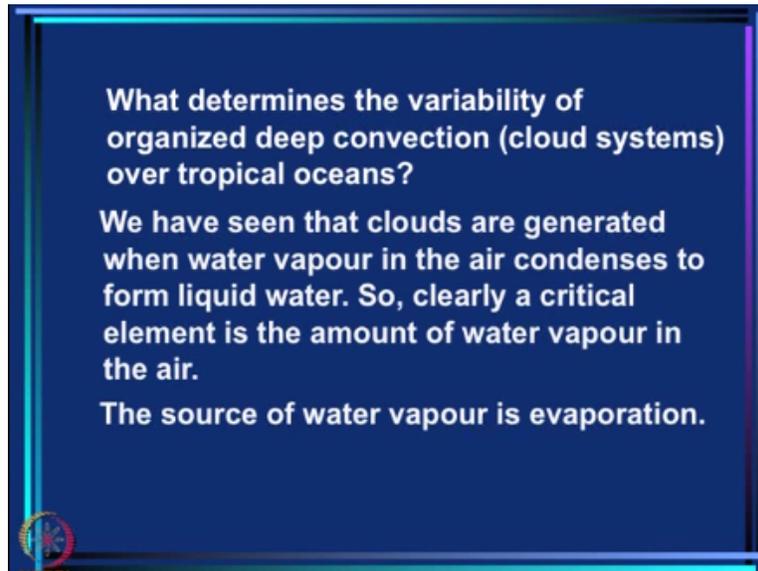


The Monsoon and Its Variability
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Lecture – 13
Variability of Organized Convection over the Tropical Oceans

We have seen that most of the cloud systems that give us rain over the Indian region are in fact born over the surrounding oceans. So, we already see that most of the cloud systems that give rain over land are actually born over the oceans around us; Arabian Sea, Bay of Bengal, Equatorial Indian Ocean. So, naturally the availability of monsoon rainfall is linked to the variability of the cloud systems or the organised convection or rainfall over the tropical oceans.

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So, it is very important to understand what determines the variability of organised deep convection that is cloud systems over tropical oceans. Now, we have seen that clouds are generated when water vapour in the air condenses to form liquid water. So, clearly a critical element is the amount of water vapour in the air. The source of water vapour as we all know is evaporation from the oceans.

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Evaporation from a liquid/water

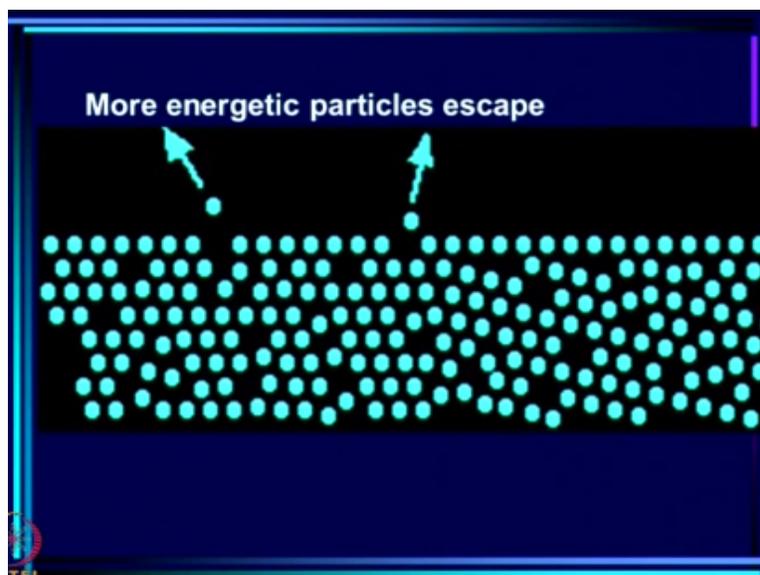
- The average energy of the particles in a liquid is governed by the temperature. The higher the temperature, the higher the average energy. But within that average, some particles have energies higher than the average, and others have energies lower than the average.
- Some of the more energetic particles on the surface of the liquid can be moving fast enough to escape from the attractive forces holding the liquid together. They evaporate and occur in gaseous form in the air above.



Now, let us consider evaporation from a liquid or water specifically. The average energy of the particles in a liquid is governed by the temperature, the higher the temperature higher the average energy. But within that average some particles have energies higher than the average and others have energies lower than the average.

Some of the more energetic particles on the surface of the liquid can be moving fast enough to escape from the attractive forces holding the liquid together. They evaporate and occur in gaseous form in the air above.

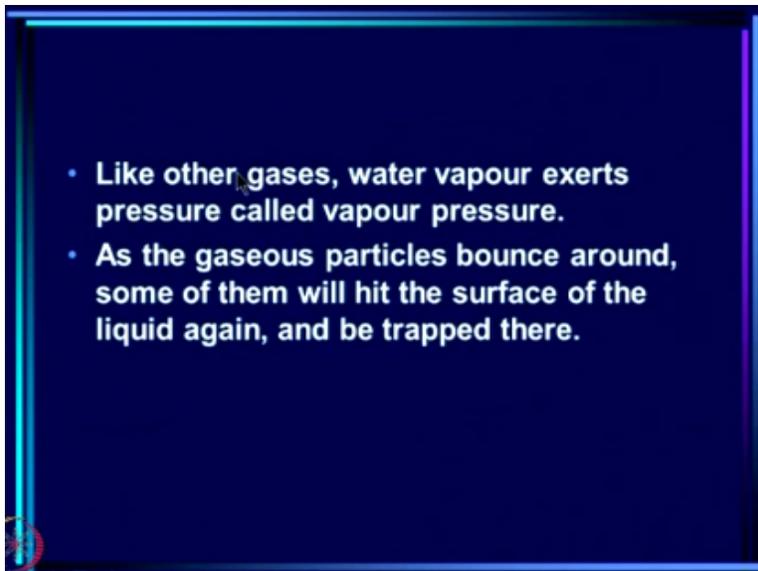
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So, this is the water vapour that we see. So, we have all these particles of water here and some of

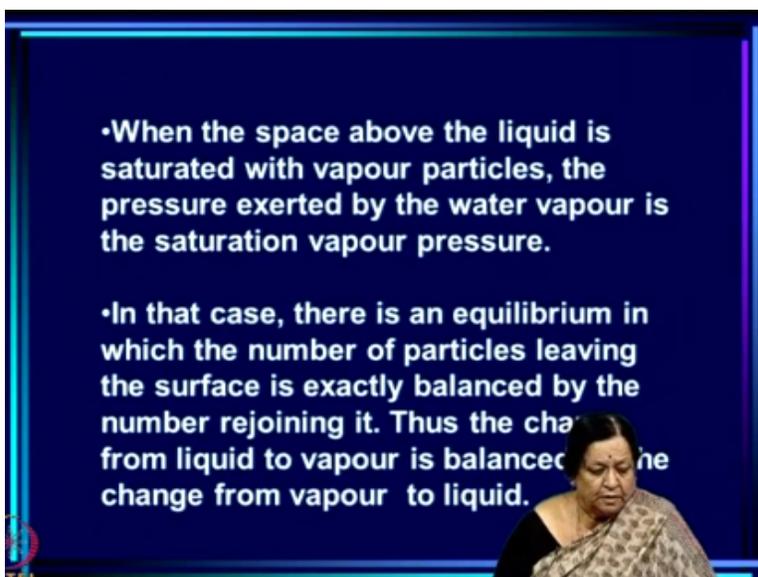
the energetic ones as you can see are escaping from the water surface and evaporating into the air above and this is what constitutes the vapour.

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Now, like other gaseous, water vapour also exerts pressure and this is called vapour pressure. As the gaseous particles bounce around, some of them will hit the surface of the liquid again and be trapped there. So, you know you have all these particles moving around in liquid and in air above and as the gaseous particles in the air bounce around, some of them will hit the liquid surface and get trapped there, okay.

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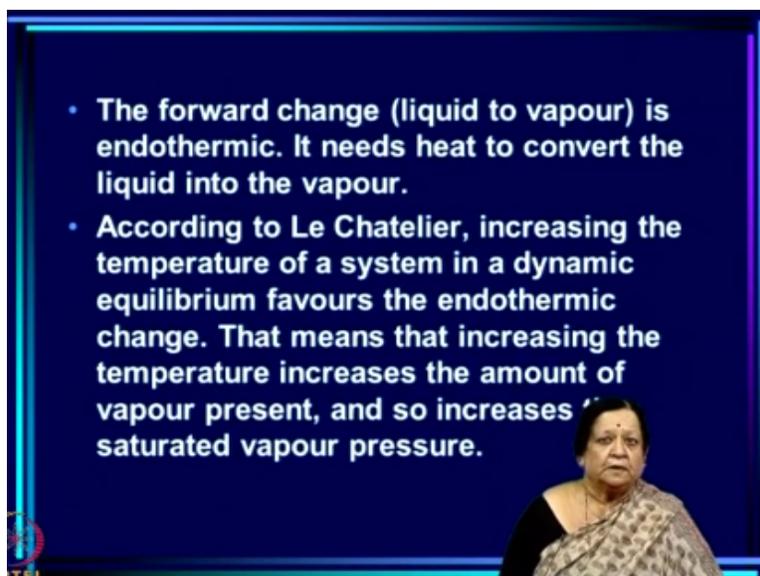


So, when the space above the liquid is saturated with vapour particles, the pressure exerted by

the water vapour is the saturation vapour pressure. So, when the space above the water surface is saturated with vapour particles, the pressure exerted by the water vapour is called the saturation vapour pressure. In this case, that is to say when the air above is saturated with water vapour, there is an equilibrium in which the number particles leaving the surface are exactly balanced by the numbers rejoining it.

So, you have a water surface here and the number of particles leaving the water surface is exactly equal to the numbers rejoining it, so there is an equilibrium maintained and thus the change from liquid to vapour is balanced exactly by the change from vapour to liquid.

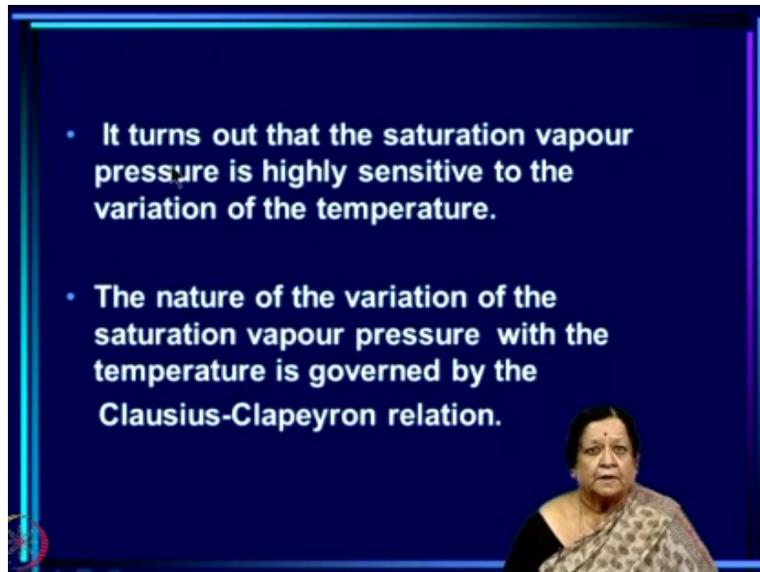
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- The forward change (liquid to vapour) is endothermic. It needs heat to convert the liquid into the vapour.
- According to Le Chatelier, increasing the temperature of a system in a dynamic equilibrium favours the endothermic change. That means that increasing the temperature increases the amount of vapour present, and so increases the saturated vapour pressure.

Now, the forward change which is liquid to vapour is endothermic. It needs heat to convert liquid into vapour. Now, according to Le Chatelier, increasing the temperature of a system in a dynamic equilibrium favours the endothermic change, that means that increasing the temperature increases the amount of vapour present and so increases the saturated vapour pressure, okay. As you increase the temperature, the particles in the liquid have more energy, more can escape and the equilibrium shifts to a larger amount of water vapour in the air.

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So, it turns out that the saturation vapour pressure is highly sensitive to the variation of the temperature. It is a non-linear function of the temperature as we will see. Now, the nature of the variation of the saturation vapour pressure with the temperature is governed by the Clausius-Clapeyron relation.

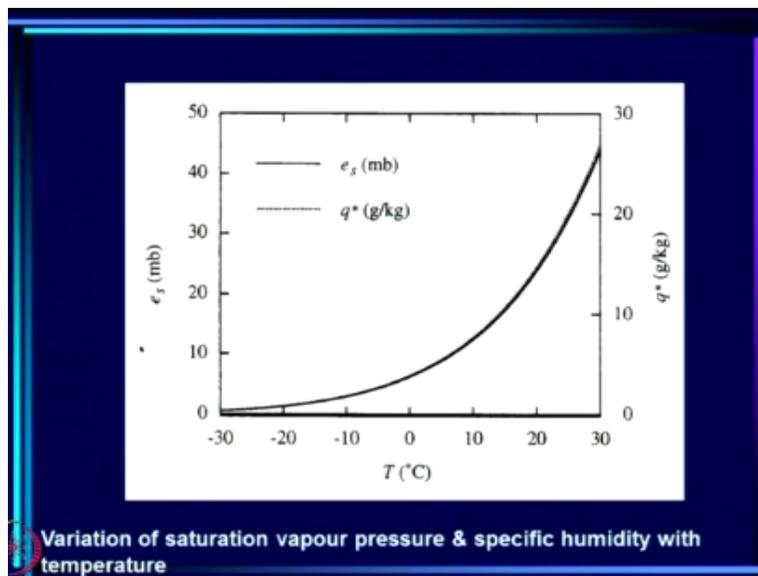
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I will just briefly mention what it is. It says de_s/dT , that is to say the variation of e_s is the saturation vapour pressure above a liquid surface, L is the latent heat of vaporisation, T is the temperature. So, this is saying what is the slope of the saturation pressure curve versus temperature, okay and that slope is $= L/T$, T is the temperature and α represents the specific volume of the vapour α_V and α_L is of the liquid.

So, alpha is a specific volume, alpha V is of the vapour, alpha L of the liquid. Now, this is the equation Clausius-Clapeyron relation that governs the rate of change of saturation vapour pressure with temperature and you can see that it is inversely proportional to the temperature. Now, this is what makes it highly non-linear. For terrestrial conditions, 1% change in temperature say about 3 degrees centigrade of Kelvin implies a 20% change in the saturation vapour pressure.

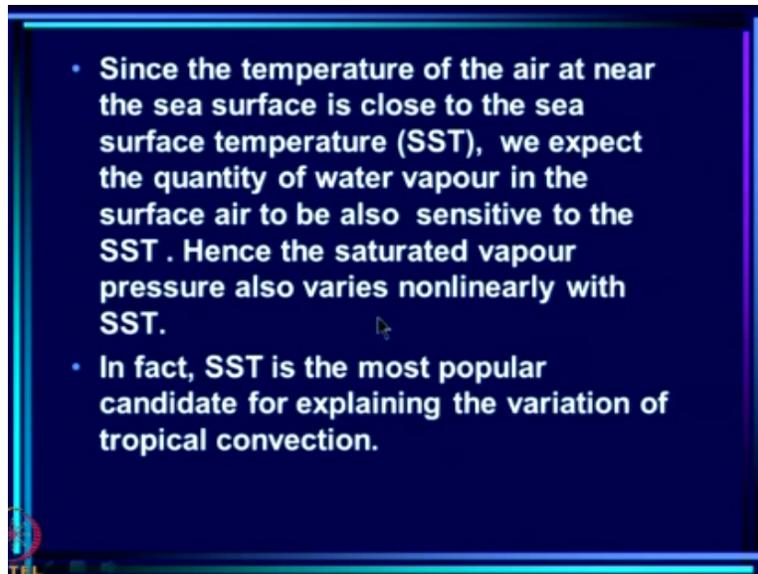
So, this is what I meant when I said that the saturation vapour pressure is a highly sensitive function of temperature. Now, the fractional change in the specific humidity at saturation which is q^* . Remember specific humidity is the mass of water vapour per unit volume. So, it is related to the fractional change of temperature by $\Delta q^*/q^*$ again proportional to $\Delta T/T$.

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Now, this is a plot of how the saturation vapour pressure which is on the Y axis varies with temperature and you can see that it is a highly nonlinear curve, this is the temperature in degrees centigrade and this is the specific humidity, okay gram per unit of air. So, this is how the specific humidity varies and you can see that around 20 degrees or so or 25 degrees it is a very, very rapid increase in saturation vapour pressure with temperature.

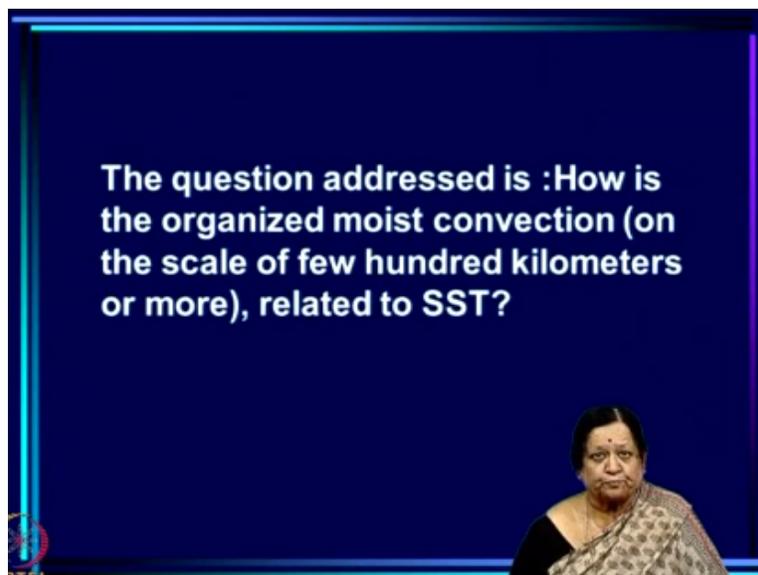
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Now, so far we have been talking about the temperature of air. Since the temperature of air at or near the sea surface is close to the sea surface temperature (SST), we expect the quantity of water vapour in the surface air to be also sensitive to the SST, right. Hence, the saturated vapour pressure also varies non-linearly with SST and in fact the sea surface temperature or SST is the most popular candidate for explaining the variation of tropical convection.

So, it is widely believed that a critical parameter which determines the variation of tropical convection over tropical oceans is the sea surface temperature (SST).

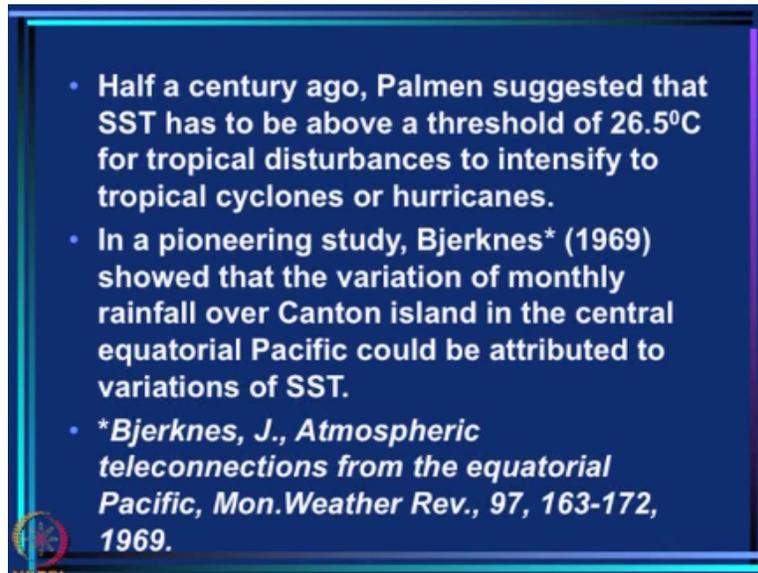
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Now, the question that is to be addressed is how is the organised moist convection on the scale of

a few 100 kilometers or more related to SST. So, this is what we will look at in this lecture.

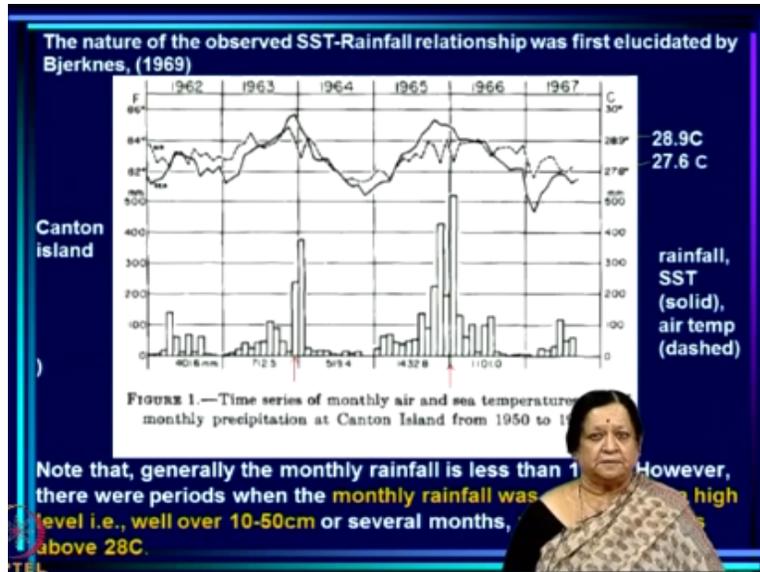
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Now, this also has a long history. Half a century ago, Palmen suggested that SST has to be above a threshold of 26.5 degrees centigrade for tropical disturbances to intensify to tropical cyclones or hurricanes. So, this is something that Palmen suggested from observations that unless the SST is about 26.5, the tropical disturbances that you get over tropical oceans will not intensify to hurricanes.

Next, came up pioneering study by Bjerknes in 1969 which showed that the variation of monthly rainfall over Canton Island in the central equatorial Pacific could actually be attributed to variations in SST.

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This is a picture from his classic paper and what you see here is the rainfall is given here below. This is the rainfall and you can see these are the units of rainfall and this sea surface temperature is in solid and air temperature region is in dash. So, let us focus on the sea surface temperature. Note, that generally the monthly rainfall is < 10 cm, okay. So, this is rainfall in millimeters.

Generally, the rainfall is < this 10 cm or so, okay but every now and then you get this high rainfall events or episodes which last for several months, 2 months here but several months here, okay and these are invariably associated with SST up a threshold of about 27.8 or 28, okay, somewhere around 28. So, if the solid line is about that, then you get these peaks in rainfall, okay.

When it is below that, what you get is these very, very small peaks and rainfall generally not exceeding 10 cm. So, this was for 1950 to 1967. So, that generally monthly rainfall is < 10 cm; however, there were periods when the monthly rainfall was sustained at a high-level, i.e., well over 10 cm to 50 cm for several months when the SST was about 28 degrees. This is shown by Bjerknes.

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- Systematic investigation of the variation of convection and its relationship with SST became possible only after the availability of satellite data.
- In the first such study, the relationship between monthly cloudiness intensity (determined from cloudiness index derived from satellite images) over the equatorial Indian Ocean, Bay of Bengal and Arabian Sea and the SST was investigated (Gadgil *et al.*,1984).

Now, actually the problem was how does one assess rainfall over the oceans or convection over the oceans. Systematic investigation of the variation of convection and its relationships with the SST became possible only after the availability of satellite data because through this eye in the sky one could actually see the cloud systems on a day-to-day basis. This is why systematic investigation of the relationship of convection with SST became possible when satellites were available.

In the first such study, the relationship between monthly cloudiness intensity determined from cloudiness index derived from satellite imagery over the equatorial Indian Ocean, Bay of Bengal and Arabian Sea and SST was investigated.

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Relationship of cloudiness intensity and SST

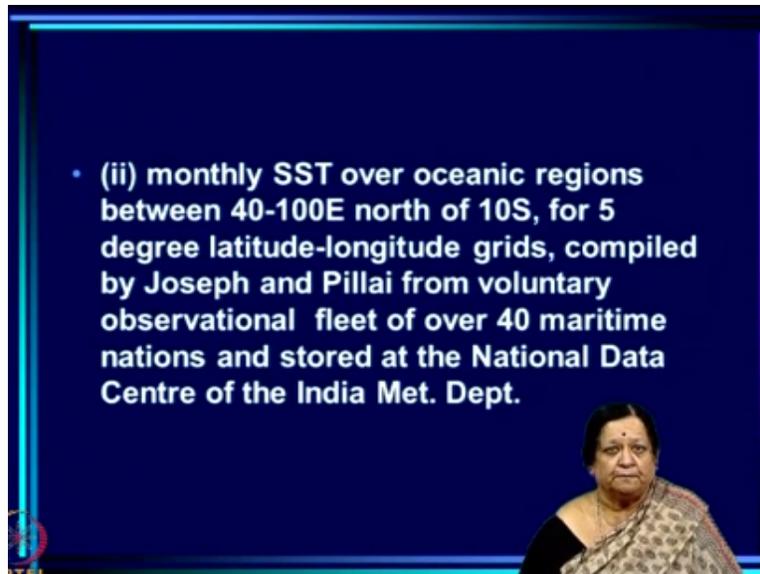
- The following data for 1966-72 were analyzed by Gadgil et. al .
- (i) daily values of a cloudiness index (ranging from 1 to 9) each 2.5 degree squares over the tropics based on operational nephanalysis prepared by NESS, NOAA and compiled by Sadler and associates, and henceforth called Sadler index



So, this was the first study of SST convection relationship and this was done by Gadgil et. al. and what we did and the data used were the following. First is daily value of a cloudiness index ranging from 1 to 9 at each 2.5 degrees squares over the tropics based on operational nephanalysis prepared by NESS and NOAA and compiled by Sadler and Associates. So, these were the basic data that was used and this is what we call the Sadler data and this was in fact nephanalysis, as you know, subjective assessment of satellite imagery.

So, subjective assessment of satellite imagery gave rise to these values of cloudiness index again which were prepared by Sadler and others. The basic satellite imagery and basic nephanalysis was provided by NESS and NOAA. So, this was the basic dataset. It is important to remember that at the time of the study, digital data from satellite like outgoing longwave radiation, etc. were not available. So, the best digital data we could get was actually these values of cloudiness index derived from an assessment of satellite imagery.

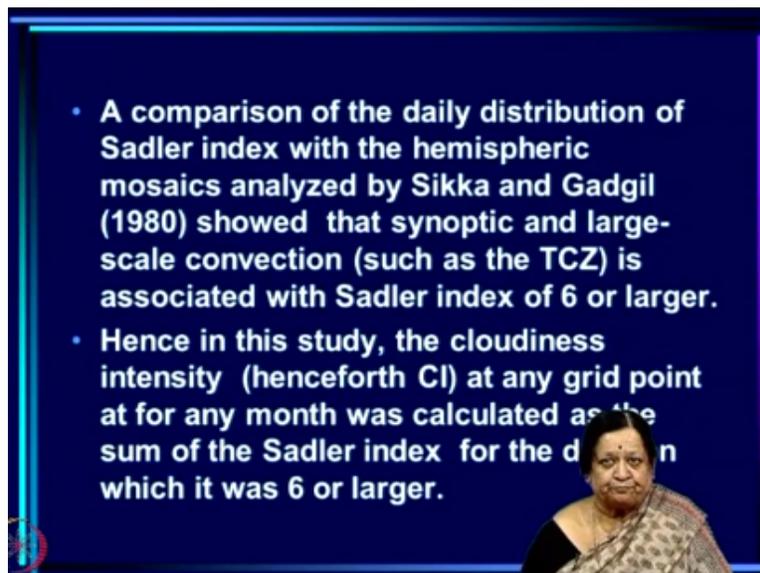
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Monthly SST over oceanic regions were available and this is because one of the co-authors of the study was in India Met. Department, PV Joseph and he had actually compiled, he and Pillai had compiled SST data for 5-degree latitude-longitude grids from 40 degrees to 100 each, i.e., entire Indian Ocean, north of then south, okay and these data were available.

And they were originally collected from voluntary observational fleet of over 40 maritime nations and stored at the National Data Centre of the India Met. Department and Joseph was working at that time in the India Met. department and he and Pillai had actually generated dataset of monthly SST using these voluntary observational fleet data that was with IMD.

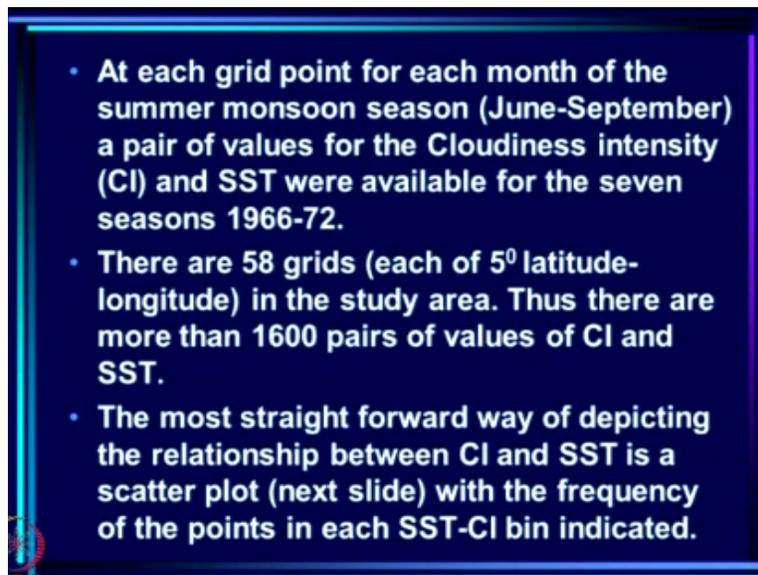
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Now, a comparison of the daily distribution of the Sadler index with the hemispheric mosaics analyzed by Sikka and Gadgil and we have seen a lot of those in the last lecture showed that synoptic and large-scale convection such as the TCZ (tropical convergence zone) is associated with Sadler index of 6 or larger. So, we subjectively decided by comparison with satellite imagery that Sadler index for cloudiness of 6 or larger implied deep organised clouds.

Hence in this study, the cloudiness intensity (henceforth CI) at any grid point for any month was calculated as the sum of the Sadler index for days on which it was 6 or larger. So, at every grid point you will have some value of cloudiness index and if there are absolutely no clouds, it will be 0. Otherwise, it will range from 1 to 9, so at every grid point for every month what we did is calculate the number of days on which CI (cloudiness index) was 6 or larger.

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- At each grid point for each month of the summer monsoon season (June-September) a pair of values for the Cloudiness intensity (CI) and SST were available for the seven seasons 1966-72.
 - There are 58 grids (each of 5^o latitude-longitude) in the study area. Thus there are more than 1600 pairs of values of CI and SST.
 - The most straight forward way of depicting the relationship between CI and SST is a scatter plot (next slide) with the frequency of the points in each SST-CI bin indicated.

Now, at each grid point for each month of the summer monsoon season, we therefore had a pair of values; one was the cloudiness intensity which is now available on monthly scale and SST available from 7 seasons of. Let me just mention that it is important to remember that cloudiness index is not simply the number of days on which the Sadler index was 6 or larger.

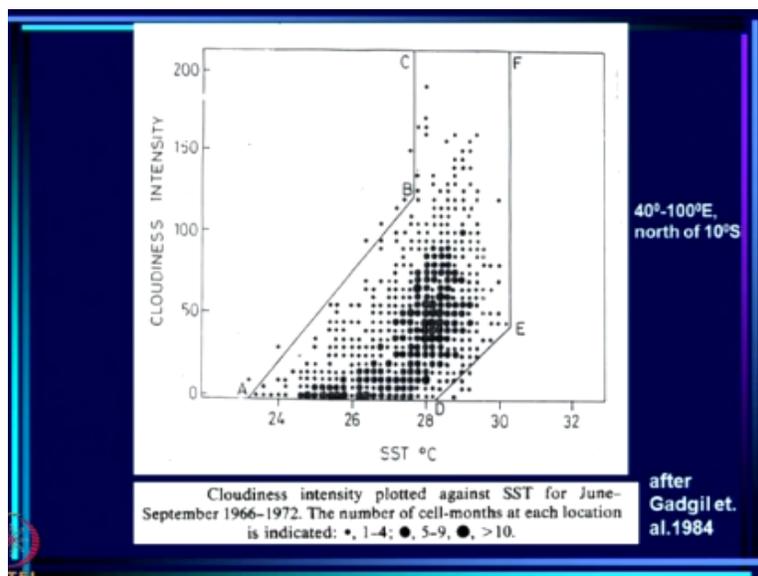
Rather, it is the sum of the Sadler index for the number of days on which it was 6 or larger safe. So, if on some days it was 7, 8 or 9, that day was counted as more than one value, right. So, one day it would be 9, one day it would be 6 and you would sum over all these days for which the

index was 6 or larger. So, there was a measure of also intensity involved in this, okay. So, at each grid point, then we had values for the cloudiness intensity (CI) and SST and they were available for the 7 seasons of 1966 and 1972.

Now, there are 50 grid points each 5-degree latitude/5-degree longitude in the study area. Thus, there are more than 1600 pairs of values of CI and SST, okay. Now, remember that the original Sadler data was a higher resolution than the SST data, so we had to make it coarser. We had to average over the SST grids to get the cloudiness intensity. So, we had several values, more than 1600 pairs of values of cloudiness index and co-located SST.

Cloudiness index of the clouds above a grid point and the SST of that same grid point. Now, we are interested in deriving the relationship between cloudiness index and SST and we have these 1600 pairs of values. So, the most straightforward way of depicting the relationship between CI and SST is a scatter plot with the frequency of the points in each SST-CI bin indicated.

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So, what you see here is a scatter plot. This is the cloudiness intensity. This is SST and we have bins of SST here and each bin of SST and cloudiness index, you either see a blank or you see a dot and the size of dot tells you that how many points there are, okay and in fact that is indicated here, 1 to 4 is the smallest dot, 5 to 9 is bigger and > 10 is the biggest, okay. So, most of the points are where the big dots are in this, okay.

So, this is a very nice way to look at a relationship between 2 variables. It is a scatter plot and it has an information of the total region and the total number of months you have, what is the relationship between cloudiness and SST.

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- The most remarkable feature of this distribution is the restriction of the points to the right of the lines AB and BC. A given level of CI occurs only if the SST is above a specific value, which is clearly a necessary condition for organized convection.
- For SST below 28°C , there is a well defined value for the maximum CI, which increases linearly with SST, whereas above 28°C it seems to become independent of SST.
- Up to about 28°C , the minimum CI is zero (i.e. Sadler index < 6 every day of the month, but above 28°C it increases linearly with SST.

The most remarkable feature of this distribution is the restriction of the points to the right of the lines of AB and BC. Now, you see here, first of all you see that all the cloudiness points are to the right of this curve here, okay. So, that is to say to the left of these 2 lines there are hardly any points at all. So, given SST, you have a restriction. See below, there is absolutely no cloudiness. Then, given an SST of 24, the cloudiness intensity is rather small restricted to < 10 .

Given an SST of 26 also, it is restricted to 50 and so with this line you see that the maximum cloudiness intensity associated with an SST is actually increasing. It is increasing from a very low value to something rather large or 100 by the time you come to about 28 degrees or 27.5 degrees. Interestingly, after this it can be anywhere. After this it does not really show any steady increase, rather it is just at a high level everywhere.

So, the maximum cloudiness intensity first increases with SST and then becomes flat. Now, look at the minimum cloudiness intensity. Interestingly, the minimum cloudiness intensity is 0 up to about 28. Beyond 28 degrees centigrade, the minimum starts to increase, okay until it comes to

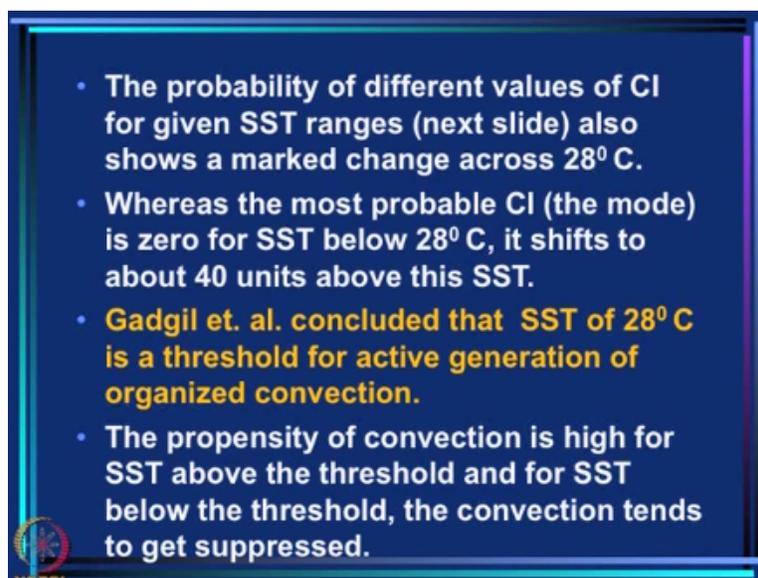
about this point and this is the point. After that, there are no points at all with clouds.

So, this is very, very interesting pattern. So, what have we seen, the most remarkable feature of this distribution is a restriction of the points to the right of the lines AB and BC. A given of CI occurs only if the SST above a specific value which is clearly a necessary condition for organized convection. For SST below 28, there is a well-defined value for the maximum CI which increases linearly with SST, whereas above 28, it seems to become independent of SST, we have also seen this. Up to about 28, the minimum CI is 0. So, let us go back and see that.

We have already seen that up to about 28, the minimum CI is 0. Above that, it increases with SST. About SST being a necessary condition is here, that unless SST is above 26, you will not get intensities of the level of hundred. See this is what one means by SST being above a specific value for a given level of CI to occur. So, it is a necessary condition for organised convection. These are very, very interesting features that we have seen how up to the threshold, maximum CI depends on SST.

Below the threshold, the minimum is independent of SST. Above, the threshold the minimum starts increasing with SST but above the threshold the maximum becomes independent of SST, okay.

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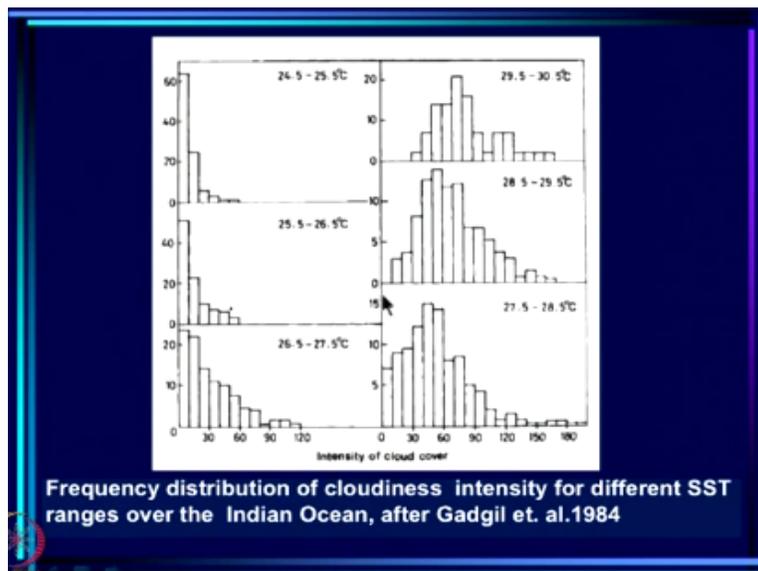


- The probability of different values of CI for given SST ranges (next slide) also shows a marked change across 28⁰ C.
- Whereas the most probable CI (the mode) is zero for SST below 28⁰ C, it shifts to about 40 units above this SST.
- **Gadgil et. al. concluded that SST of 28⁰ C is a threshold for active generation of organized convection.**
- The propensity of convection is high for SST above the threshold and for SST below the threshold, the convection tends to get suppressed.

Now, another way of looking at this variation is what is the probability of different values of CI for given SST ranges. Now, if we go back to this graph, suppose we specify an SST range somewhere here, then you can say that largest number of points are at 0, right. So, maximum number of points are at 0 and then slowly you will have some number of points as you go higher and higher CI.

Now, here if you see the probabilities at 28 then the maximum number of points seem to have some cloudiness intensity somewhere between 50 and 100 or so and so one can talk of probability of occurrence of different cloudiness intensity levels for a specific range of SST and that is what is plotted in the next diagram here.

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So, what we see here is we go from 24.5 to 25.5. So, these are 1 degree specified limits of SST and what you have seen here is frequency of cloudiness intensity is on the X axis, this is 0, this is 30, 60, 90 and so on, 120, okay. So, these are monthly values of cloudiness intensity and over very cold oceans you can see most likely that you will have no clouds at all. Then, possibility of having 10 CI becomes is little bit, maybe around 20 or so and so on and then higher becomes very, very small.

Same, pattern you see as you go to somewhat warmer seas, i.e., 25.5 to 26.5. But now you can say that the probability of getting high CI is a slightly more than it was earlier and again for

somewhat higher 26.5 to 27.5, you see actually that this mode has now become shorter, whereas 60% chance of 0 CI was there, now it is much more like a < 30% and probability of getting other values of CI has increased and you have got somewhat long tail here, okay.

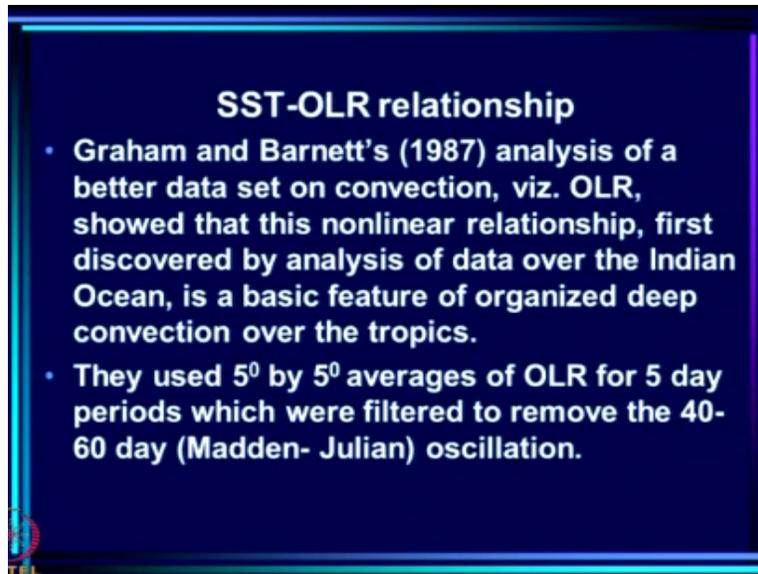
Then, as you cross 27.5 and go to 27.5 to 28.5, there is a remarkable change in pattern. Note is that all along here the mode or the most likely CI was at 0. Now, suddenly the mode of the distribution are where the peak is or the most likely CI has shifted from 0 to somewhere around 30 between 30 and 60 and that is how it remains for SST beyond this.

So, there is indeed a very remarkable change across this 27.5 here in which the likelihood of 0 cloudiness is much less than the likelihood of substantive cloudiness between 30 and 60 above the threshold whereas likelihood of zero cloudiness is the maximum likelihood below the threshold. So, you see across 27.5 which I kept calling the threshold. In fact 27.5 turns out to be a threshold. Below the threshold, the distribution is like this, above the threshold, the mode has shifted.

If we go back to the scatter plot, there also we have seen 28 as a limit. We could see that below 28, you had a certain kind of distribution where you had actually the maximum CI determined by SST and above 28 there is a huge spread of CI given any kind of specific SST range. So, we said the propensity of convection is very high above the threshold of about 28 or 27.5 and below the threshold the propensity of convection is low and the mode shifts across the threshold from 0, here you can see the mode at 0 to some substantive cloudiness intensity once you cross the threshold.

So, this is what we have seen now. So, the probability of different values of CI for a given SST ranges which we saw also shows a marked can change across 28. So, whereas the most probable CI, that is the mode 0 for SST below 28 it shifts to about 40 units about this SST. So, Gadgil et. al. concluded that SST of 28 degrees so is a threshold for active generation of organised convection. The propensity of convection is high for SST above the threshold and for SST below the threshold, convection tends to get suppressed, okay.

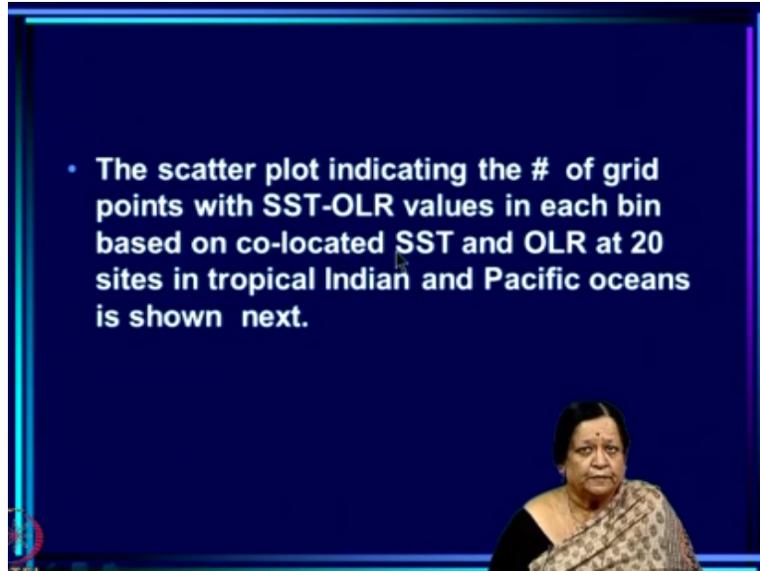
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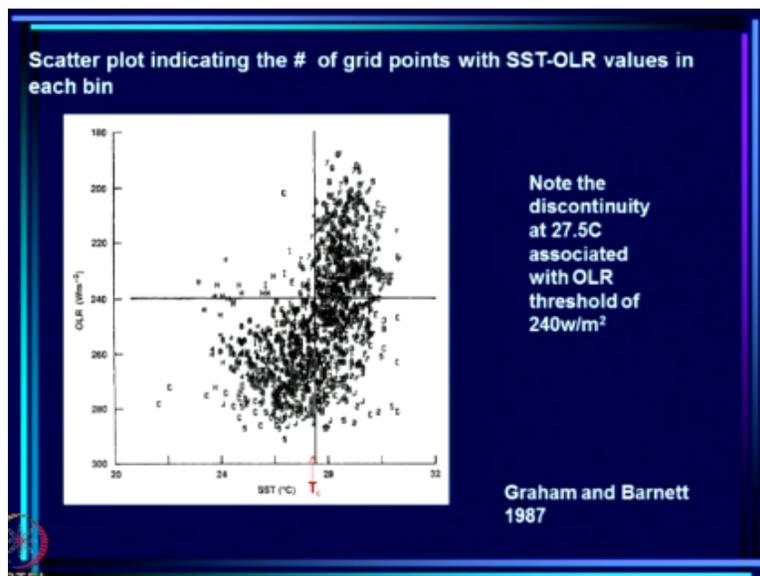
So, far we have been talking of studies using cloudiness intensity, but now this paper was published in 1984 in Nature. Subsequent to this, digitised data on outgoing longwave radiation or OLR became available and Graham and Barnett revisited the same problem, what is the relationship between SST and convection using actually OLR (outgoing longwave radiation) as a measure of convection and using this much better digital dataset.

In fact, they found that the relationship that was discovered using cloudiness intensity actually remains the same even if you use these better datasets. So, what did Graham and Barnett use. They used 5-degree/5-degree average of OLR for 5-day periods and they filtered the 40- to 60-day Madden-Julian oscillation from these data but we will say later on just by using raw OLR data, it makes no difference to the result, okay.

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Now, the scatter plot indicating the number of grid points with SST-OLR values in each bin based co-located SST and OLR at 20 sites in the tropical Indian and Pacific Ocean is shown here. (Refer Slide Time: 28:17)



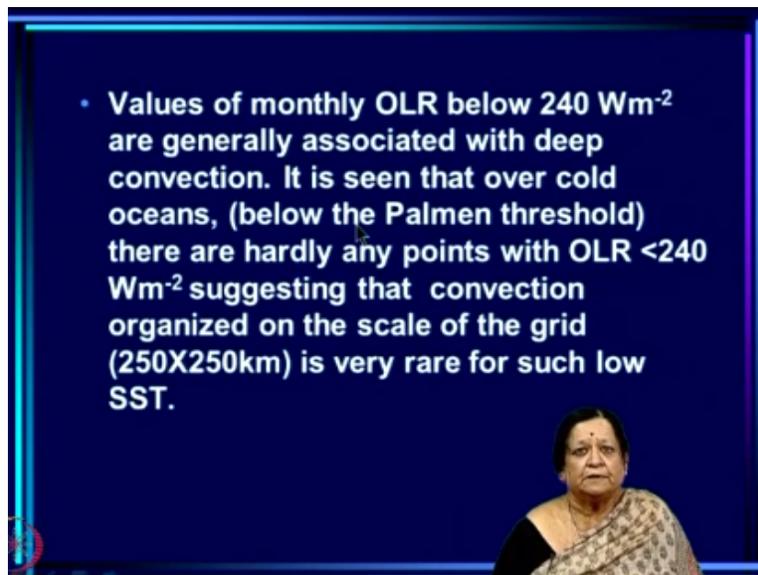
This is from Graham and Barnett. You see, the features are very similar to what we had seen here. This is the threshold that they get. They get around 27.5 and what you see is that for SST now this is OLR. You must remember that low values for OLR corresponds to high cloud tops and therefore more convection. So, this OLR axis is shown in a reverse way. Maximum OLR 300 is here and minimum is up there and 240 watts per meter square is considered as a limit.

So, for monthly scales, OLR should be below 240 for the clouds to be considered sufficiently

deep to represent deep convection. So, below 240 is what we have to look at and these are the clouds here you see and propensity of these deep clouds becomes higher once that threshold is crossed. Again in the same way, you know the minimum convection that increases with SST here beyond the threshold and maximum convection increases with SST before the threshold.

Above the threshold you can see that there is a very large variation of OLR given the SST. So, there is hardly any relationship between SST and convection once that threshold is crossed. So, all these features were what we had seen earlier with cloudiness index.

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So, values of monthly OLR below 240 are generally associated with deep convection. It is seen that over cold oceans that is below the Palmen threshold, there are hardly any points with OLR < 240 watts per meter square suggesting that convection organised on the scale of 250/250 is very rare for a such low SST.

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- As for CI, when SST increases beyond the threshold, the maximum OLR decreases with SST.
- The value of OLR with maximum chance of occurrence, i.e. the mode, shifts towards lower values of OLR as SST increases but remains higher than 240 Wm^{-2} for $\text{SST} < 27.5^\circ \text{ C}$.



Now, as for CI as I mentioned this when SST increases beyond the threshold, maximum OLR decreases with SST, i.e., to say the minimum convection increases with SST. The value of OLR with maximum chance of occurrence that is the mode shift towards lower values of OLR as SST increases but remains higher than are 240 watts per meter square, that is to say SST below the threshold.

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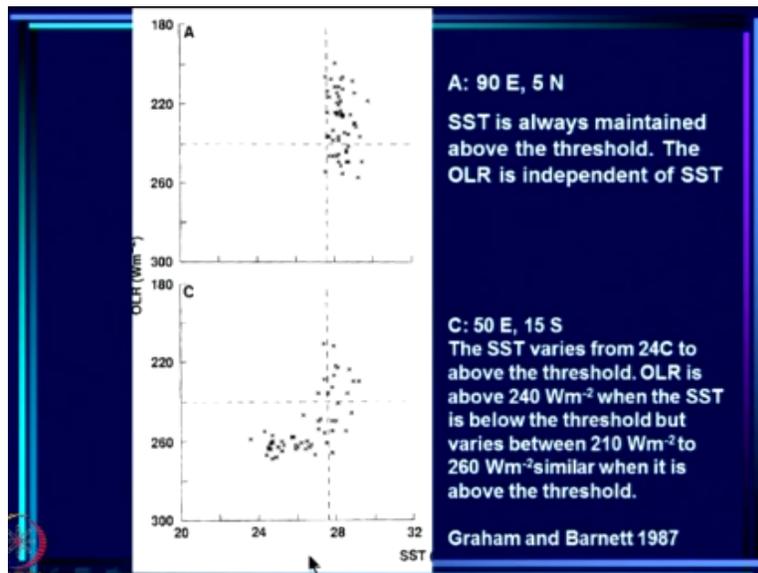
- If the SST at an individual point is always above the threshold (A, in the next slide), the scatter plot shows a large variation of OLR for each SST; whereas if the SST variation is across the threshold (B, in next slide) the scatter plot is a mini version of that for the larger tropical oceanic region.



Now, in addition to pulling all the points together as we saw Graham and Barnett actually present data also for individual points and they select 2 points, one is A. At the point A and I will mention where it is located. The SST at that individual point is always above the threshold and what do we expect in that case that there will be no relationship between convection and SST,

whereas if the SST variation is across the threshold, i.e., to say at point B.

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Again I will just show the plot, then the scatter plot we get is a mini version of what we had seen earlier. So, A is the Bay of Bengal, 90 degrees east and 5 degrees north, SST is always maintained above the threshold and the OLR is independent of SST. So, you are always in this part of the scatter plot. On the other hand, if we look at 50 East and 15 South, then we have an SST variation going all the way from almost 24 to beyond 28 and what you see is that no convection below 28 and above 28 convection has become independent of SST.

So, SST varies from 24 to above the threshold, OLR is above 240 when SST is below the threshold but varies between 210 to 260 watts per meter square similar when it is above the threshold. So, this is very similar. This is like a mini version of the scatter plot you had seen earlier which was here. So, what you get in the case of that point B is just this part here but a mini version of the entire one, okay.

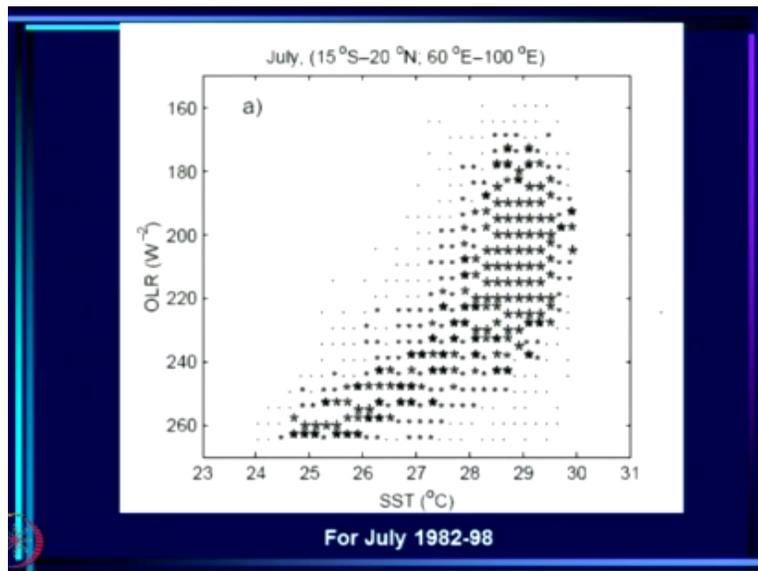
So, these relationships hold not only when you consider a large region together where space-time variation is mixed up but also where you consider the temporal variation at fixed points in space, okay.

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- Major results:
- 1. high propensity for organized convection over warm oceans with SST above about 27.5 or 28^o C, called the threshold, T_c.
- 2. When the SST is above T_c, the cloudiness intensity/OLR varies over a large range from almost no convection to intense deep convection.
- The scatter plot for co-located SST-OLR over the Indian Ocean based on July data is rather similar (next slide).

So, what are the major results now from cloudiness intensity and OLR relationship to SST. High propensity for organised convection over warm oceans with SST above about 27.5 or 28 degrees centigrade called the threshold. Second is when the SST is above the threshold, the cloudiness intensity or OLR varies over a large range from almost no convection to intense deep convection. The scatter plot for co-located SST and OLR over the Indian Ocean based on July data is also rather similar.

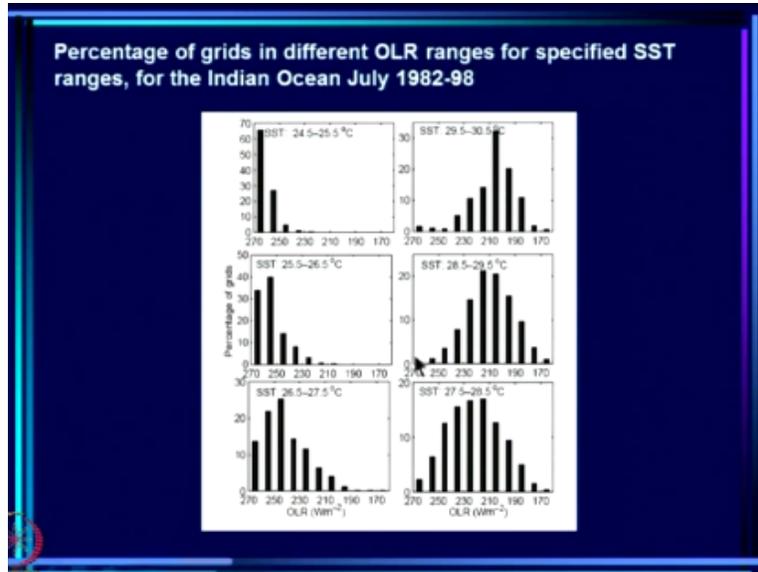
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So, one does not have to do the filtering that they did of 40- to 60-day mode and what you see here is for the Indian Ocean 15 South to 20 North 60-degree East to 100-degree East, again the size and intensity of the stars show how many points there are and what you see is exactly the

same shape and you know these total enormous scatter ones you cross above 28 or 27.5. So, this is similar.

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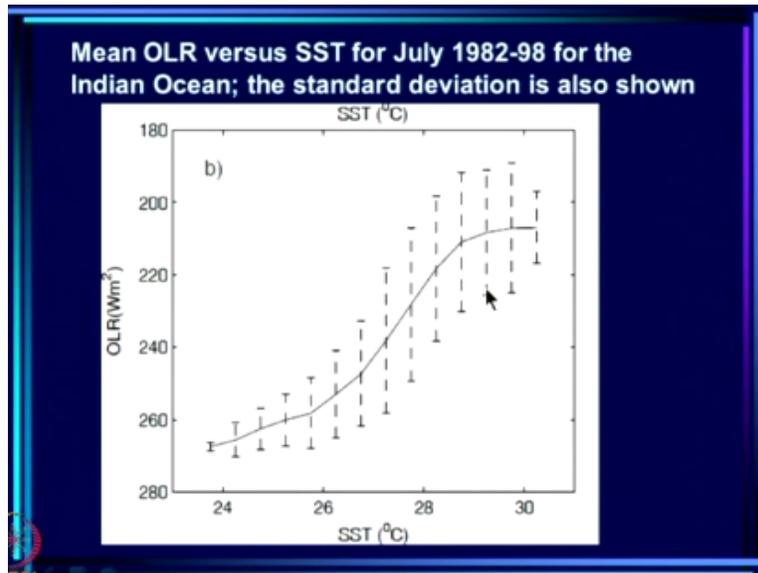
Again, one sees percentage of grids in different OLR ranges for specified SST. Again same story you see that SST is 24.5, again it has now increased to 25.5 and this is 26.5, 27.5 and so on and so forth. Now, here the only difference is that mode has shifted a little bit even before the threshold.

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- Consider next the variation with SST of the mean OLR and the standard deviation of OLR for each SST for July for the Indian Ocean (next slide).
- It is seen that the mean OLR decreases rapidly from about 26C to about 29C and remains more or less constant for higher SSTs.
- The standard deviation is large for SST higher than about 27.5 C.

Now, consider next the variation with SST of the mean OLR and the standard deviation of OLR for each SST for July for the Indian Ocean.

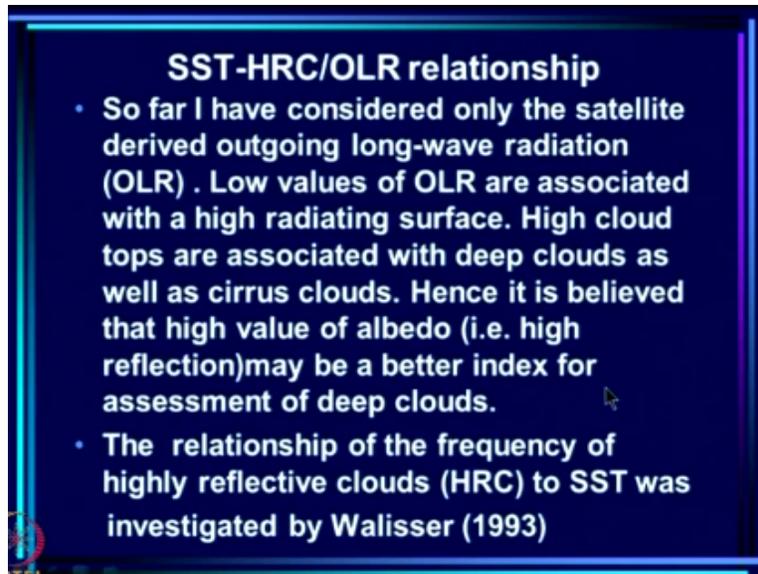
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So, here what we are saying is at each range of SST we derive the mean and also the standard deviation and what you see here is plotted variation of mean OLR versus SST and what you see is that there is a very sharp increase in mean OLR across the threshold, you see from about here maybe 27 to about 28.5 or so. There is a sharp increase in the mean and after that it remains flat and the standard deviation becomes very large from about 27.5 or so.

So, this is what we see. It is seen that the mean OLR decreases rapidly from over 26 to about 29 degrees centigrade and remains more or less constant for higher SST. The standard deviation is large for SST higher than about 27.5, okay.

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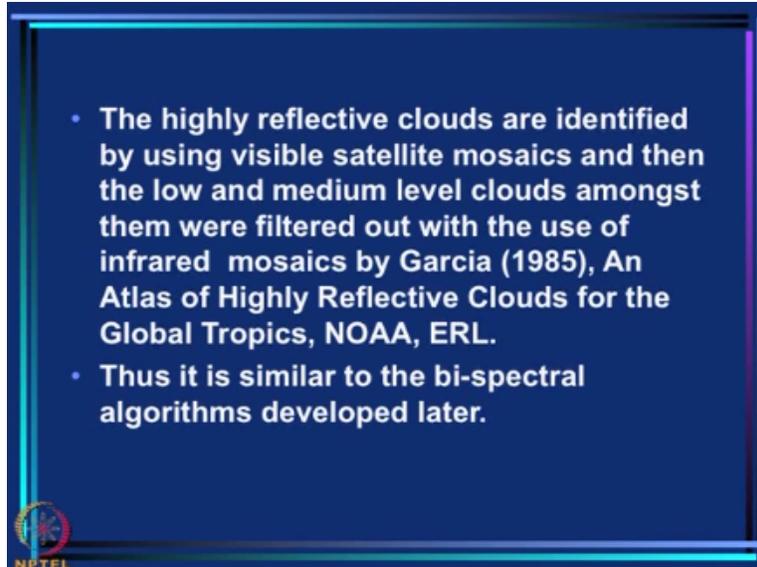


So, far we have seen that when we used OLR, the relationship is very similar. Now, Walisser actually used one more dataset which was so-called HRC dataset. Let me first of all explain to you what this is. See, so far I have considered only the satellite derived outgoing longwave radiation (OLR) and low values of OLR are associated with a high radiating surface, i.e., to say a high cloud top. A high cloud tops are associated with deep clouds as well as cirrus clouds, that the problem.

You can have thin clouds that you see on top, you know very near the top of our troposphere and those clouds are not deep convective clouds but the radiating surface is high. So, they will also have low values. Now, hence it is believed that high value of reflectivity is albedo, maybe a better index for assessment of deep clouds, okay. But actually one needs both albedo and OLR.

One has to make sure that a lot of light gets reflected from the cloud, i.e., to say it is deep and also that its top is high enough, so OLR also has to be low. The relationship of the frequency of highly reflective clouds that is to say HRC to SST was investigated by Walisser.

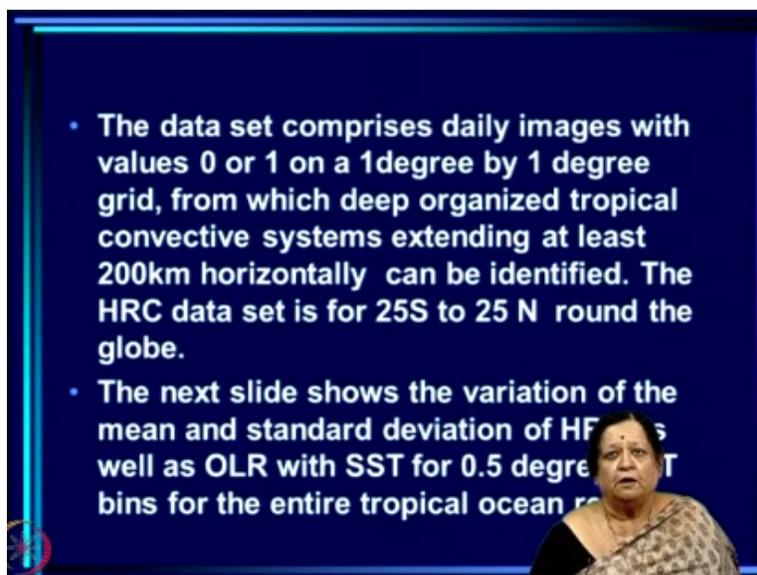
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Again this is all done by subjective analysis. Highly reflective clouds are identified by using visible satellite mosaics and then low and medium level clouds amongst them are filtered out with the use of infrared mosaics by Garcia. So, this is a way of using bi-spectral information, both visible and infrared. Visible to first filter out which are the regions with highly reflective clouds and then from that regions.

Those regions remove the clouds whose tops are not sufficiently high by using infrared which is what we use by OLR. So, this is similar to the bi-spectral algorithms used later.

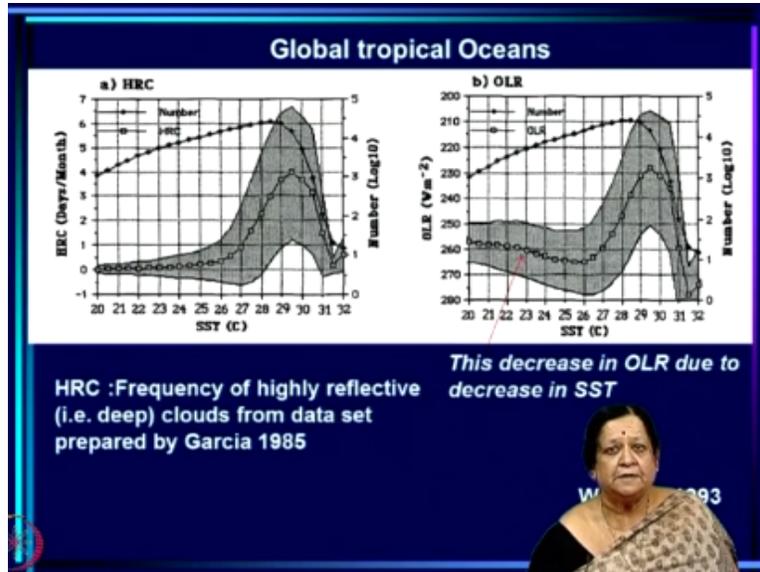
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So, these dataset comprises of values 0 or 1 on a 1 degree by 1 degree grid from which deep

organized tropical convective systems extending at least 200 km horizontally can be identified. The HRC dataset is for 25 South to 25 North around the globe.

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So, now using that dataset for the entire global tropical oceans what Walisser shows is the following. This is again the mean and this time it shows the standard deviation by shading. So, what you see here is just the number of points corresponding to each SST range and what you can see interestingly is that, beyond 29 the number of points with SST higher than 29 decreases very rapidly with SST. But now let us go to SST-HRC relationship.

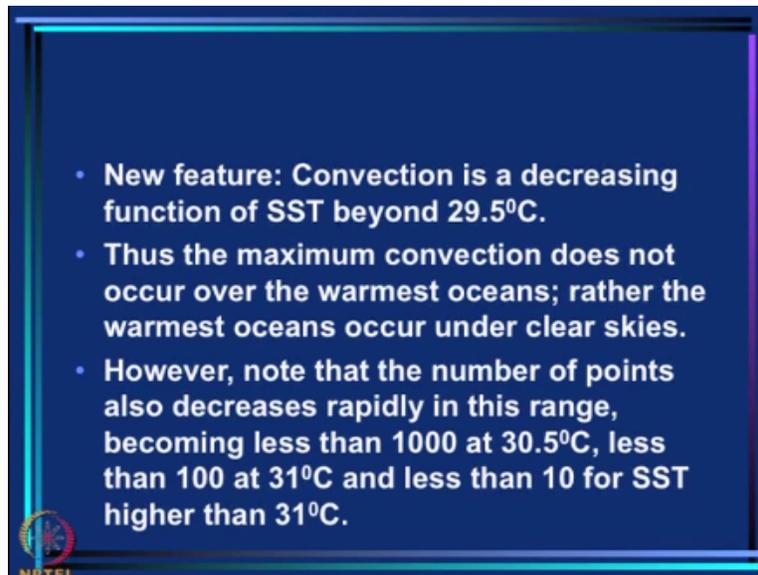
What you see is that the mean is very flat. Mean is almost 0, very close to 0 until a certain point about 26 which is the Palmen threshold. Then, the mean begins to increase up to 29 which is what we have seen in OLR as well and then it decreases. Now, this decrease is something that was first pointed out by Walisser. Although the decrease becomes a little less reliable because the sample of points also become much less than they were in the earlier part, but Walisser showed that the decrease was real.

When we compare with OLR mean, then this is the OLR mean for global tropical oceans and it appears that actually the convection is decreasing with SST as you go here but this is not due to convection decreasing. Rather, it is true that OLR is increasing as you go here and here. So, OLR is decreasing with SST here, right and that is simply because there are no clouds but the ocean

surface is cooler, so the OLR is less.

So, this decrease in OLR is due to decrease of the SST itself. It has nothing to do with clouds and when we look at HRC we see that below 26 or so actually there is no change in HRC, it is very, very close to 0. Now, above this the patterns are very, very similar. As you can see, there is an increase from about 26 to about 29 and a decrease after that.

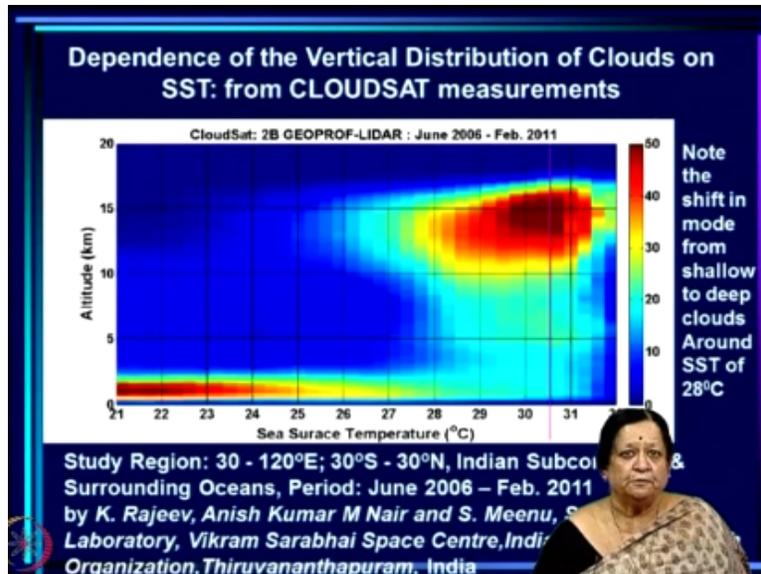
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So, the new feature that Walisser found was that convection is a decreasing function of SST beyond 29.5. Thus, the maximum SST does not occur over the warmest oceans. Rather the warmest oceans occur under clear skies. See, we are looking at SST convection relationship but always in the backup meteorologist mind is that somehow SST is the cause and convection is the effect but in fact what Walisser pointed out is true.

More SST means more water vapour which may increase the propensity of convection but the highest SST you get under cloud free skies because radiation directly goes to heat the topical ocean. So, this is an important point to remember.

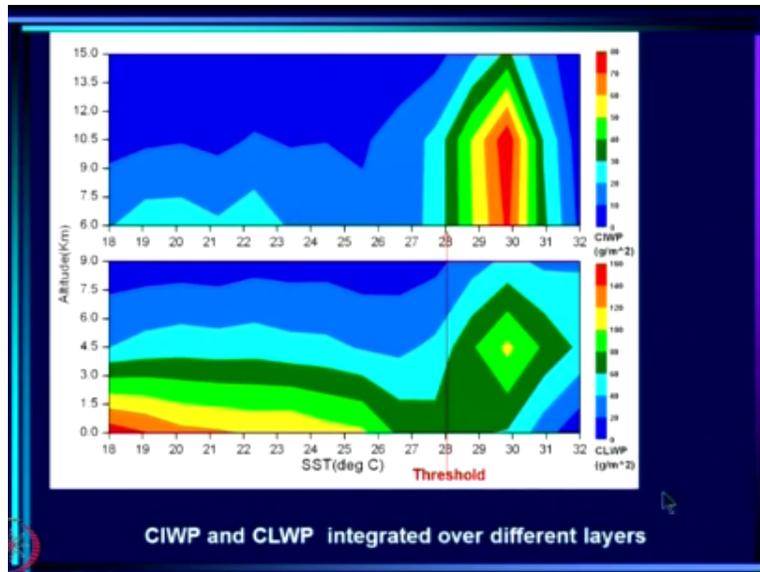
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Now, in fact it turns out that the basic relationship we have seen from the scatter plots of cloudiness intensity versus SST as well as from OLR versus SST, HRC versus SST, the same pattern is faithfully shown by all the later day and better assessments of clouds. So, there is a very special satellite called CloudSat from where you can get dependence on the vertical distribution of clouds on SST from clouds at measurement.

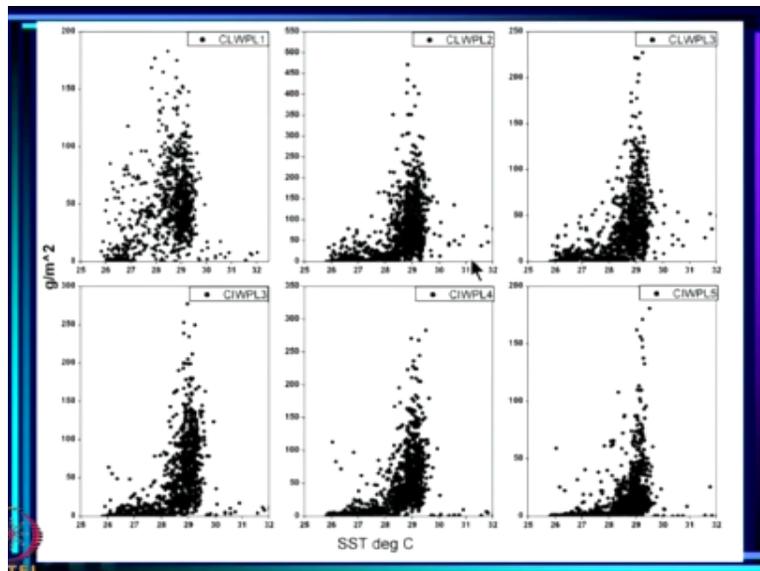
And this is from some work done by Rajeev et. al. and this is for 30 to 120, 30 South to 30 North Indian subcontinent and period June to February. So, it includes actually all the months of the year and what you see is that the shift in the mode you see from about 0 till 27 and by 28, the entire mode has shifted to deep clouds. This is where clouds have reached very high. So, note the shift in the mode from shallow to deep clouds around SST of 28 degrees.

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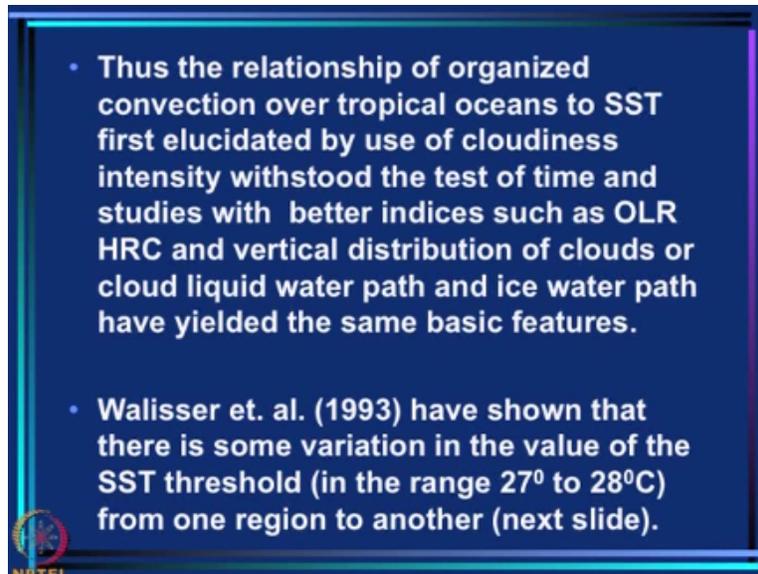
This is a result from Rajeev studies and again you will see the same thing. This is the cloud ice water path and cloud liquid water path. These are also from CloudSat integrated over different layers and what you see again is that you get very deep presence of liquid water and ice beyond 28.

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So, this threshold stories are born out and again when you look at scatter plots over different regions, again the same story appears that you have a kind of exactly similar in nature above 28 suddenly you start getting a huge spread in the values of cloud liquid water.

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Thus, the relationship of organised convection over tropical oceans to SST first elucidated by use of cloudiness intensity has withstood the test of time and studies with better indices such as OLR, HRC and vertical distribution of clouds or cloud liquid water path and ice water path have yielded the same basic features. So, this is as far as the relationship is concerned but the value of the threshold need not be exactly the same from one region to another and this was very elegantly shown by Walisser.

What he did was plot the same curve but now for different regions, so you a North Indian, West Pacific, ITCZ and equatorial Pacific and Atlantic ITCZ and what you see is that actually there are major differences. See this is the equatorial Pacific and you can see that for it the threshold is around 28, that is also true for West Pacific. West Pacific actually the convection tends to be more but again the threshold is 28 or so but when we talk of the ITCZ, equatorial Pacific we have seen, West Pacific we have seen.

Then, there is the Atlantic. This is the West Pacific. Atlantic is the dashed curve. So, Atlantic should be this one and Atlantic you see that the threshold is somewhat lower. It is 27.5. So, this is an important point that Walisser made and you can see it also very clearly here that you see Atlantic is flattening out after 27.5, whereas for some of the other ones, it can be even larger. It appears that for West Pacific and so on the mean seems to be increasing almost till 29. So there is some variation from region to region in the actual value of the threshold.

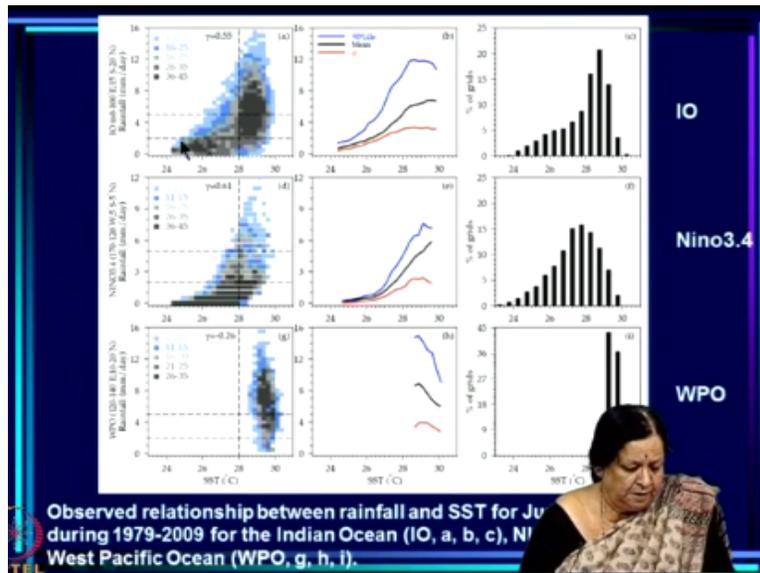
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SST-rainfall relationship

- The relationship between rainfall and SST for the Indian Ocean, Nino3.4 (a key region for El Nino) and tropical West Pacific, which is always warm, is shown in the next slide (after Rajendran et. al. 2012).

Now, let us see. So, far we have been talking only of clouds. It is also important to see how the rainfall varies.

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These are from a study by Rajendran and others in 2012 and what you have seen here is scatter plots of the same kind but now you have rainfall on Y axis is of convection measures, SST on the X axis and the number of points is given here from blue to grey it increases very much. This is for the entire Indian Ocean which you have seen before.

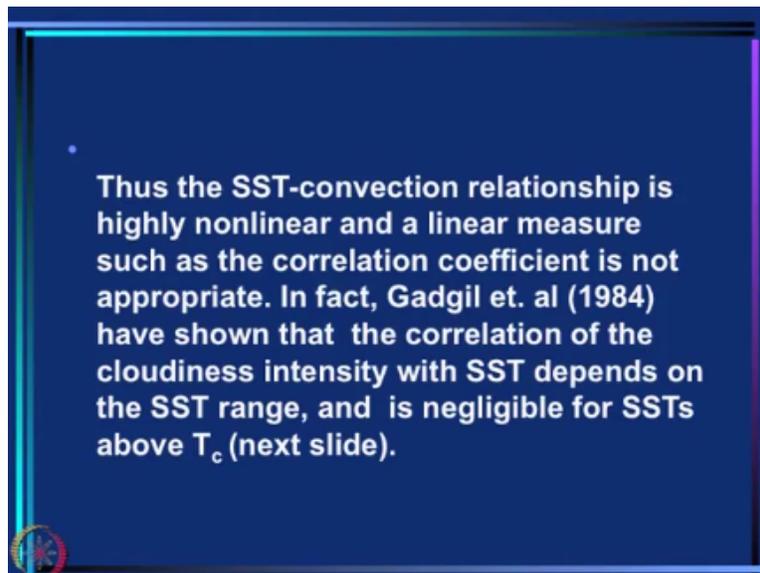
What you see here is also plot of the mean and you can see mean increasing and then beyond 28

or so becoming flat. This is 90% percentile and this is the standard deviation. Standard innovation also behaves very similarly as the mean. Now, let us go to the Central Pacific and the importance of this region will come clear to you once we talk about the El Nino, Southern oscillation and so on. This is the Central Pacific.

Note is that Central Pacific there is a large variation across the threshold, okay. Large number of points are below the threshold and not that many about the threshold and that is actually a considerable variation across the threshold in case you see that the mean is very sensitive to SST. Beyond 26 mean in fact varies linearly with SST.

So, depending on the region, depending on how the SST is distributed in the region, you get different kind of characteristics of the mean and this is tropical West Pacific region like the point in Graham and Barnett is maintained above the threshold and there is no relationship at all between this. You can see here, in fact, this in the Indian Ocean SST distribution. And you can see the mode is above the threshold for Nino 3.4 which is the Central Pacific region. In fact, it is spread out here and for WPO it is here. So, you get entirely different patterns.

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Now correlation of the rainfall with local SST. Note that for a region such as tropical West Pacific for which the SST is always maintained above the threshold. There is hardly any relationship between the rainfall and SST with a large range of the variation of rainfall for each

SST. On the other hand, for the Nino 3.4 region of the Central Pacific, the rainfall varies across the threshold and mean rainfall does increase with SST.

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Thus the SST-convection relationship is highly nonlinear and a linear measure such as the correlation coefficient is not appropriate. In fact the correlation depends on the SST range, and is negligible for SSTs above T_c

SST greater than (°C)	No. of data points	Correlation coefficient ($\pm 95\%$ confidence limits)
24.5	1,602	0.564 \pm 0.034
25.0	1,568	0.548 \pm 0.035
25.5	1,502	0.517 \pm 0.037
26	1,418	0.468 \pm 0.041
26.5	1,340	0.418 \pm 0.045
27	1,212	0.364 \pm 0.050
27.5	1,064	0.282 \pm 0.056
28	823	0.183 \pm 0.067
28.5	468	0.094 \pm 0.092
29	190	0.01

From Gadgil et. al 1984

In fact, in the Gadgil et. al. paper itself, we had shown that if we restrict our attention to SSTs beyond a certain value. If we take entire region of SST beyond 24.5, the correlation is 0.5 or so. But as we increase to higher and higher SSTs, then beyond 28 it has already dropped to 183 and beyond 28.5 it has become insignificant. So, the correlation decreases and this is because the spread of the CI increases enormously.

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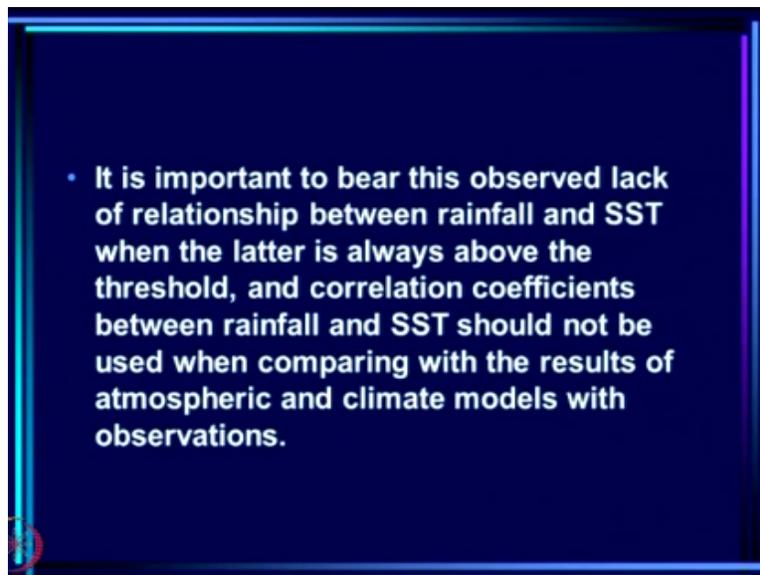
- Graham and Barnett (1987) have pointed out that *“One might be tempted to fit a sharp looking curve to the distribution which suggests a strong dependence of convection on SST. However, associations between SSTs and OLR for SSTs above 28°C at applicable locations suggest that the dependence of the level of convection in this temperature range is usually slight.”*
- They further suggested that when the SST is maintained above the threshold, convection is determined by the low level convergence. Thus above the threshold the SST is no longer the limiting resource but dynamics can be.

In fact, Graham and Barnett have pointed out that one might be tempted to fit a sharp looking

curve to the distribution which suggests a strong dependence of convection on SST. However, associations between SSTs and OLR for SSTs above 28 degrees at applicable location suggest that the dependence of the level of convection in this temperature range is usually slight. They further suggested that when the SST is maintained above the threshold, convection is determined by the lower-level convergence.

Thus, above the threshold, the SST is no longer the limiting resource for convection but dynamics can be.

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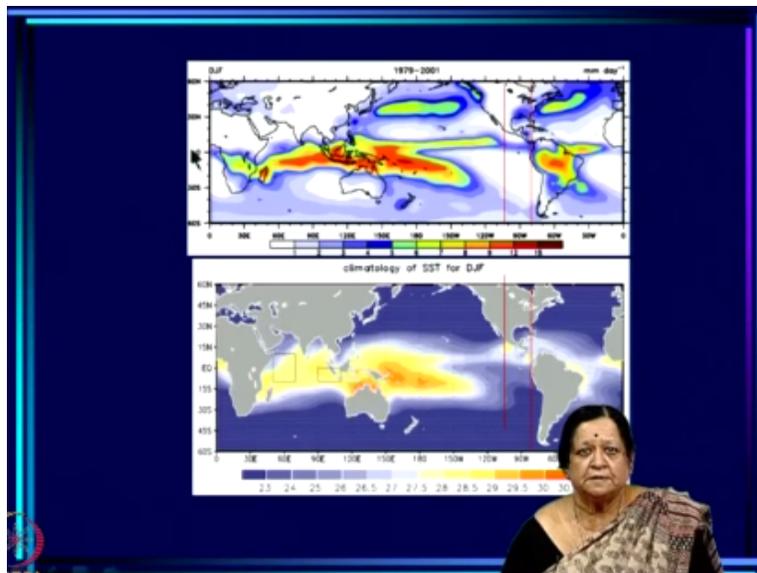
This is a very important point to remember because it is important to bear this observed lack of relationship between rainfall and SST when the latter is always above the threshold and the correlation coefficient between rainfall and SST should not be used when comparing with the results of atmospheric and climate model with observations. Unfortunately, meteorologist have done that and come to wrong conclusions, okay.

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Implications of the SST-convection/ rainfall relationship

- The regions with significant mean seasonal rainfall are contained within the regions of SST > 27.5^o or 28^oC.
- Note that in DJF, over the east Atlantic and east Pacific the SST is below the threshold south of the equator and there is no rain.
- In JJA over the western Arabian Sea also, the SST is below the threshold and there is no rain.

Now, let us see what are the implications of this SST convection relationship.
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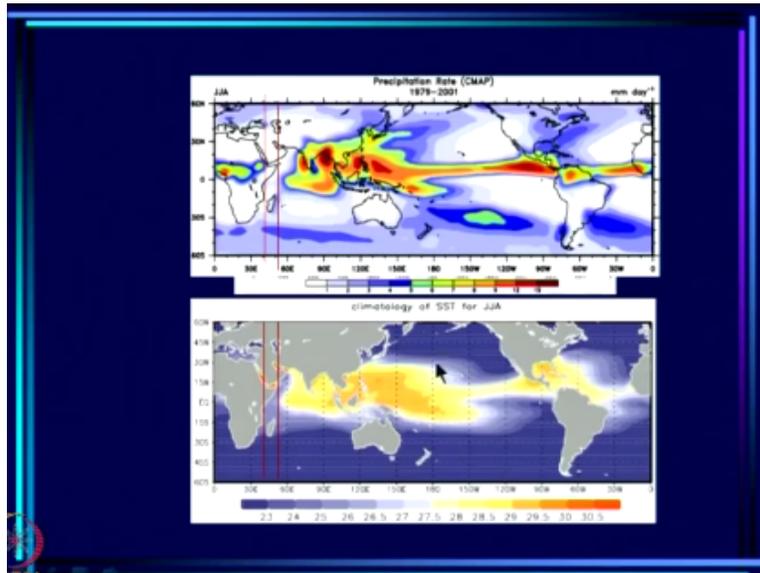


What we can see here, this is the rainfall pattern here, okay and you can see higher rain means from green to red basically. This is the SST and SST colouring is such that this is above 27.5 – shades of yellow, okay and what you can say very nicely. You look at this region, this is December, January, February, okay and look at this region and you will find most of the region, the SST is below the threshold and you get hardly any rain here, okay.

This is December, January, February and in December, January, February, you would have expected that in the southern hemisphere you should get a tropical convergence zone but

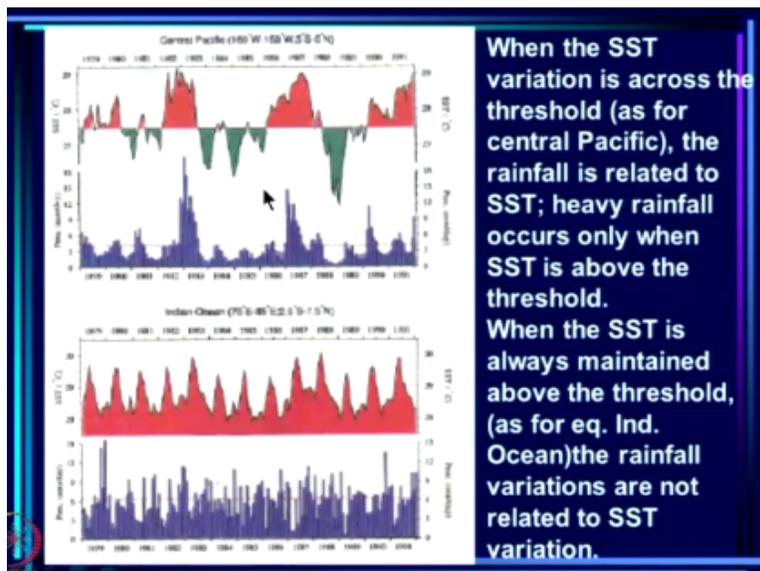
southern hemisphere is extremely cold and there is no such TCZ. In fact, there is a little bit of warm water here and little bit of rain to the north but you can see that SST being below the threshold has completely suppressed you know the possibility of having TCZ over the southern hemisphere in equatorial East Pacific.

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Now, we go to the summer and summer thing should be in the north and they are but you see here, this is our Arabian sea, this is Madagascar region and you can see that there is no rain here at all and that is the region which coincides with all the blues in SSTs. So, SST is so cold here. This is because of the upwelling that you cannot have rainfall in this region.

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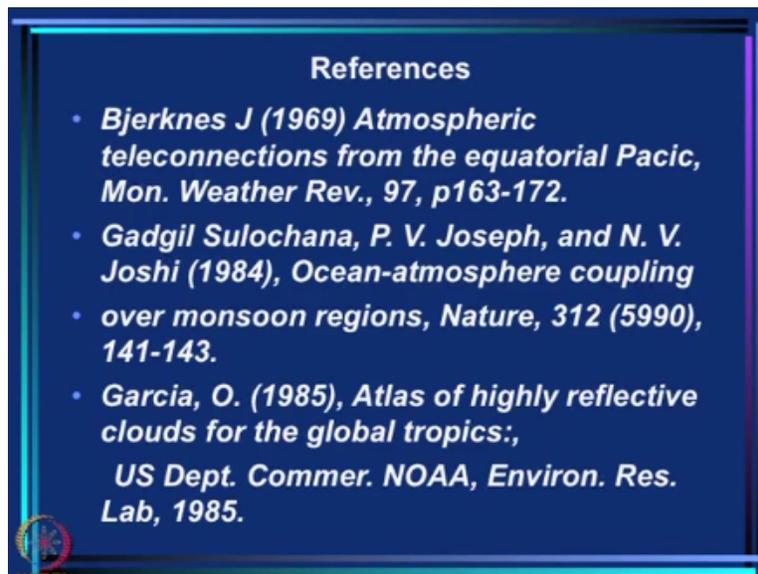


So, the implication of the relationships we have talked about are these, that when SST is below the threshold you cannot have organised convection. Now, the implications also are therefore variability of convection and that is the most important thing because we began with saying how is the variability of convection related to SST and what we find is that in fact this is the Central Pacific and in the Central Pacific now what you can see here is this is the SST.

And this is the rainfall here and you can say whenever SST is larger than about 27.5 or 28, these are these big red things here and that is when you get rain events. So, there is a one to one correspondence between the SST and rain here because SST is varying across the threshold. You know, it may be above, it may be below but it is varying across the threshold. You take on the other hand equatorial Indian Ocean where SST is perpetually above and in that case there is hardly any relationship between rainfall and SST.

So, this relationship between SST and convection is a very interesting relationship and it has very important implications for our understanding of the variation of organised convection over tropical oceans and eventually thereby of our understanding of monsoon variability and its links to variation of convection over tropical oceans. Thank you.

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