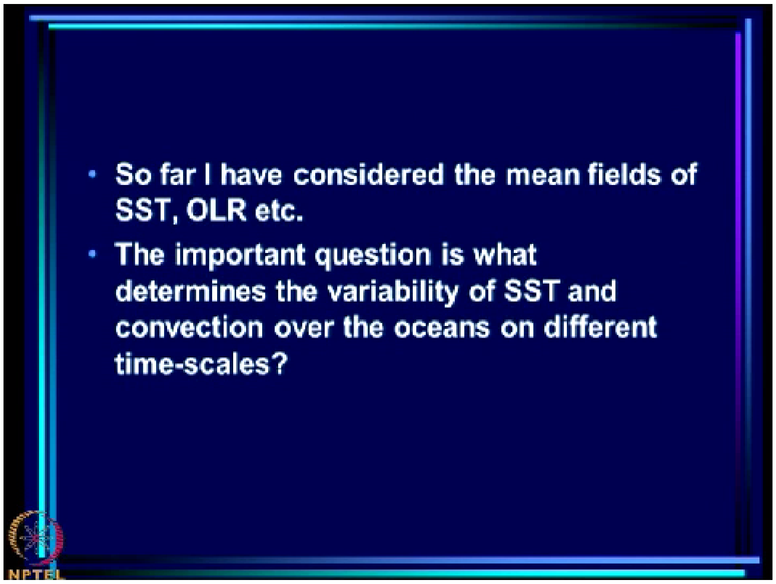

Now so far in this lecture, what we have looked at is the mean fields of SST, monthly means, seasonal pattern, heat budgets of monthly means and so on and so forth. So we have understood the mean patterns in terms of the relationship of convection to SST, what determines SST in terms of the heat budget and so on and so forth. But the important questions is, what determines the variability of this SST and hence of convection over oceans on different timescale.

Because it is the variability of convection which is linked to the variability of the monsoon. So we will start looking at that from the next lecture. Thank you.