The Monsoon and Its Variability
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Lecture – 08
Monsoons and The Seasonal Variation of Tropical Circulation and Rainfall

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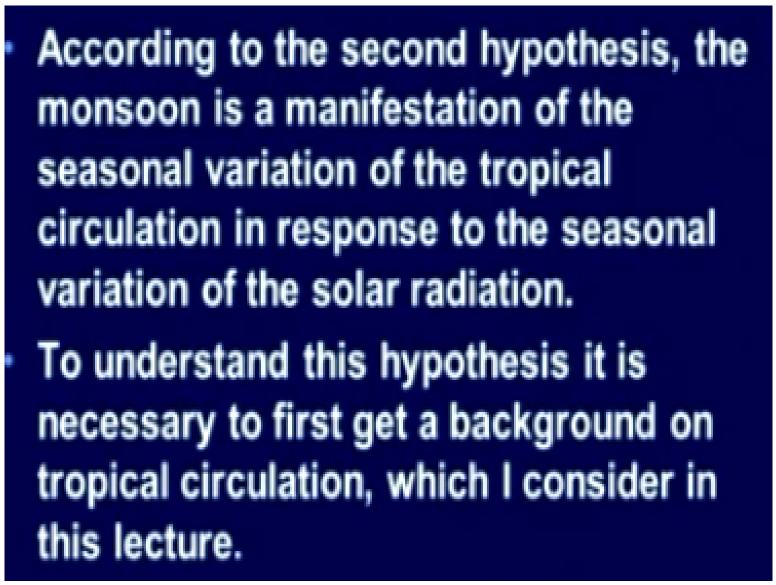

Now in the last lecture, we have looked at the first hypotheses proposed for the basic system responsible for the monsoon which said that the primary cause of the monsoon is the land-ocean contrast in surface temperatures and we showed that that hypotheses is not tenable and is inconsistent with the observed variability in space and time of the monsoon. Now, today we will consider the second hypotheses, which look at monsoon as a manifestation of seasonal variation of tropical circulation and rainfall.

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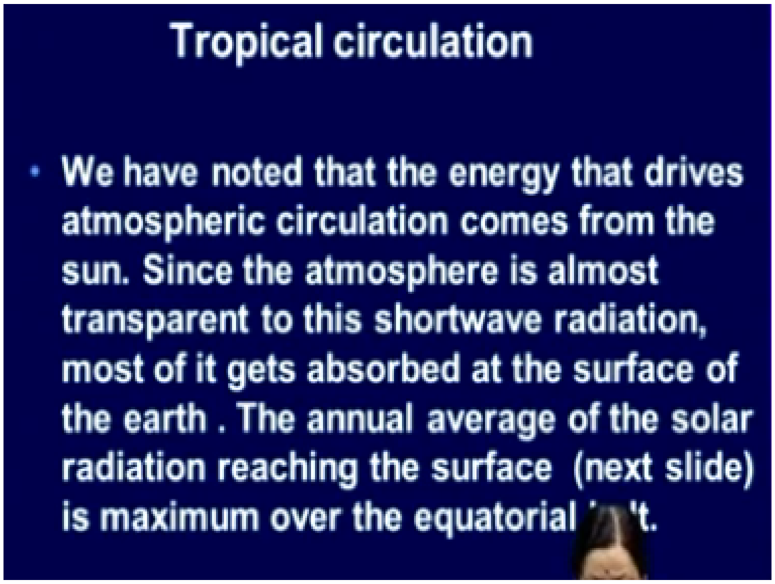

So, according to the second hypotheses, the monsoon is a manifestation of the seasonal variation of tropical circulation in response to the seasonal variation of the solar radiation. Now, to understand these hypotheses, it is necessary to first get a background on tropical circulation itself, so I will consider that first in this lecture. So, we first consider tropical circulation. Now, we have noted before that the energy that drives the atmospheric circulation comes from the sun.

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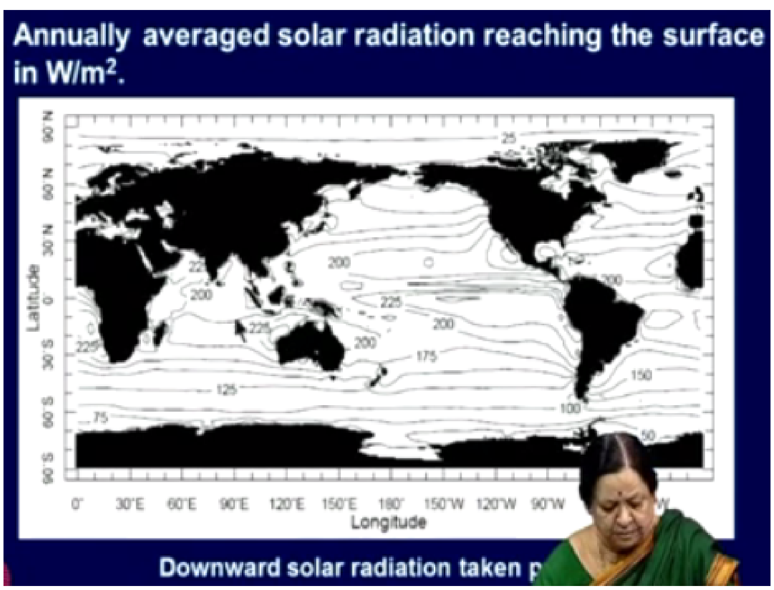

Since the atmosphere is almost transparent to the short wave radiation, most of it gets observed at the surface of the earth be it land or ocean, so the annual average of the solar radiation reaching the surface, which is here is in fact, maximum in the equatorial region, so this is the annually average solar radiation reaching the surface of the earth in watts per metre square and you can see that it is very large in the equatorial region.

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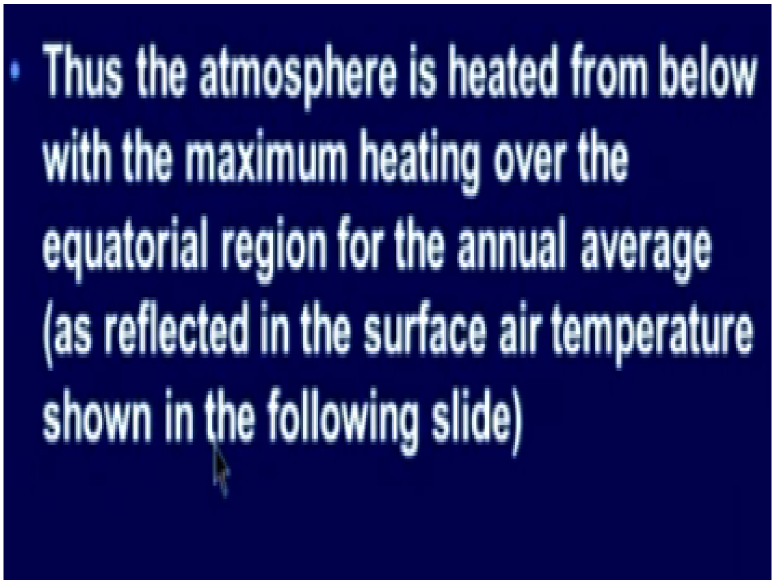

So, it is maximum, in the equatorial regions of the earth. Thus, the atmosphere is heated from below with the maximum heating over the equatorial region for the annual average. So, if we look for a simplicity; first let the annual average, then the atmosphere is heated from below with heating being maximum at around the equatorial region and decreasing as you go pole ward on either side.

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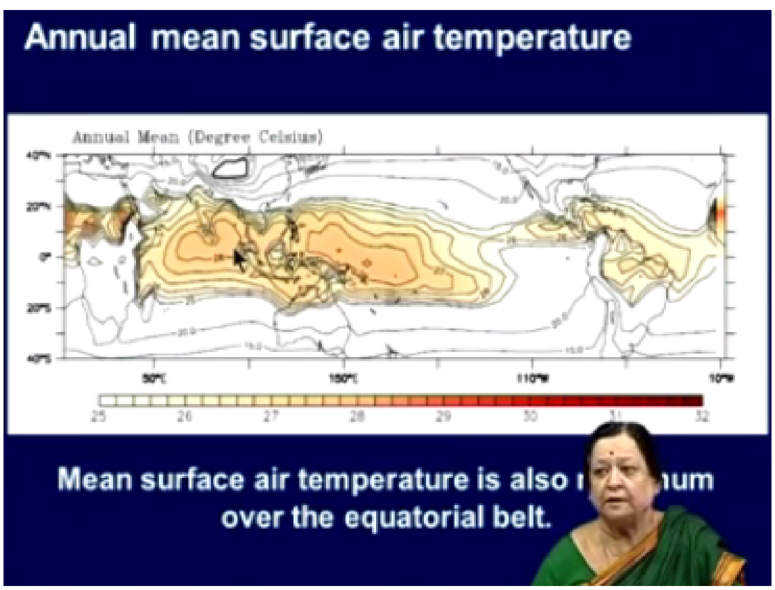

Now, this implies that the surface temperature also behaves in the same way, this is the annual mean surface air temperature and shaded regions are where it is very warm and you see that in the annual mean also, the surface temperature is maximum in the equatorial regions and decreases, as you go pole ward, okay. So, we have a situation in which the radiation incident at the surface is also maximum in the equatorial region and the surface temperature is also maximum in the equatorial region, if we look at the annual average.

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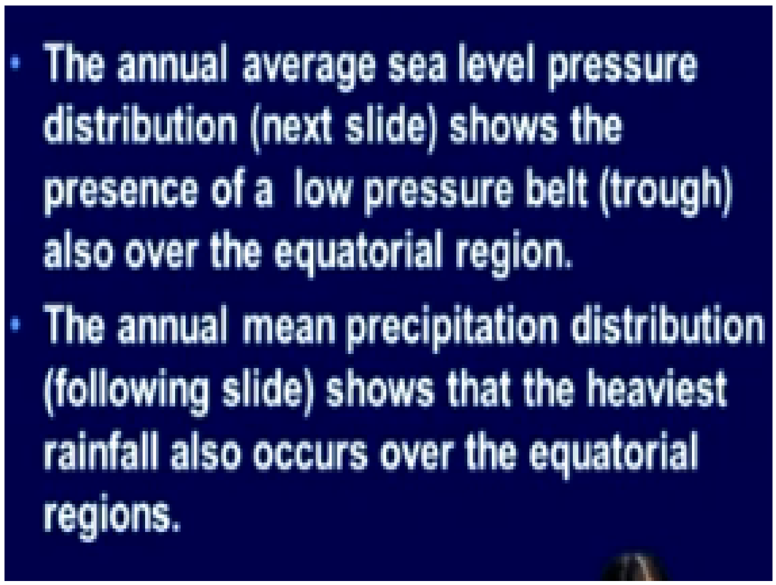

Now, so in response to this, the annual average sea level pressure distribution also shows the presence of a low pressure belt or trough over the equatorial region.

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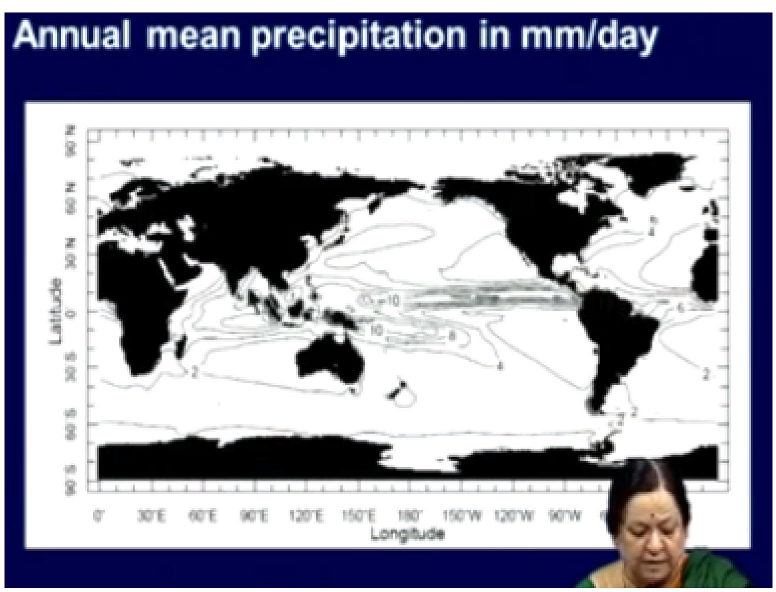

So, this is the annual mean sea level pressure distribution and what you see is again, this is where the low pressure region is or the trough is and that is also roughly in the equatorial region. So, the incident solar radiation as well as the temperature, at the surface as well as the pressure have extrema near the equatorial region, radiation and temperature being maximum and pressure being minimum around the equatorial region.

Now, if you look at the annual mean rainfall, annual mean precipitation in millimetres per day that also is maximum in the equatorial region. This is the belt; rain belt, if we look at the annual average. So, the annual average sea level pressure distribution also shows the presence of a low pressure belt or trough over the equatorial region and the annual mean precipitation distribution shows the heaviest rainfall occurs over the equatorial region.

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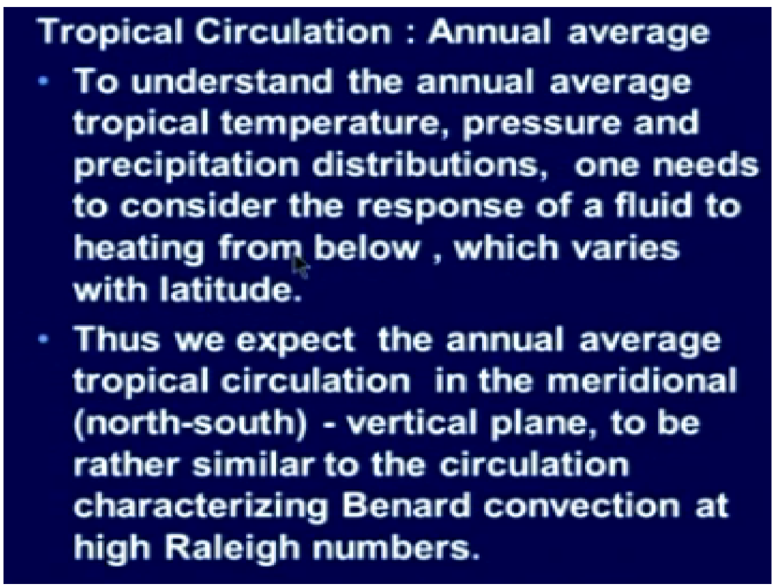

So, if you look at the annual average than the entire action is over the equatorial region, where there is maximum temperature, there is a trough and also maximum rainfall. Now, to understand the annual average of tropical temperature, pressure and precipitation distribution, one needs to consider the response of fluid to heating from below which varies with latitude, okay. So, we expect the annual average tropical circulation in the meridional, that is to say, north south vertical plane to be rather similar to the Benard convection, we looked at in the last lecture.

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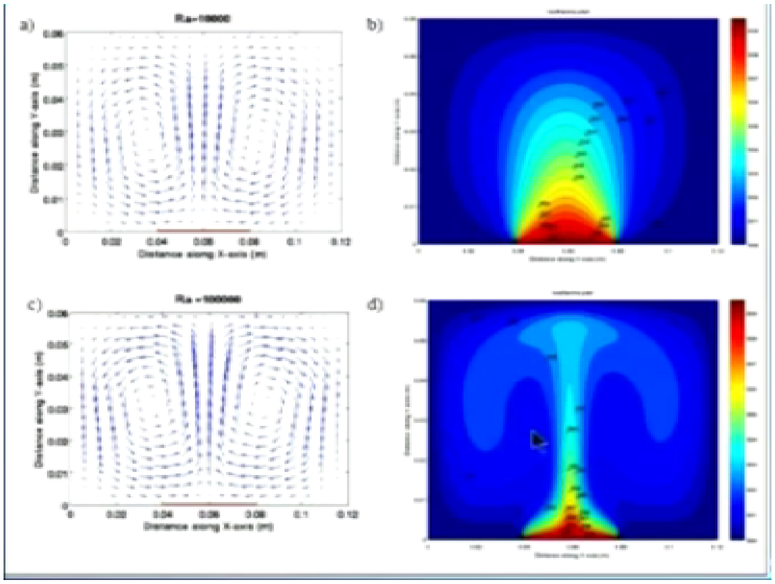

This is; if you remember Raleigh number measures how much the heating is vis-a-vis the viscous effects and effects of conduction and larger Raleigh numbers means viscous effects are relatively less and this is what happens to a fluid, now we are assuming in this case, the fluid is non-rotating, when it is heated over this region, what you get is a circulation with ascent here and descent in the surrounding region and these are the temperature contours.

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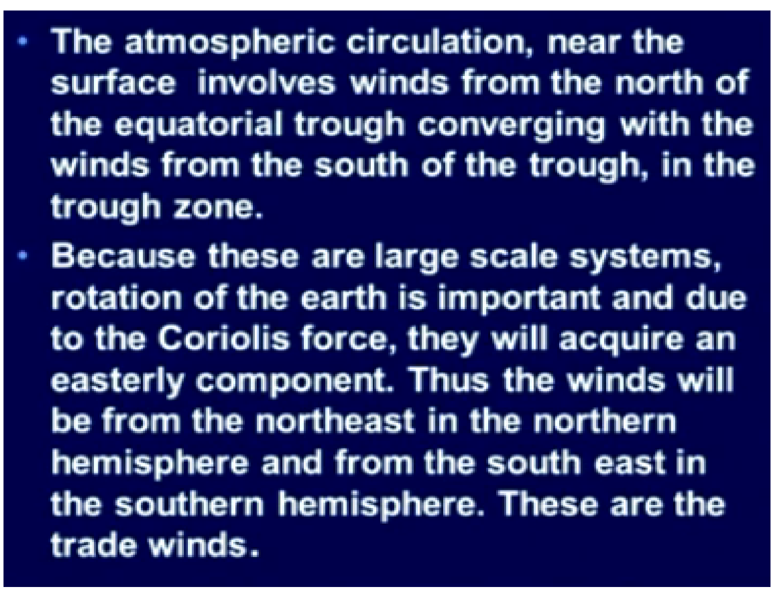

So, you get hot region here and it becomes successively colder as you go up and notice that the; as the Raleigh number increases, that is to say the viscous effects become less and less important, we get a very, very narrow zone of strong ascent and a broader zone of slow descent, this is Benard convection. So, the atmospheric circulation near the surface would; so this is what we would get when the atmosphere is heated from below with the heating being maximum at the equatorial region.

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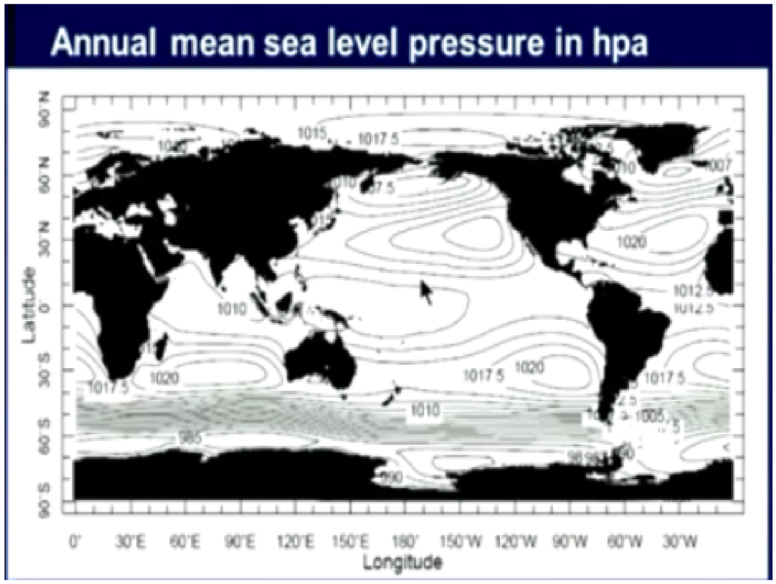

You expect to get ascent over the heated region, over the trough region and descent in the surrounding region. Now, the atmospheric circulation near the surface involves winds from the north of the equatorial trough converging with the winds from the south of the trough; in the tough zone, okay. So, if you remember when we looked at the pressure distribution, if we have a trough zone around here, around the equatorial region; in this trough zone.

You will get a winds coming from the north in the northern hemisphere and from the south in the southern hemisphere. And remember, we are looking at a very, very large scale system extending over thousands of kilometres, so far such a system then Coriolis force will also become important, so because these are large scale systems, rotation of the Earth is important.

And due to the Coriolis force, both these winds; the wind coming from the north in the northern hemisphere, northerly winds as well as the winds coming from the south in the southern hemisphere, southerly wind will acquire an easterly component, okay.

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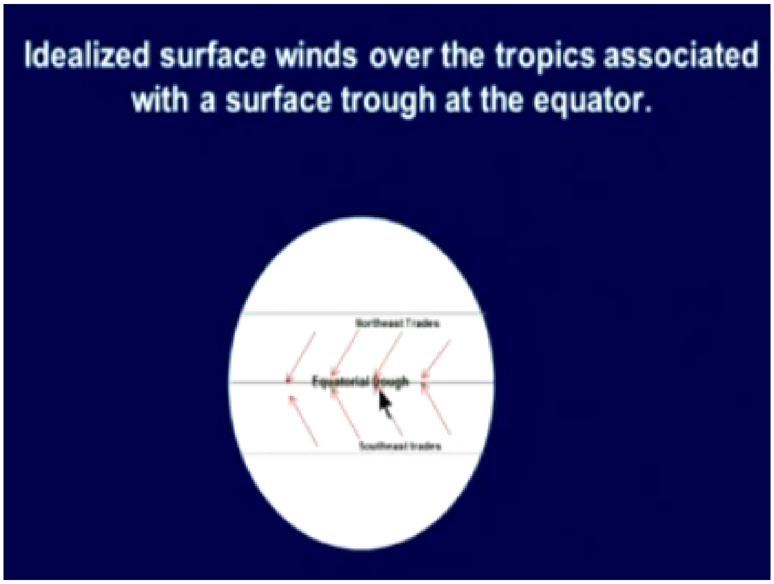

Thus, the winds will be from the north east in the northern hemisphere and from the south east in the southern hemisphere, so in idealised picture of annual average circulation in the tropics would be as follows that there would be an equatorial trough, here this is the region of low pressure around the equator where the heating is maximum when the temperature is maximum and into this low pressure, you will get winds at the surface.

But, because of the Coriolis force, they will get an easterly component because now the wind that tries to go this way will have a Coriolis force acting to its right in the northern hemisphere and to its left in the southern hemisphere. So, both these winds will components from the East and the net result then is, that the surface winds towards the equatorial trough will be from the north east in the northern hemisphere and from the south east in the southern hemisphere.

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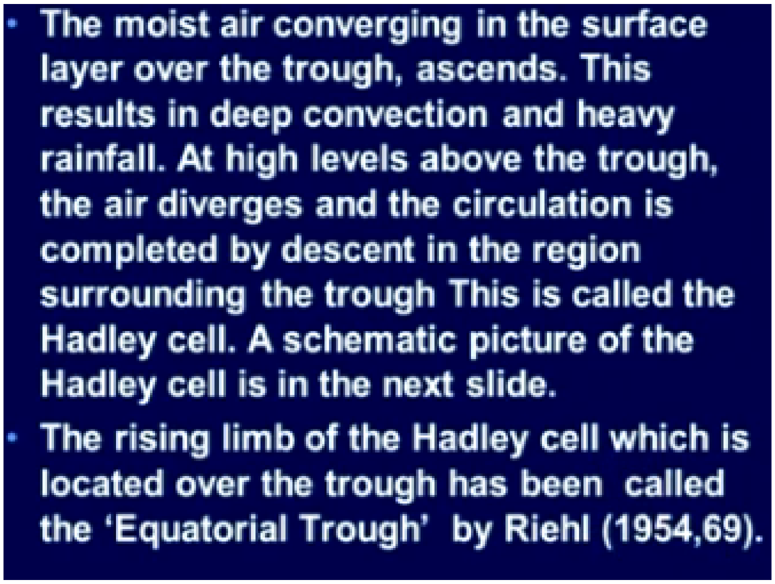

These are the north east and south east trades, okay and they emanate from the high pressure regions here in the subtropical region. Now, the moist air converging in the surface layer over the trough ascents, this results in deep convection and heavy rainfall. So, at high levels about the trough, the air diverges and the circulation is completed by descent in the regions surrounding the trough. This is called a Hadley cell.

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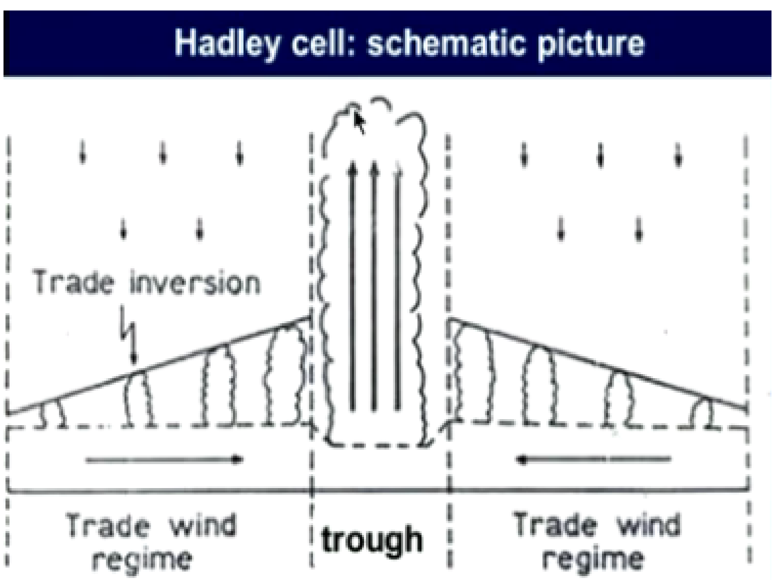

So, in fact the rising limb of this Hadley cell, which is located over the trough has been called equatorial trough by Riehl. Now, Riehl is one of the great contributors to our understanding of tropical meteorology and he called it the equatorial trough. So, here is a schematic picture of the tropical circulation, this is a; remember it is an annual average and so this trough region is over the equatorial region.

And what you get is trade winds converging into the trough ascending here and ascending throughout the troposphere, diverging at high levels and then descending around this, so this is the Hadley cell, which is the circulation in the North South, this is the north south and vertical plane, if you look at the annual average, so this is an idealised circulation that you have and the rising limb of this cell, this is the rising limb of the Hadley cell.

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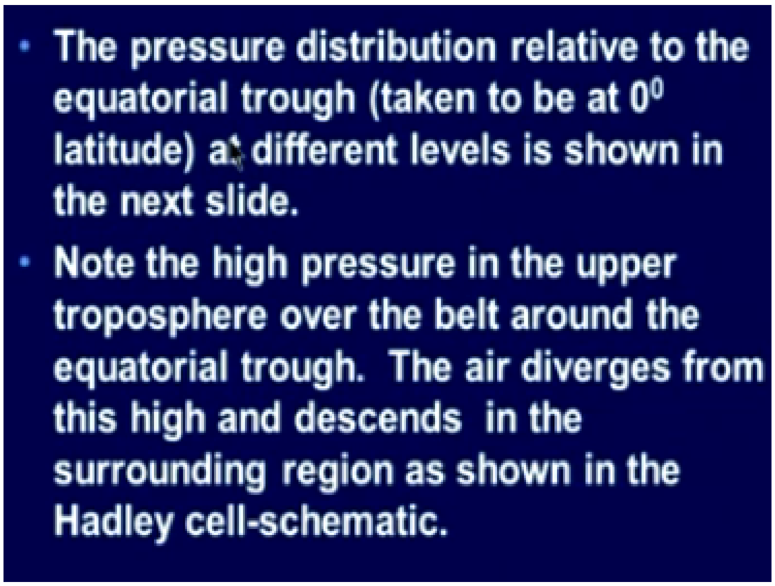

This rising limb in fact, inverse the convection or deep clouds and rainfall and this is called the equatorial trough by Riehl and also ITCZ by Charney and will come to that. Now, Riehl has also shown what the pressure distribution relative to the equatorial trough at different levels is okay.

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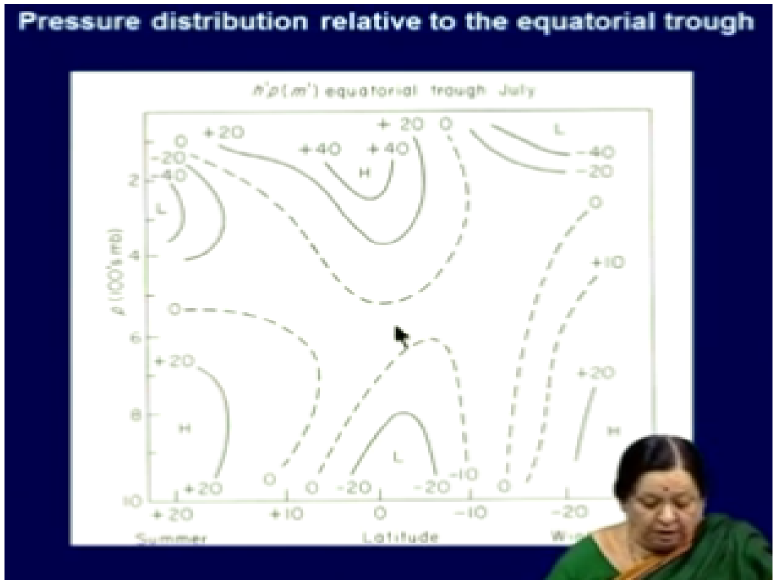

So, now this is pressure distribution relative to the equatorial trough, which is supposed to be at this latitude, 0 okay. So, near the surface and up to even 2 km or more, there is a low pressure belt here, this is the equatorial trough and above, say at the height of; these are actually in 100 millibars, so around say 200 millibar or, so what you see is a high overlying a low and air will diverges from this and then descend in the surrounding region.

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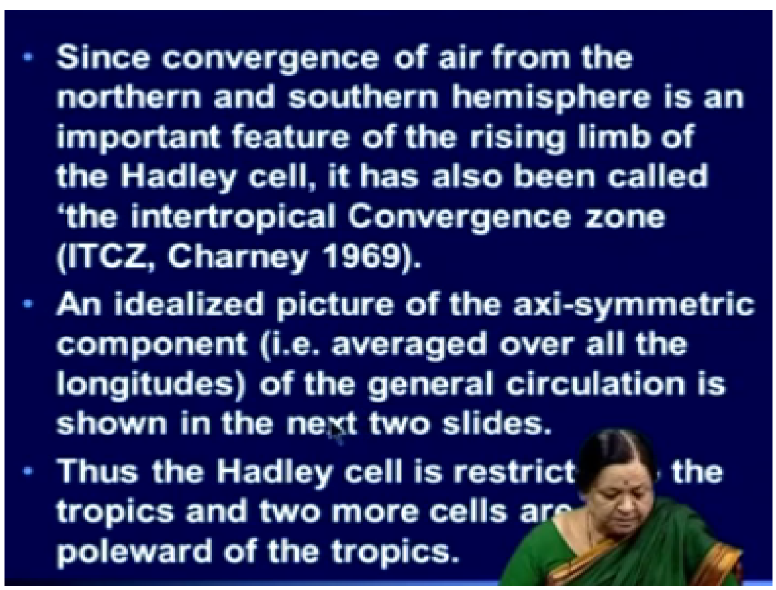

So, this is the vertical structure of the pressure distribution around the equatorial trough. Now, since convergence of air from northern and southern hemisphere is an important feature of the rising limb of the Hadley cell, it is also been called inter tropical convergence zone because it is characterised by convergence of air from the two hemispheres; northern and southern hemisphere.

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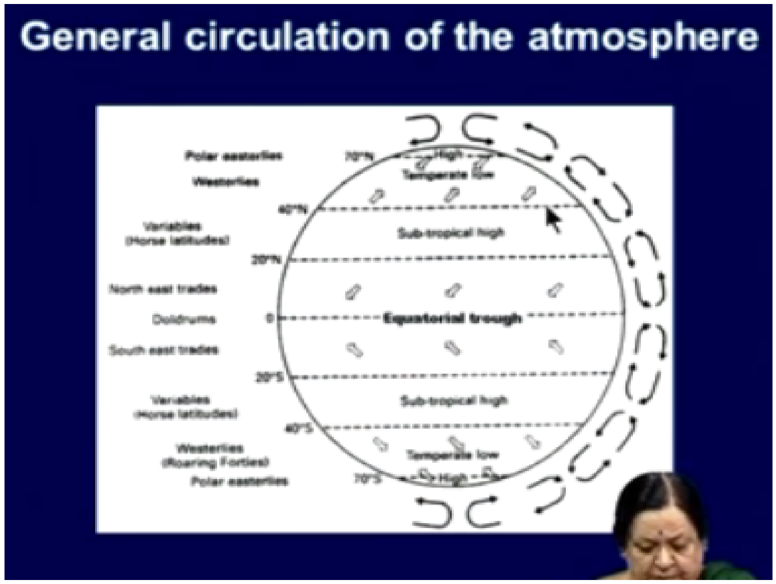

So, it has also been called ITCZ by Charney, now an idealised picture of axisymmetric component which is to say, average over all the longitudes of the general circulation of the earth looks like this. So, we have a case, this is an idealised picture of circulation which is averaged over all the longitudes, remind you, these are the tropics, this is the equatorial trough and you have the north east and the south east trades.

Actually, in reality this cell; the Hadley cell is restricted to the tropics and north of the Hadley cell is a mid-latitude cell here which you can say, so it also has a descending limb here and an ascending limb north of 60, north also, and a similar one here and then there is a polar cell. Now, why we get 3 cells and not just a single cell with the Hadley cell extending to the pole is a question I will not consider in this lecture.

But it really depends on various parameters such as the rotation of the; rate of the rotation of the earth, the heating that comes from the sun and so on and so forth. The parameters for the present earth atmosphere system which is driven by the given solar radiation are such that in fact, the circulation; the solution for the circulation breaks up into these 3 cells and it is only in the tropics that we see a direct circulation of rising about the heating and sinking in the subtropical highs.

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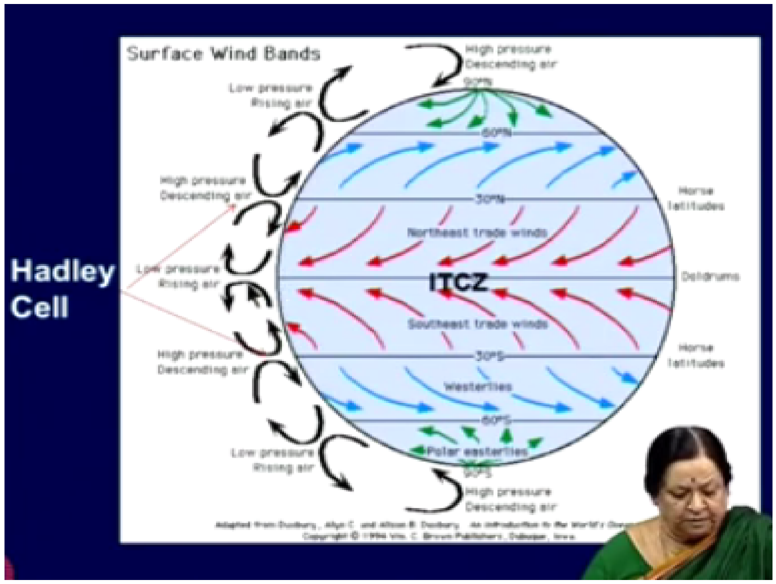

So, these are the subtropical highs that I mention. So, this is the picture, these are the polar regions and these are the mid latitudes here. Now, this is the same picture which shows the surface winds much more colourfully perhaps and this is the ITCZ, you see the north east trade winds, south east trade winds converging in the ITCZ, which also can be called the equatorial trough and these are the mid latitude westerly is.

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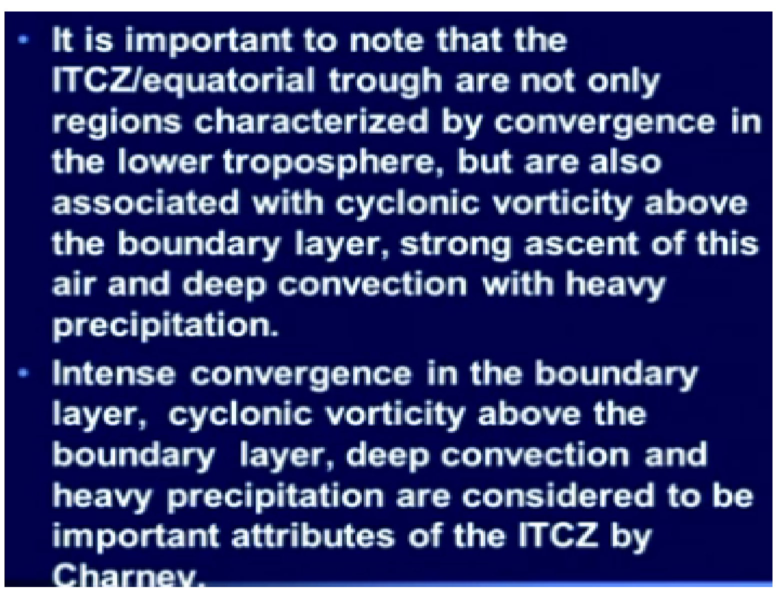

These are the subtropical highs which are also called horse latitudes and these are the polar; this is the polar circulation that you have. So, this then is the Hadley cell we talked about with rising in the equatorial region, low pressure here and diverging at high levels and sinking in the surrounding region. So, this is an idealised picture of the general circulation of the earth. Now, it is important to note that the ITCZ as Charney called it and the equatorial trough is Riehl called it are not only characterised by convergence in the lower troposphere.

In fact, the word convergence comes also in the name ITCZ that Charney and others before him have referred to the system as, so not only is their convergence in the low troposphere but they are also associated with cyclonic vorticity above the boundary layer okay, strong ascent of this air and deep convection with heavy precipitation. So, the important attributes are features of this ITCZ are that there is strong cyclonic vorticity above the boundary layer okay.

Convergence within the boundary layer towards this region such as zone of convergence, there is strong cyclonic vorticity above the boundary layer, there is strong upward velocity or ascent of air above the boundary layer and this ascent in fact, extends almost throughout the troposphere until have a 200 millibar or so, at which point there is, anti-cyclonic vorticity and the air diverges and then the circulation is completed with descent in the surrounding region.

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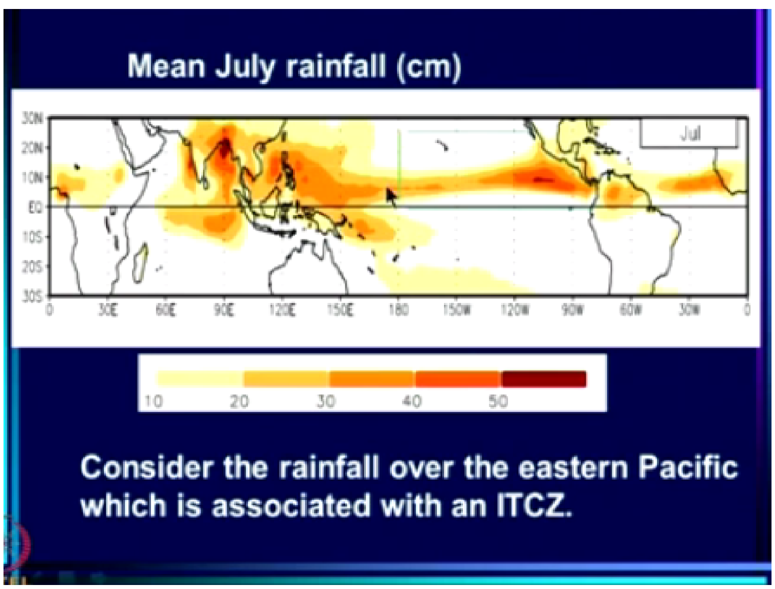

So, intense convergence in the boundary layer, cyclonic vorticity above the boundary layer deep convection and heavy precipitation are considered to be very important attributes of the ITCZ by Charney okay. Now, let us consider, you know the case of; what I can call a canonical ITCZ are the inter tropical convergence zone over the oceanic region of the Pacific and let us consider it over the region; east of the dateline.

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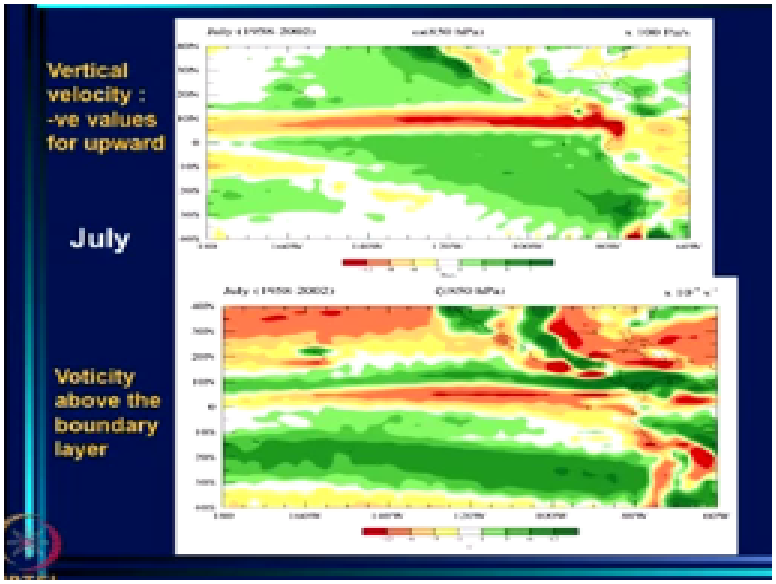

This is the mean July rainfall and you see a very coherent zone, zonal band of rain belt here and this is believed to be associated with the equatorial trough or the ITCZ. So, let us see what it looks like? Now, what you see here is actually the vertical velocity above the boundary layer, this is omega at 850 hpa and this is the relative vorticity above the boundary layer and what you can see is this band here of yellows and reds corresponds to cyclonic vorticity.

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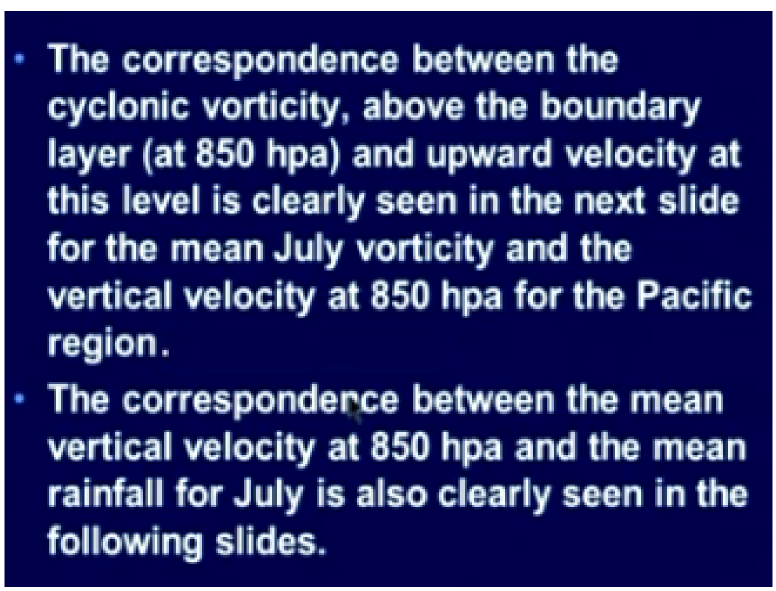

And corresponding to this band of cyclonic vorticity, you see that there is ascent at the level above the boundary layer, so this is, you know what we expected from Ekman layer theory that if we had cyclonic vorticity above the boundary layer, they will be ascent of this moist air at the level above the boundary layer and this is what we had expected, so the correspondence between cyclonic vorticity above the boundary layer and upward velocity at this level is clearly seen.

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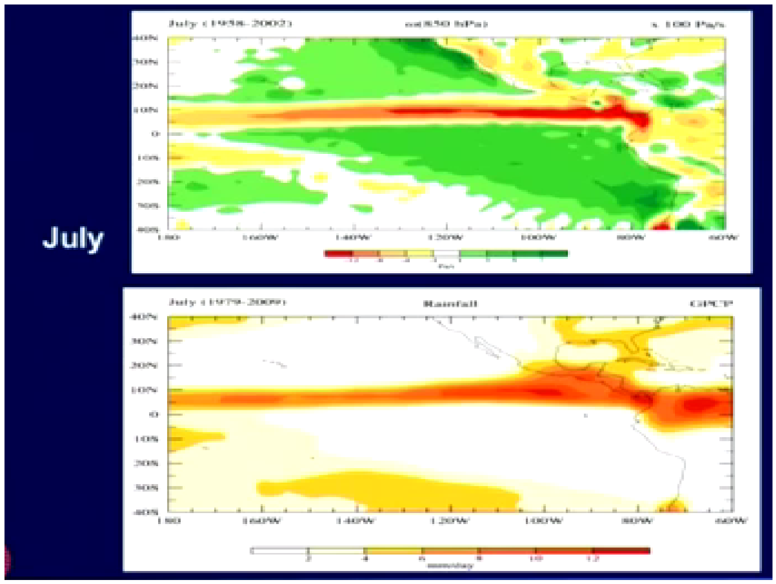

This is what we just saw now in fact, over this classical ITCZ, there is also a correspondence between; now this is the rainfall over the region, this is mean for July and this is omega at 850 or the upward velocity at 850 above the boundary layer and you see that there is a very, very close correspondence between the upward velocity just above the boundary layer at 850 and rainfall for the classical ITCZ.

And you remember that this was the basis of the six theory that the Charney propose that this cyclonic vorticity by having convergence in the boundary layer can create upward velocity here, this is a ascent that is required for clouds to form and then the clouds form, heat the region intensify the trough and actually give rainfall here. So, the basic elements of this; what happens in a rotating fluid in the presence of a cyclonic vorticity are actually now here seen to be in operation.

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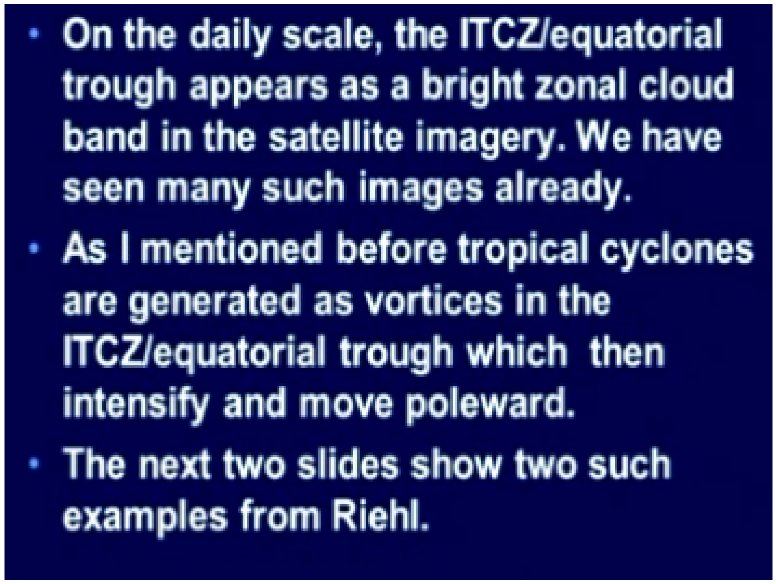

For a classic ITCZ, which is over the eastern Pacific? Now, let us see what happens in the daily scale? First, we have to understand what the canonical ITCZ or equatorial trough has really calls it looks like. So, on the daily scale, it appears as a bright zonal; zonal meaning east west cloud band in satellite imagery, we have actually seen many, many instances of such.

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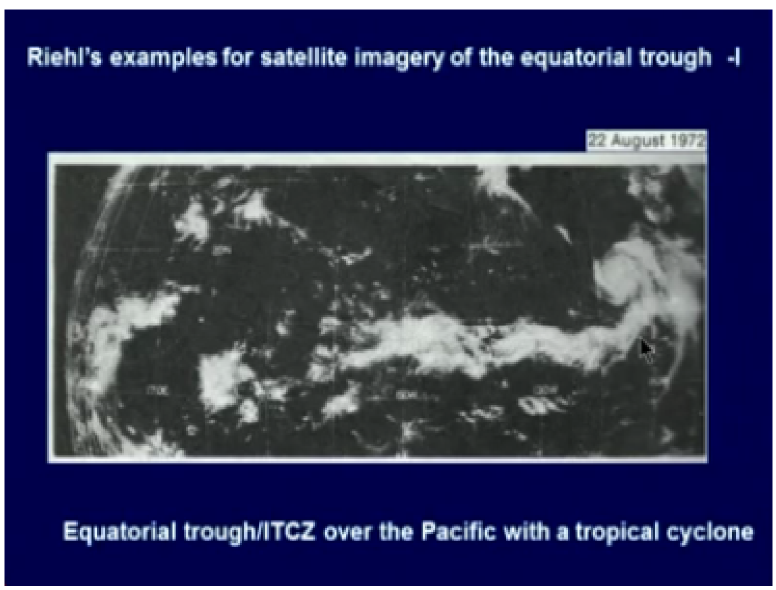

And you see one here, now this is actually from Riehl's book and what you see here is, this is the Pacific region here and this is the band; zonal band, you know over eastern Pacific and what you see here is a cyclone taking, now this is the case that we saw last time about interaction between the planetary scale and synoptic scale, how all cyclones are born as cloud blobs or lows within the ITCZ and then they start intensifying and take off and this is such a picture.

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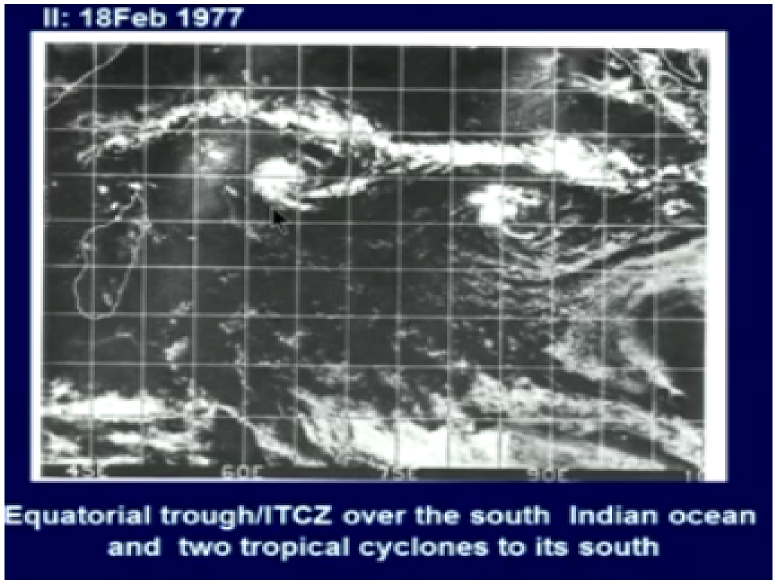

So, this really is a canonical ITCZ, a picture of the canonical ITCZ over the Pacific Ocean okay. Next picture is again from Reihl and this is over South Indian Ocean in fact, you can see Madagascar here, okay. So, this is over South Indian Ocean on 18 February 1977 and what you see here is this nice band of cloud, this is ITCZ from it, 2 cyclones were born and they have taken off.

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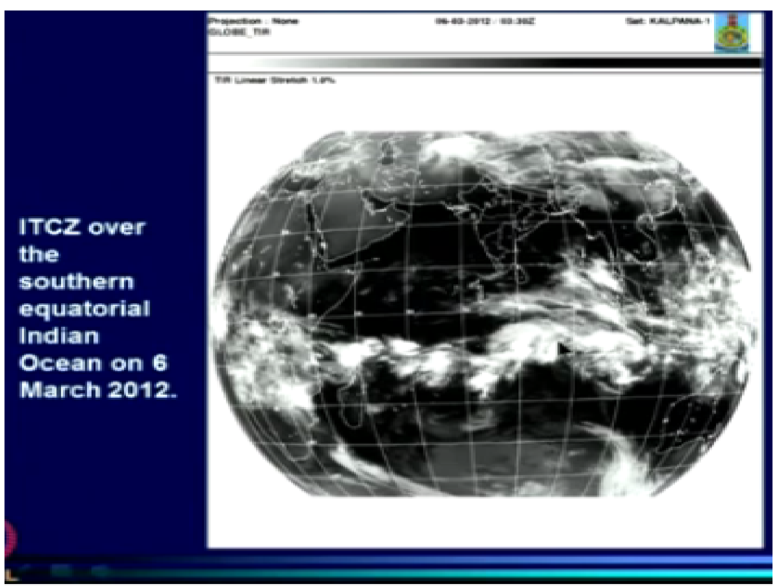

So, you see that equatorial trough or ITCZ over South Indian Ocean and two blobs of cloud, we show 2 tropical cyclones on that region. Now, this is another example of ITCZ, over southern equatorial Indian Ocean and you see a very coherent band of clouds and notice that almost in every picture of the ITCZ , the intensity of the clouds is not uniform throughout rather the cloud band comprises blobs which are at the synoptic scale blobs which are embedded in this larger planet rescale.

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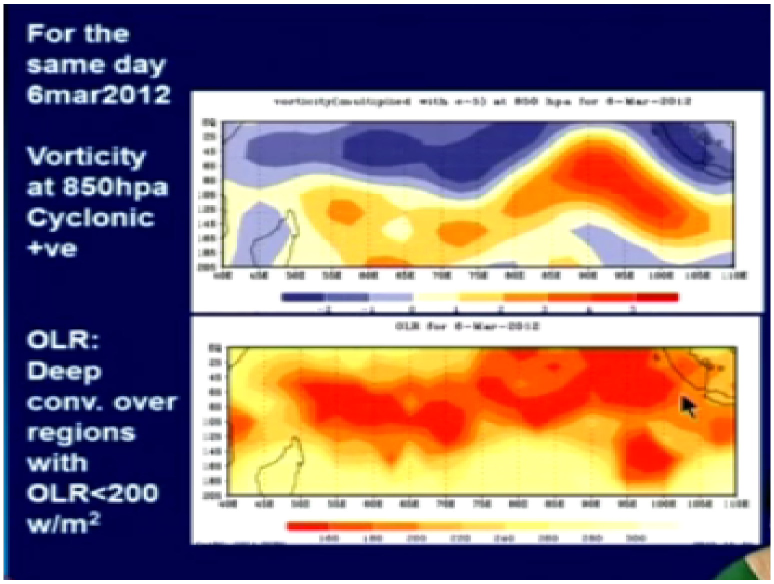

So, this is again a typical picture of a canonical ITCZ taken by satellite and it happens to be taken this year, 6 March 2012. So, let us see, if you know this argument about cyclonic vorticity coincide; cyclonic vorticity above the boundary layer coinciding with the rain belt or with the cloud band is actually seen in this as well and in fact, what it is here; what you see here is the cyclonic vorticity for the same region.

This is the equator and this is 20 south and you see a band of cyclonic vorticity here and below is shown the outgoing long wave radiation and the colours indicate where the outgoing long wave radiation is very low which means we have a very tall clouds; clouds with very, very high tops. So, these are the deep convection areas of this, which actually look as bright; look like bright white clouds in the imagery I showed you.

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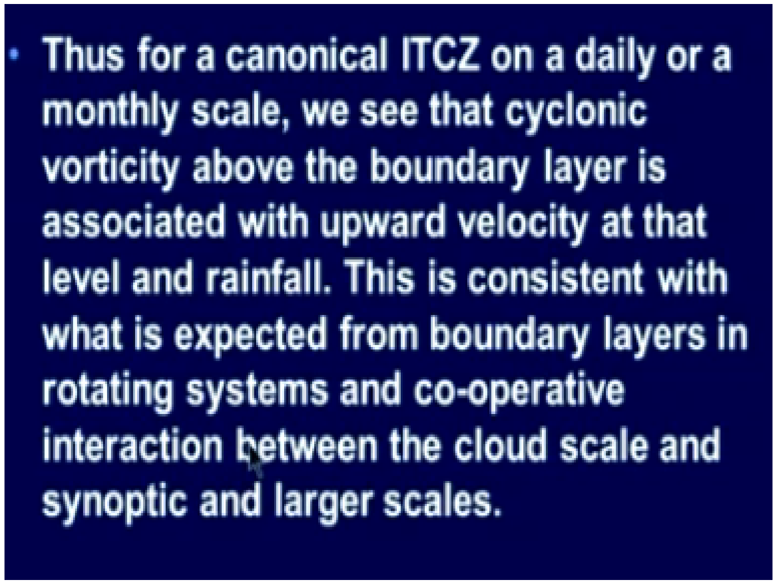

And you see that there is a correspondence between the cyclonic vorticity above the boundary layer and this OLR, okay. So, for a canonical ITCZ on a daily or a monthly scale, we see that cyclonic vorticity above the boundary layer is associated with upward velocity at that; is associated with upward velocity at that level and rainfall okay, so this is consistent with what is expected from boundary layers in rotating systems and co-operative interaction between cloud scale and synoptic and larger scale.

So, we see that for a canonical ITCZ on a daily scale and I will show later that this is also true on a monthly scale in fact, we have seen it on a monthly scale for the Pacific. So, for daily as well as monthly scale, we see that cyclonic vorticity above the boundary layer is associated with upward velocity at that level and rainfall. So, this is all consistent with whatever we have developed as background material, the boundary layers in rotating system.

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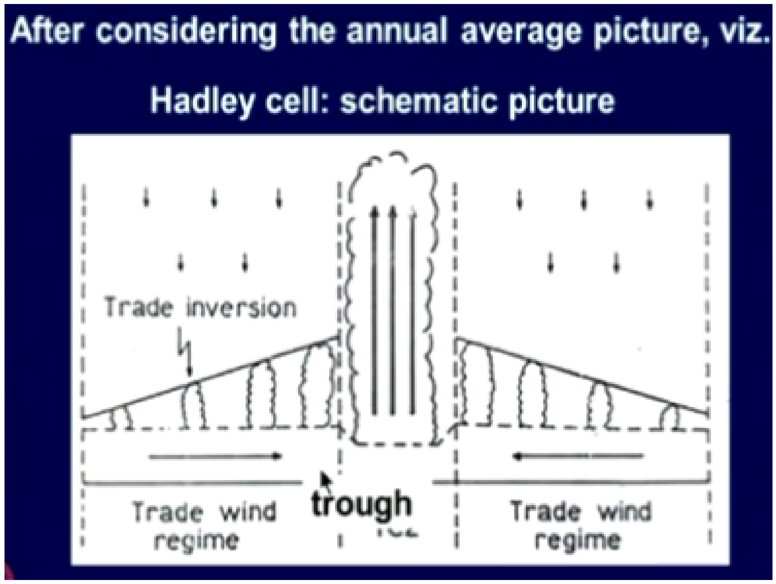

The special feature of boundary layer in rotating system which imply that there is convergence in the boundary level in the cyclonic vorticity above the boundary layer and cooperative interaction between cloud scale and large; synoptic and larger scale. Now, so now we have so far focused on the annual picture, right and the annual picture comprises this cell trough region, the Hadley cell with the trough region and the ascending over the trough region, descending in the surrounding region.

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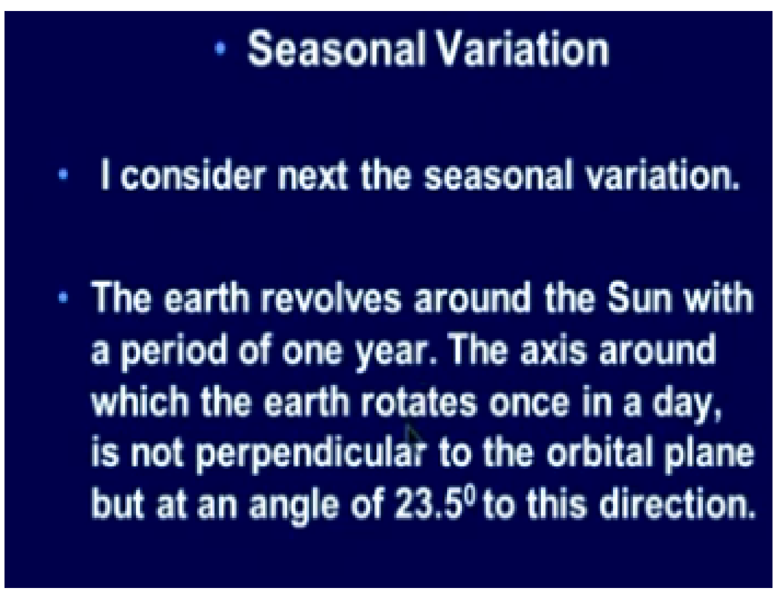

And a convergence in the boundary layer, whereas divergence at the higher level, this is the annual average picture. Now, next we have to look at, how it varies in, which season okay, so we now consider seasonal variation. Now, why do we have variation with season at all? So, let us revise a little bit of our basic geography now, you know that the Earth revolves around the sun with a period of one year.

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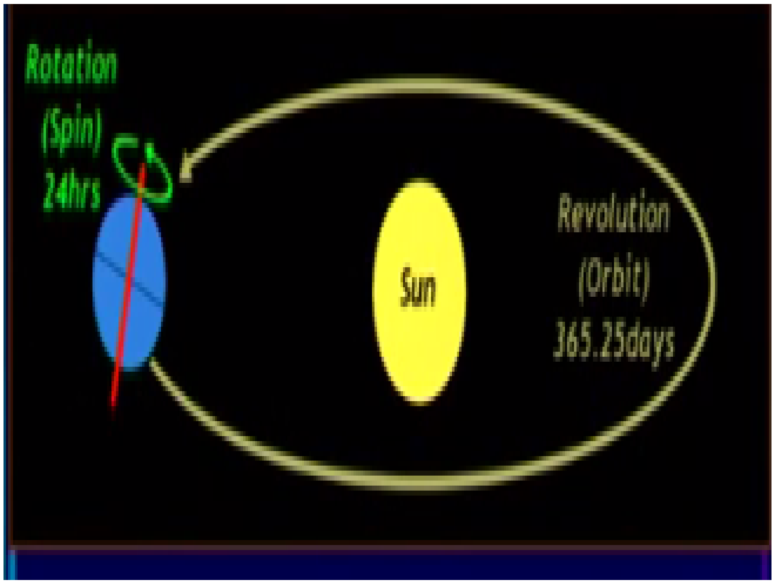

The axis around which the Earth rotates once in a day is in fact, not perpendicular to this plane, so this is the plane; ecliptic plane in which the earth is rotating, revolving rather around the sun and it takes 365 and 14 days to complete one revolution but the earth, in addition to revolving around the sun is rotating about an axis.

And axis; this angle, that this axis of rotation of the Earth makes with the perpendicular to the ecliptic plane is 23.5 degrees, so the Earth revolves around the sun with a period of one year, the axis around which the Earth rotates once in a day is not perpendicular to the orbital plane but at an angle 23.5 degrees to this direction, this is what you have seen. So, the earth is rotating around this axis and is revolving around an axis which is perpendicular to this plane, okay.

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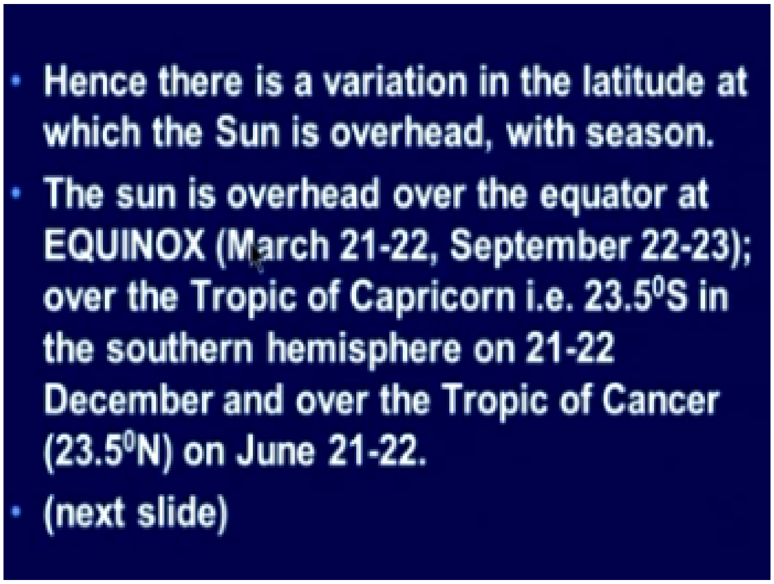

So, there is a variation in the latitude at which the sun is overhead with the season.

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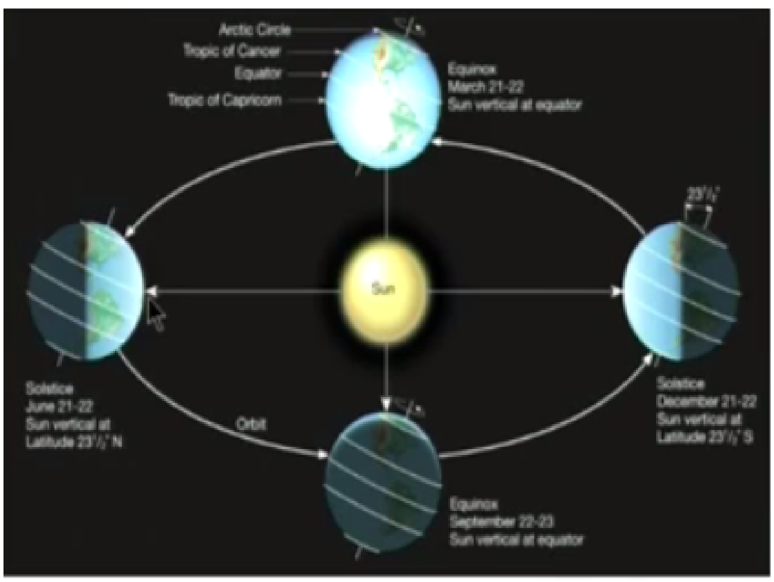

And that is seen here, okay, so you have the sun here okay, and this is the North Pole of the earth and this is the South Pole and this is the situation in the summer. So, in the summer, the sun is overhead, over this tropic 23.5 degrees north which is the tropic of cancer, so this is the summer style solstice as we call it in the northern hemisphere. On June 21, 22nd the sun is overhead over the tropic of cancer.

Then, comes the Equinox which is actually the September 22, 23rd, this is when the sun is overhead over the equator and then comes the; what we call winter solstice which is the summer solstice of the southern hemisphere, when the sun is overhead over the tropic of Capricorn which is the tropic in the southern hemisphere and then in March again, it is overhead over the equator okay.

So, this declination of the axis around which the Earth rotates to the orbital plane leads to this kind of a story that in the northern hemisphere; in the northern hemispheric, summer which is in June, the peak of the summer as far as the radiation is concerned is in June, at that time the sun is overhead over the tropic of cancer and in our winter which is December, it is overhead over the tropic of Capricorn.

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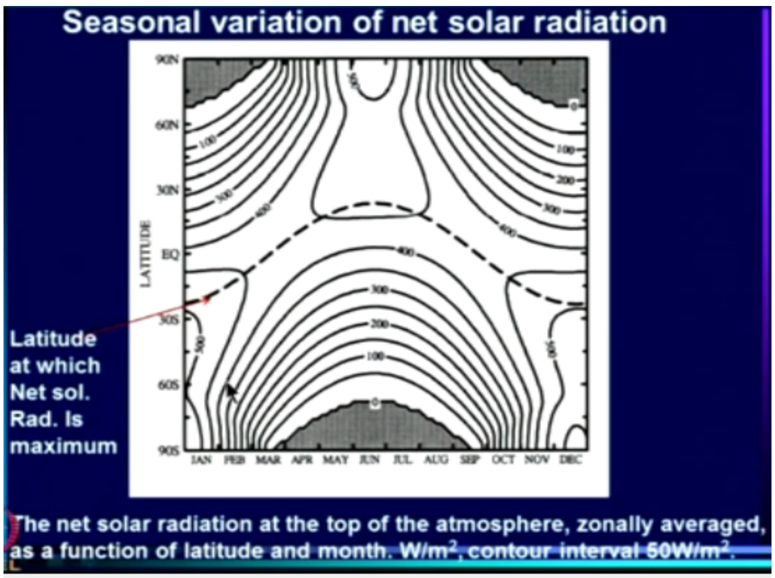

So, the sun is overhead over the equator at the Equinox which is March 21, 22nd and September 22, 23rd over the tropic of Capricorn in the southern hemisphere at 23.5 degree south on 21st, 22nd December and over the tropic of cancer on June 21, 22nd, this is what we have seen. Now, what does this mean? This means that the net solar radiation actually varies with season as you can see, this is from January to December.

And this is the latitude now, southern pole to the northern polar, 90 south to the 90 north, what you see is that the maximum net radiation is always in the equatorial region but the latitude at which it is maximum goes from the southern hemisphere in December, it starts moving northward in June, it is in the northern hemisphere and then again moves outward. So, this is the seasonal migration of the latitude of; at which the net solar radiation is maximum.

So, this is the seasonal migration of this latitude okay, so the net solar radiation at the top of the atmosphere when it zonally average as a function of latitude and month shows very clearly the seasonal migration of the belt of the region where it is high, which is this migration here and the maximum is shown by the dashed line, which you can see going from the southern hemisphere to the northern hemisphere in June and returning to the southern atmosphere in December.

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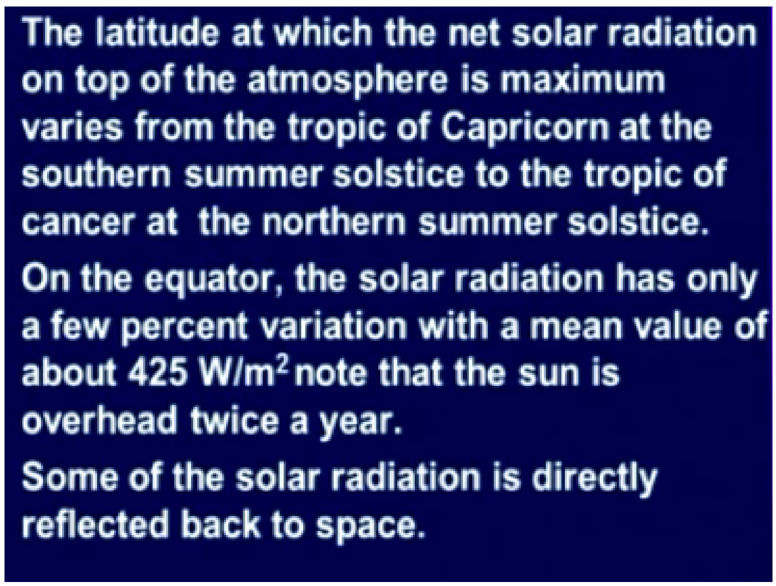

So, this is the seasonal variation of the radiation which actually drives the atmospheric circulation, so the latitude at which the net solar radiation on top of the atmosphere is maximum varies from the tropic of Capricorn at the southern summer solstice to the tropic of cancer at the northern summer solstice. On the equator, the solar radiation has only a few percent of radiation with a mean value of 425 watts per meter squared.

And the sun is overhead twice a year at the equator, so the sun is overhead at this time as well as this time at the equator and so you have; so at the equator, the solar radiation has very little variation, so you can see by and large at the equator, there is very, very little variation of the solar radiation, see its around; its more than 400 watts throughout the year, okay. Now, some of the solar radiation is directly reflected back to space.

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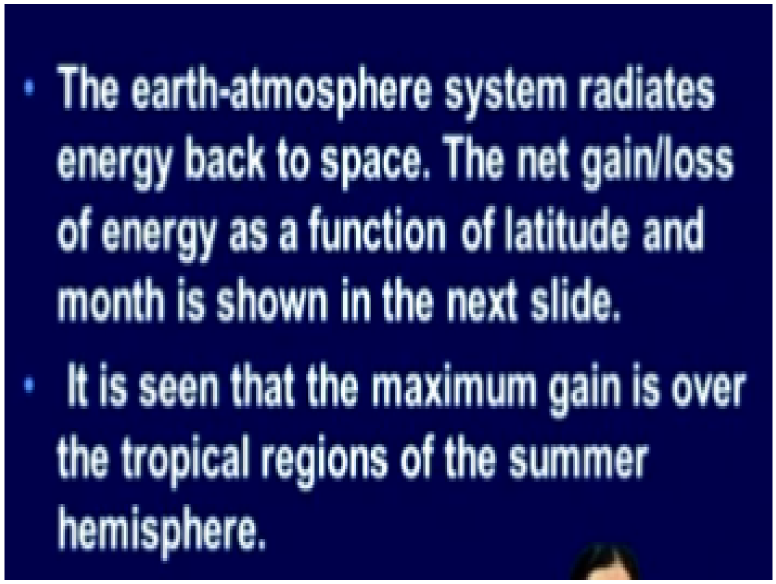

So, the earth atmosphere system receives radiation from the sun and in turn radiates energy back to space because otherwise, it would keep on hitting up, equilibrium is there only because the Earth atmosphere system radiates energy back to space. Now, the net gain or loss of energy as a function of latitude, we see here.

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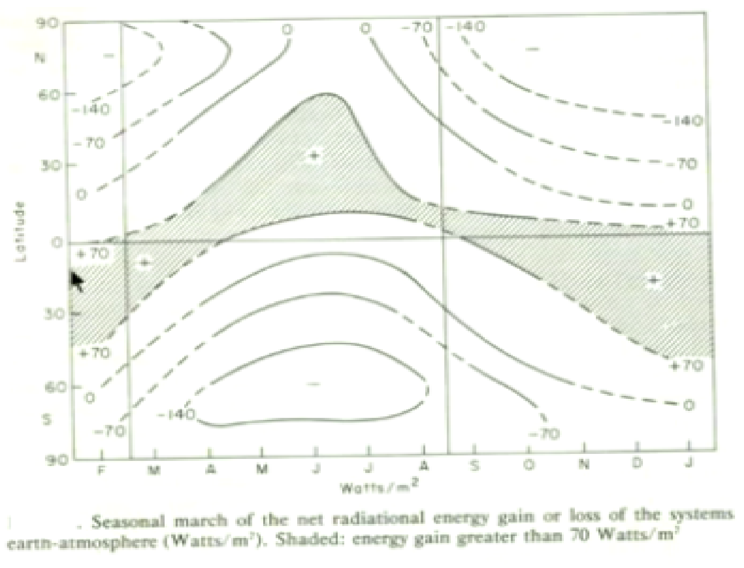

So, this is net gain or loss of energy, this is the balance of what you get from the sun; the incoming solar radiation and what is all emitted by the Earth atmosphere system and you see here that this is net gain here in this region, again this is beginning with January here and this is our winter, when the net gain; maximum gain is in the southern hemisphere, this belt of maximum gain actually moves north, in the northern hemisphere in a summer.

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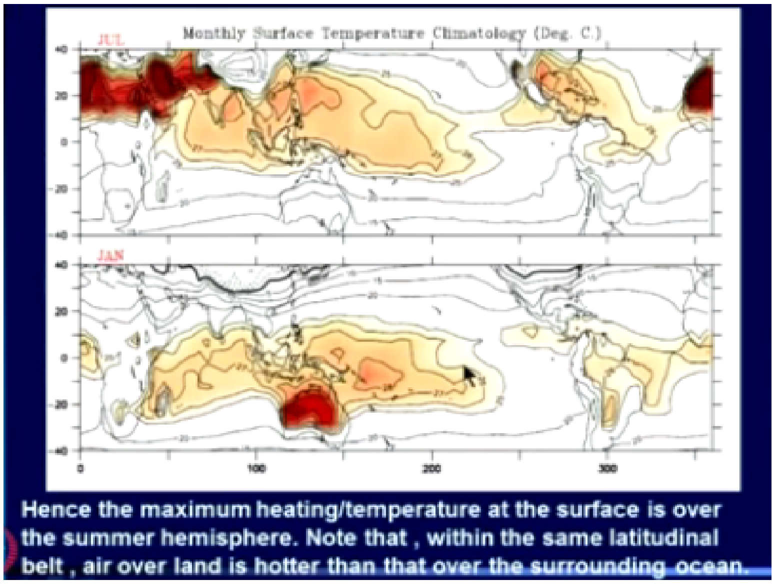

And then retreats to the southern region in our winter, so this is the seasonal march of the net gain in heat okay, so in response to the seasonal March, how does the surface temperature change? We have seen that the; this maximum gain in the northern hemisphere in our summer and in the southern hemisphere in our winter, so this is a surface temperature of a typical month in our summer; July.

And what you see here is that the maximum temperature is in fact, also in this northern hemisphere in July which is not a surprise because that is where the net gain in heat is maximum, so this is the maximum temperature here and in January, the maximum temperature is in the southern hemisphere, so hence the maximum heating and temperature at the surface is over the summer hemisphere, this is the summer hemisphere.

Northern atmosphere is the summer atmosphere in July, southern hemisphere is the summer hemisphere in January but you also notice another feature that given the same latitude, the land gets much hotter than the ocean okay, this is something to be noted, you see here also, in Australia is much, much hotter than the ocean at the same latitude which receives the same radiation okay.

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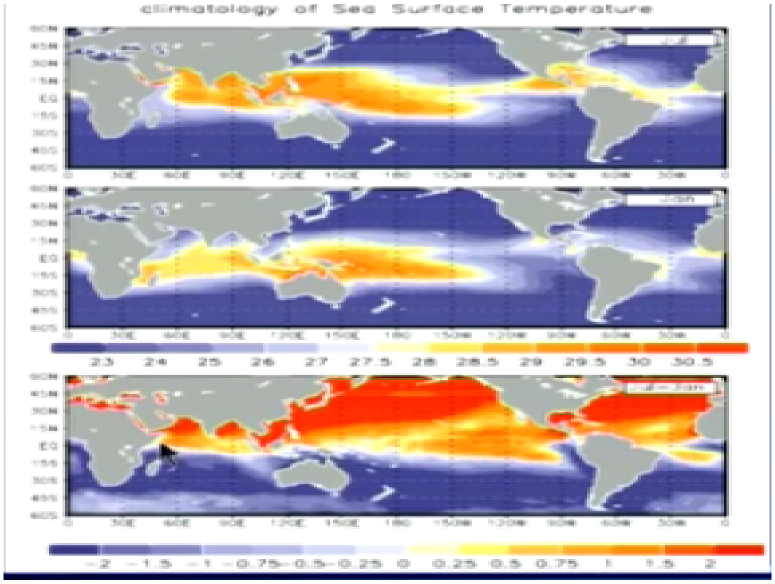

Now, this is the sea surface temperature, what we saw earlier was the surface air temperature, this is the sea surface temperature and in the sea surface temperature also, you see that the maximum sea surface temperature is in the northern hemisphere in our summer in July and shifts to the southern hemisphere in January, which is the southern hemispheric summer and what you see here, is the difference between July and January.

And you see that there is a lot of heating of the northern hemisphere in July related to January.

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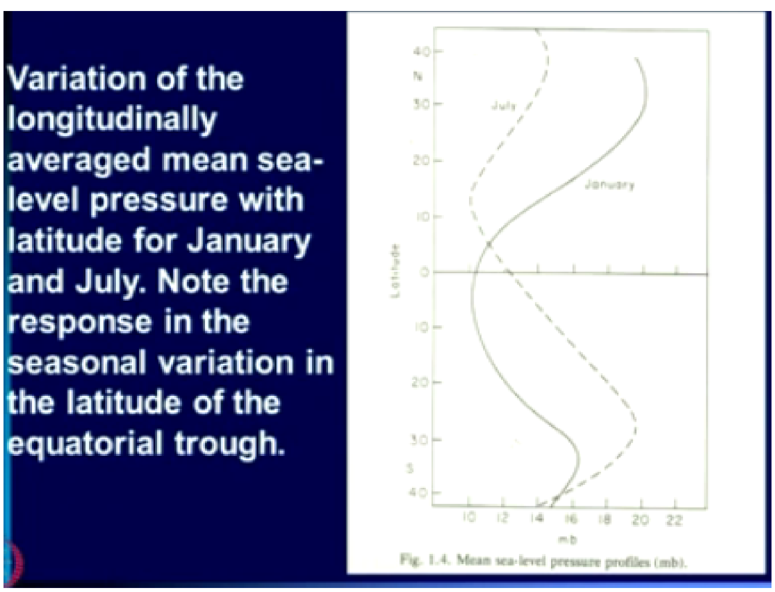

The SST or the sea surface temperature is much warmer here in July than January okay. Now, in response to this, what does the equatorial trough do? Remember that for the annual average, the maximum heating was at the equator and that trough was also in over the equatorial region, now the maximum heating; the latitude of maximum heating is changing with the season. In July, it is in the northern hemisphere, in January it is in the southern hemisphere.

So, what happens to the location of the equatorial trough, so mean sea level pressure with latitude for a January and July is shown here. This is again average over all longitudes, so if you look at July, then you find of course, high pressure here, the higher latitudes and the minimum pressure is around 15 degrees north, in January, it is nearer the equator, so there is a seasonal variation in the location of the minimum of surface pressure, that is seen which is consistent with the seasonal variation of temperature.

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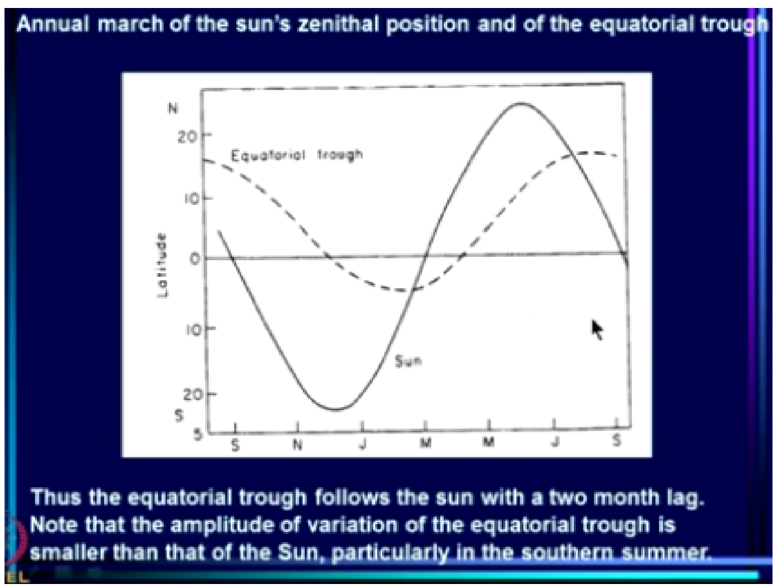

So, now this is an idealised picture again, annual march of the sun zenithal position; position or the latitude over which the sun is vertically above, sun is overhead and of the equatorial trough, so we have the surface trough, equatorial trough, which moves north in the summer and come south in the winter, this is January and this is March, so the equatorial trough comes south and this is in response to the sun okay, which in fact has its southernmost location in December and the northernmost location in June.

So, in response to the seasonal variation of the heating, we have seasonal variation of the location of the surface trough, note that the amplitude of the response is smaller than the heating itself that actually the region over which the equatorial trough varies; the latitudinal extent or the amplitude of the equatorial trough variation with season is smaller than the latitudinal extent of variation of the sun itself.

And secondly noticed that there is a lag, which again we expect because the atmosphere; earth atmosphere system does not respond instantaneously. So, there is a lag between the forcing by the sun and the equatorial trough, so the equatorial trough gets its southernmost position about 2 months after the sun has got its southernmost position and similarly here also, there is a lag of about 2 months and this is primarily from the oceans.

Because the sea surface temperature, you know it takes time to respond the ocean is somewhat sluggish and it is only after the sea surface temperature attains the maximum latitude that the equatorial trough moves there. So, first and foremost that the equatorial trough follows the seasonal march of the sun but with a lag of 2 months and the amplitude of variation of the equatorial term; trough in terms of latitude is less than that of the sun which is forcing it, okay.

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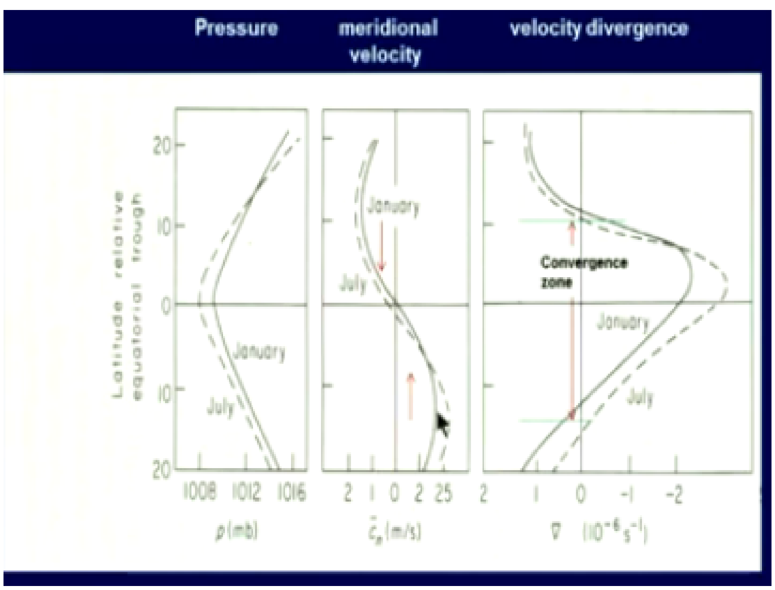

So, now relative to the equatorial trough, what do the different distributions look like? First, is just the pressure; surface pressure and obviously since we have made the equatorial trough at zero latitude obviously, the pressure will increase both in January and July, north and south of the trough. Now, these are the meridional velocity or the north south velocity. So, from the south of the trough, the velocity is towards the trough or southerly.

From north of the trough, the velocity is northerly or towards the trough, okay and this is true both for January and July. What you see here is convergence or divergence and so this is the zone of convergence around the equatorial trough zone, so this is a zone in which convergence occurred, this is why it is called ITCZ or inter tropical convergence zone; inter topical because the converge is coming by winds from both the hemisphere and this is the convergence zone.

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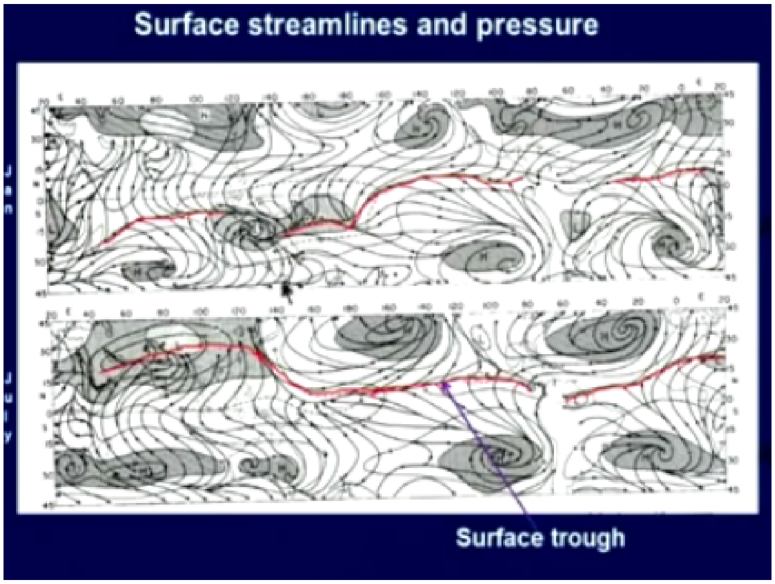

So, what do the surface stream lines look like? These are the surface stream lines and pressure and what you see here is that in fact, you can see this is India around here and the winds in January are start from the north east but since the trough is in the South, they actually turn here and these are the south east trades, these are the north east trades and here you see very clearly over a classical region, how convergence occurs between north east trades and south east trades.

And this is the surface pressure and you can see that the surface pressure trough in fact, moves from the southern hemisphere to the northern hemisphere as we go from January to July, so there is a seasonal migration which we saw earlier in the zonal average also of the trough from the southern hemisphere to the northern hemisphere. This is over our region which is the monsoonal region, it does not move as much over this Pacific, as you can see it is roughly at the same location.

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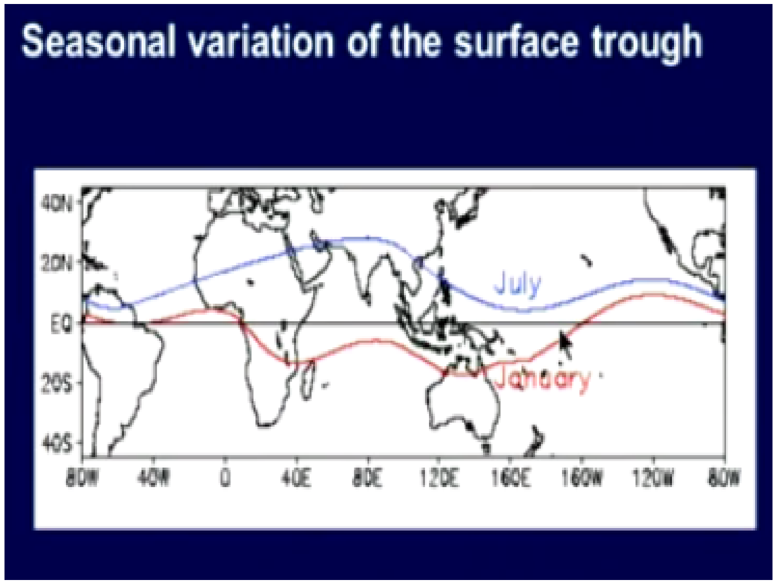

So, the amplitude of seasonal variation is not the same overall longitudes, it is moreover some longitudes and less over other longitudes, so in fact, you can see this depicted here that it is over continents that the amplitude of the variation is largest, this is African and this is the Asian region, whereas over the oceanic region, the amplitude of variation is very small.

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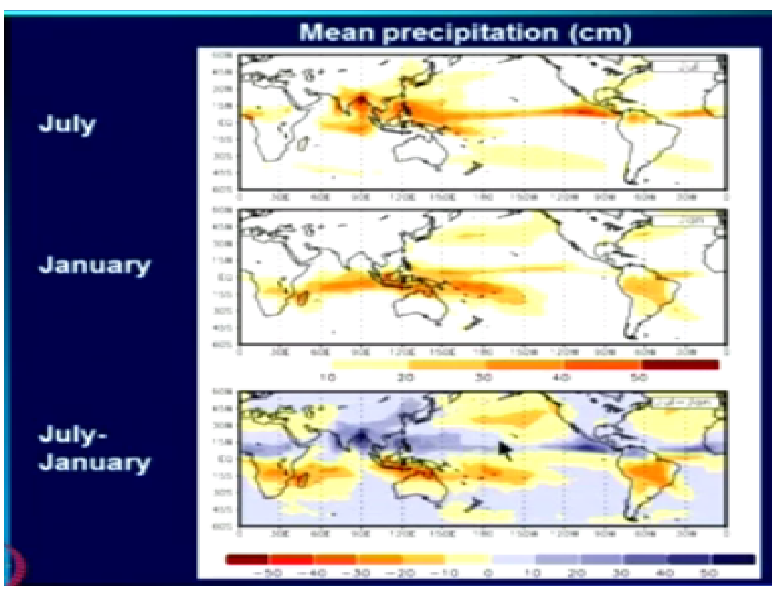

Now, let us look at precipitation, so we have rainfall for July and you can see that the rain belt is in the northern hemisphere, this is the rain and you also see a second mode if you wish in the equatorial region in July and then this is the rainfall in January, so if you subtract from July the rainfall in January, you will see that in fact, the rain increases in July throughout the northern hemisphere here but that the signal is very, very large over our region, okay.

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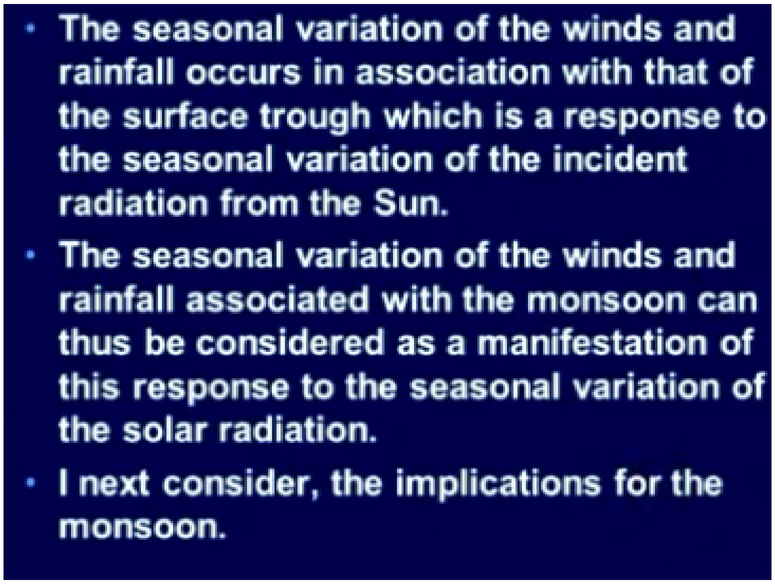

And it decreases here this in fact, this change in sign across for the difference, just signifies the shift of the system from here to here okay or when you go from January to July, this rain belts shift from here to here, that is why you see an intensification here and decrease in rain here, okay. Now, the seasonal variation of the winds and rainfall occurs in association with that of the surface trough, which is a response to the seasonal variation of the incident radiation from the sun.

Now, the seasonal variation of the winds and the rainfall associated with the monsoon can therefore, be considered as a manifestation of this response to the seasonal variation of the solar radiation, so you see, we have now looked at a very simple picture of how the tropical circulation arises due to the incident solar radiation being maximum at the equatorial region and decreasing as you go pole ward in either the hemisphere.

Then, we have also noted the fact that actually this incident radiation varies with season and you have a maximum incident radiation in the northern hemisphere in the northern hemispheric summer, maximum solar radiation in the southern hemisphere in the southern hemispheric summer as a result of that, the net radiation game also is maximum in the southern hemisphere in the summer, this is the net from what we get from the sun minus what the Earth atmosphere system emits back to space.

So, that is also maximum in the northern hemisphere in the northern hemispheric summer and in the southern hemisphere in the southern hemispheric summer. So, there is the seasonal variation in the location of where the heating is maximum in response to that, there is the seasonal variation of the temperature, this is the temperature of the ocean which is sea surface temperature and the temperature of the land as well.

So, overall the temperature at the surface of air actually is maximum in the summer hemisphere, it is maximum in the northern hemisphere in our summer which is June, July, August and it is maximum in the southern hemisphere in our winter or the southern hemispheric summer, which is December, January, February. So, now with the maximum temperature varying; the location of the maximum temperature or the heating varying from the southern hemisphere to the northern hemisphere, as we go from our winter to our summer, the pressure distribution also responds.

And so, the equatorial trough as the real cause it or the surface pressure trough actually goes from the southern hemisphere in December, January, February to be located in the northern hemisphere in our summer okay, and we see the surface trough over all the longitudes including our own monsoonal regions or Indian monsoon region and this trough in fact, comes over India in our summer monsoon time okay.

Now, in association with the seasonal variation of the trough will be seasonal variation in the direction of winds, so the seasonal variation of the winds and rainfall associated with the monsoon can thus be considered as a manifestation of this response to the seasonal variation of the solar radiation okay. So, now we have to consider the implications of the monsoon, let me just go back for a minute into what we are seeing now.

So, the second hypotheses say that the system which gives us rain, which is responsible for the monsoon which is; which in fact, leads to the seasonal variation of winds by which Arabs define the monsoon and also leads to a seasonal variation of rainfall, which we observe over our region and this system according to the second hypotheses is nothing other, then the inter tropical convergence zone or a equatorial trough, which gives rain in other parts of the tropics.

So, whereas, the first hypotheses said that the monsoon arises because of land-ocean contrast, so they actually attributed the monsoon to a system, which is special to the monsoonal regions of the world okay, which arises there, because of the land-ocean contrast. The second hypotheses which is a fallout of all the analysis that was done by Charney, Riehl and so on actually, says that the system that gives us rain in the monsoon or that the seasonal variation of winds and rain which we associate with the monsoon is simply a manifestation of the arrival of the system onto our region

Arrival of the ITCZ onto our region during the summer and then, the system retreats from our region to the winter hemisphere, in a winter. So, it retreats from our region to the southern hemisphere in our winter. Now, this is actually, a totally different approach to seeing it because if the system is special to our region, then we have to figure out, what is going to be the variability associated with it.

Why is it important to; first of all, identify what is the basic system responsible for the monsoon as we saw in the critique of the land-ocean contrast as the primary source; primary forcing of the monsoon that Simpson talked about. He said that you know, actually the land-ocean contrast is minimum, when the rain is maximum and where the rain is maximum? Remember, he pointed out that when India is at its hottest in May, there is no rain.

And when it cools down in July, there is plenty of rain, so this is opposite to what one would expect from the land-ocean contrast being the primary driving force of the monsoon. Similarly, he mentioned that actually, the rain is least, where the temperature is hottest, this is over Rajasthan. If you look at the mean picture, we have maximum rain over the eastern part of the monsoon zone; Orissa and Eastern European zone on and so forth.

Whereas, the western part of the monsoon zone towards the north west, which actually tapers into the Rajasthan desert, that is the region where the temperature is highest, so for that reason the land-ocean contrast would be highest but that is not where most of the rain occurs, that is where the rain is minimum and he also pointed out that if you compare seasons; rainfall seasons in which we get a lot of rain vis-a-vis seasons in which we have droughts.

Like, we had a recent droughts in 2009 and we had very good rains in various years; 1998, 1975 and so on and so forth. If we compared those 2 seasons, then with land-ocean contrast theory, we would have expected that actually, land would be hotter in those years in which the rain is more but the opposite is seen and this was shown very nicely by Kothawale and Rupakumar, that if we compare years of extremes that is droughts vis-a-vis excess rainfall season.

Then, systematically what we see is, that at the surface in fact, that the air temperature is colder for excess monsoon seasons and warmer for droughts, so the land-ocean contrast is actually less for good rain seasons than it is for poor rain season, so this again goes against this theory, that suggests that in fact, it is a system, which is primarily driven by a land-ocean contrast. On the other hand, what we are now saying is, that the monsoon is a manifestation of the annual visit to our region of the ITCZ, inter tropical convergence zone or the equatorial trough as really called here.

So, it is a region, it is in fact, an annual visit of the system which gives rain all over the tropics, it is the same system that gives rain over is specific that we saw the, second hypotheses say it is the same; dynamically, the same system that actually comes over us in our summer and leads to the seasonal variation in winds and the seasonality of rainfall that we experience, so the 2 hypothesis are totally different.

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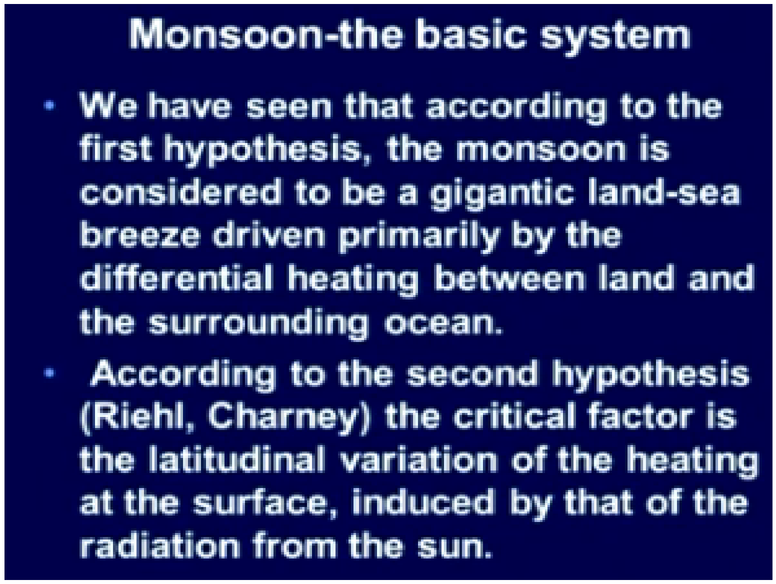

And we have to now considered the implications for the monsoon, hoops; okay, so this is the January and July pattern okay, so, no next we are going to consider, what are the implications of saying that the system that gives us the monsoon is not a system which is special to the monsoonal regions of the world driven by primarily by land-ocean contrast but rather is a system that is responsible for the rainfall all over the tropics which comes to visit us every monsoon season.

So, according to the first hypotheses, monsoon is considered a gigantic land-sea breeze driven primarily by the differential heating between land and the surrounding ocean and according to the second hypotheses, the critical factor is the latitudinal variation of heating at the service induced by that of the radiation of the sun. So, the system according to the second hypotheses is driven by the latitudinal variation in the heating of the sun at the surface.

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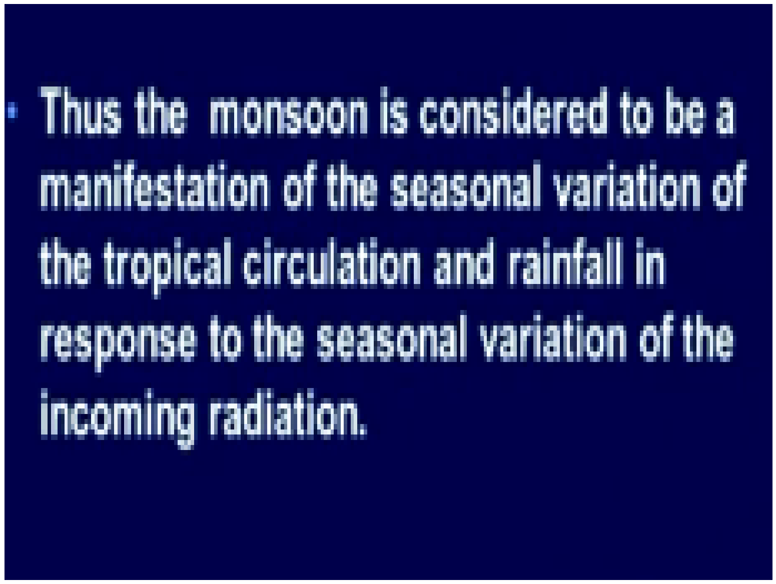

And the seasonal variation of this heating, so the second hypotheses says that the critical factor is latitudinal variation of the heating and seasonality of the latitudinal variation of the heating from the sun. Thus, the monsoon is considered to be a manifestation of the seasonal variation of the tropical circulation and rainfall in response to the seasonal variation of the incoming radiation. Now, the implications in terms of variability and on, is a very different.

A lot of work has been done on the inter tropical convergence zone on the oceans and what we are now saying is that the basic feedbacks that operate the basic mechanisms which lead to the variability of the inter tropical convergence zone, the classical canonical inter tropical convergence zone that we see over the Pacific, will also in fact, be operating over the monsoonal region, when the ITCZ visits us.

So, the hypotheses to explain the variability of the monsoon will be very different because now, we are saying that the system is the same one that we see over the tropical oceans, only thing is, now it has come overland and that would mean that other factors will also become important when it comes overland but the inside gained into the dynamics of the ITCZ, over the years, over various studies can now be used to gain an insight into the variability of the monsoon.

So, now in the next lecture we will actually see, what are the implications of assuming this and why do we believe that the monsoon is just a manifestation of the seasonal variation of tropical circulation and rainfall, there have been, you know this has been asserted by me at this point but we need to actually show that the system is indeed the same as the one that gives rain over the tropics and that is what I will show you in the next lecture. Thank you.