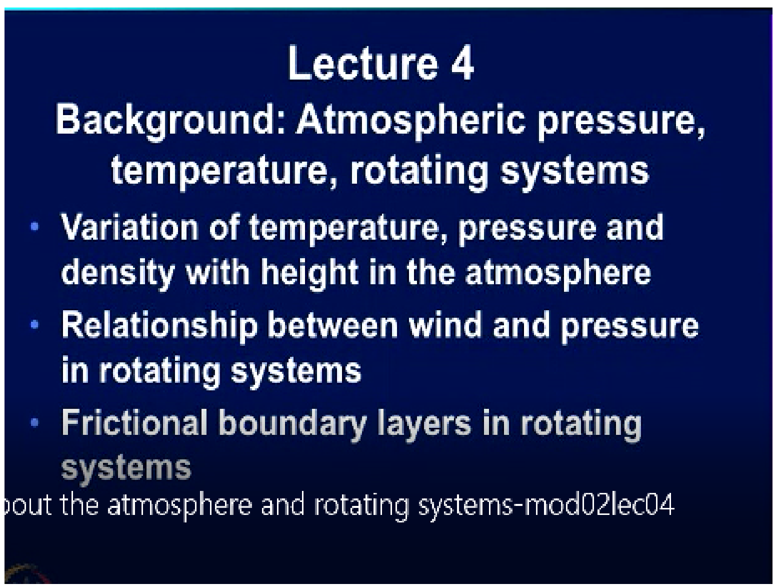
The Monsoon and Its Variability
Prof. Sulochana Gadgil
Centre for Atmospheric & Oceanic Sciences
Indian Institute of Science – Bangalore

Lecture - 04
Background about the Atmosphere and Rotating Systems

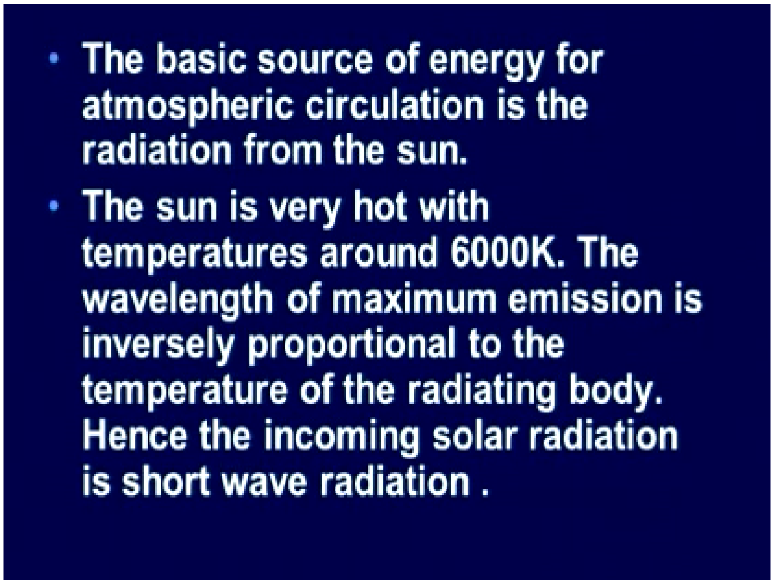
So last time, we have looked at the seasonal variation of the detection of winds associated with the monsoon and we also looked at the pressure pattern now to understand the relationship between rainfall which is what we focused on in the first 2 lectures the wind on the basis of which monsoon, regional monsoonal regions were defined and pressure and so on. One needs a little bit of a background.

(Refer Slide Time: 00:41)



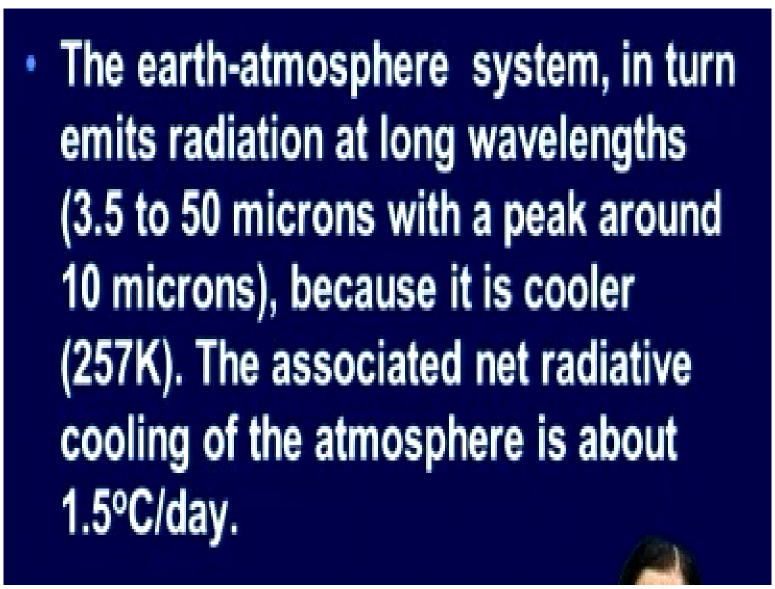
So that is what I am going to prepare in this talk to begin with you know the basic source of energy.

(Refer Slide Time: 00:50)



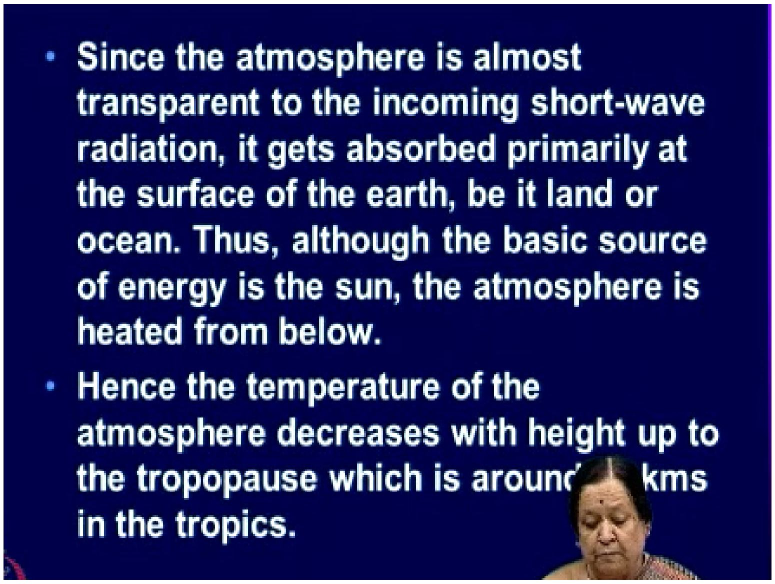
For the atmospheric circulation is the radiation from the sun now the sun is extremely hot as you know with temperatures around 6000 K that their wavelength of maximum emission is inversely proportional to the temperature of the radiating body.

(Refer Slide Time: 01:09)



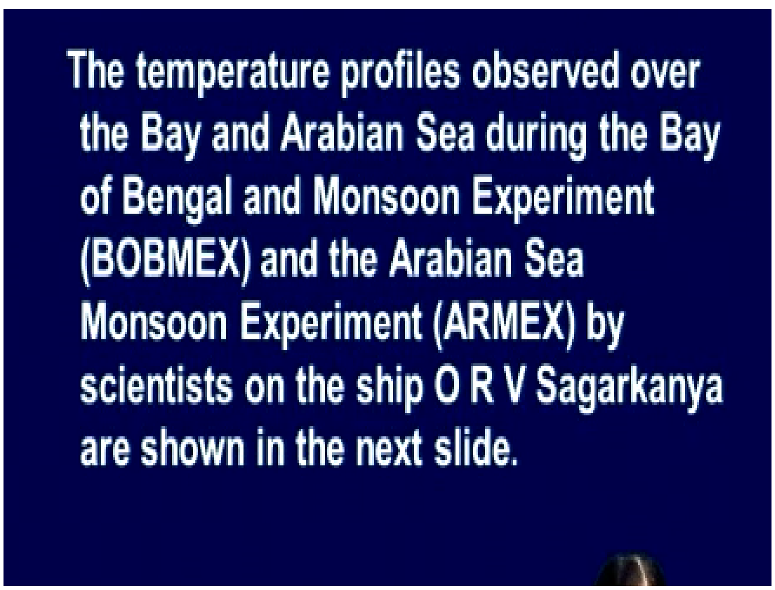
So the incoming solar radiation is short-wave now in turn the earth atmosphere system emits a radiation at long wave lengths that is with a peak of us around 10 microns because it is much cooler right it is about 257 K. So the associated net radiated cooling of the atmosphere is about 1.5 degrees a day so the atmospheric circulation is driven by the solar energy which comes in short-waves and the earth that must be a system in turn emits longwave radiation.

(Refer Slide Time: 01:45)



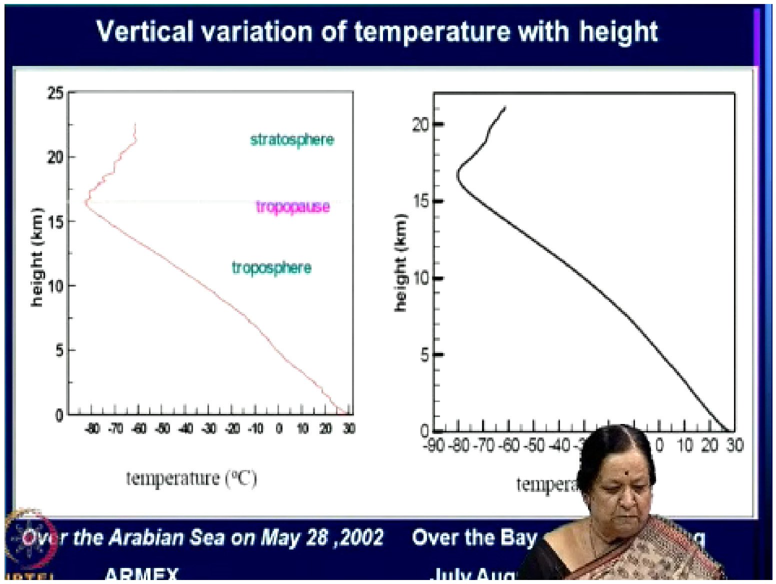
Now since the atmosphere is almost transparent to the incoming short-wave radiation it gets absorbed at the surface of the earth be it land or ocean so all the other basic source is far way it is the sun in fact the atmosphere is heated from below because the solar energy is observed at the surface so the atmosphere is heated from below hence the temperature of the atmosphere decreased with height up to the tropopause or so.

(Refer Slide Time: 02:11)



Now in the next slide I will show you temperature measurements reach out actually taken by scientists from our center over the Bay of Bengal and Arabian Sea during the BOBMEX Bay of Bengal monsoon experiment and the Arabian sea monsoon experiment.

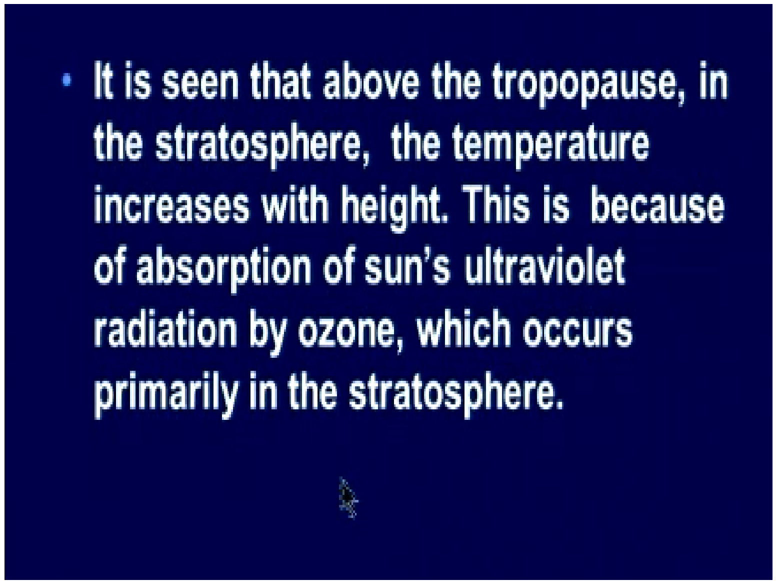
(Refer Slide Time: 02:26)



Now this is the vertical variation of temperature with height what you see is that temperature decreases with height steadily up to about maybe 15 or 16 kilometers or so and then it begins to increase with height this is the stratospheric increase of temperature that I talked about when I quoted low rains as not being anticipated or done by the meteorological theories, so this is a tropopause up to the tropopause.

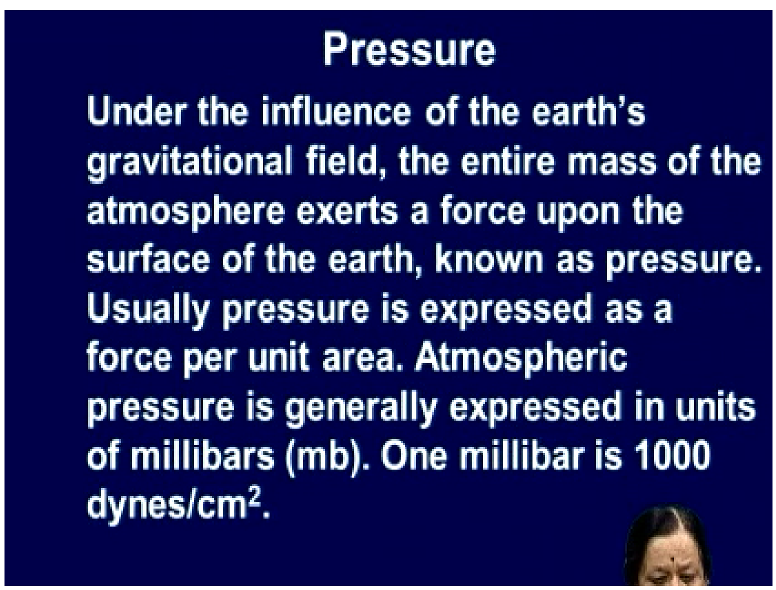
We have the troposphere in which we have a decrease of temperature with elevation above the tropopause is the stratosphere in which it actually increases but we will mostly focus on the troposphere because that is that all the action is in terms of winds that are climate winds now this is another profile this is from the Bay of Bengal and -this is from the Arabian sea actually very very similar you see that the tropopause was around 16 kilometers or so so the temperature decreases with height because the atmosphere is heated from below okay.

(Refer Slide Time: 03:42)



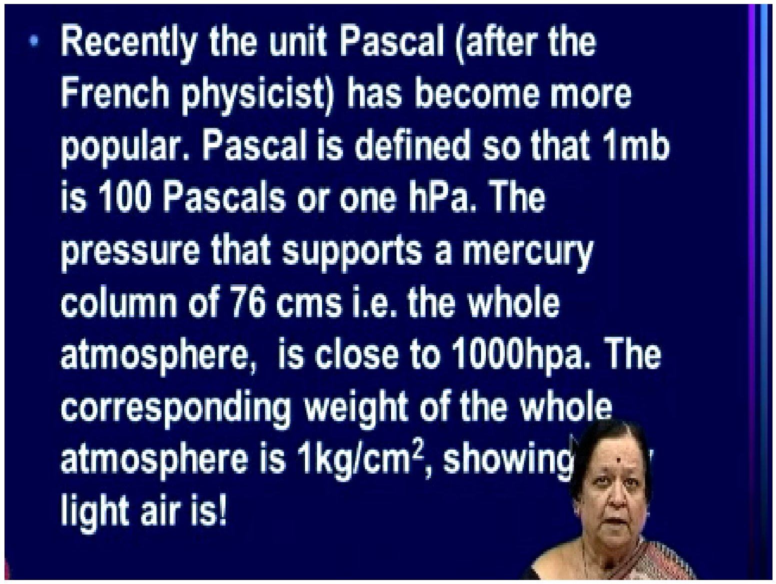
Now we have seen that about the tropopause in the stratosphere the temperature actually increases with height now why does that happen this is because in the stratosphere we have ozone ozone in fact primarily occurs in the stratosphere and ozone can absorb suns ultraviolet rays, so ultraviolet radiation on absorption by ozone creates warming in the stratosphere and that is why in the stratosphere temperature increases with height.

(Refer Slide Time: 04:10)



Okay so this is how the temperature varies in the atmosphere now consider the pressure and at the very important climatic element under the influence of the earth gravitational field the entire mass of the atmosphere exerts a force on the surface of the earth known as pressure usually pressure is expressed as force per unit area and atmospheric pressure is expressed in units of millibar which is the order unit with 1 millibar=1000 dynes per centimeter square.

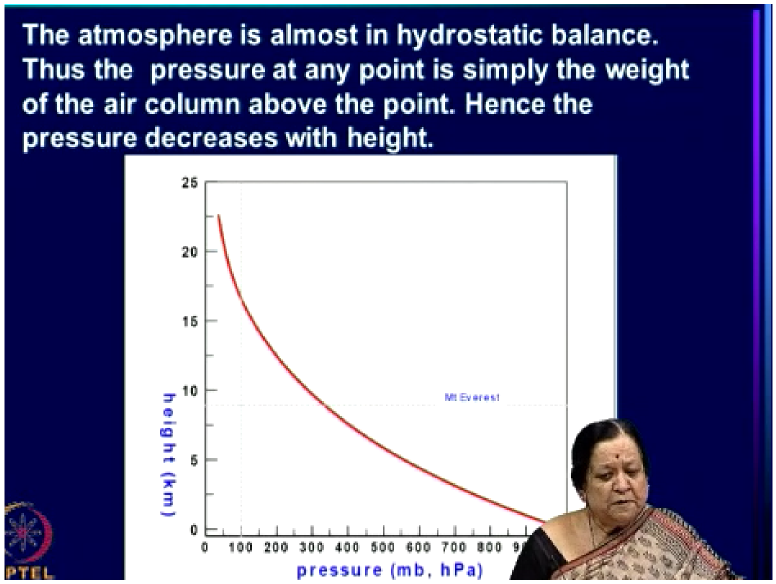
(Refer Slide Time: 04:51)



Dynes being of course a unit of force so force per unit area is dynes per unit square and 1 millibar=1000 dynes per centimeter square now recently meteorologist have begun to use another unit which is called Pascal named after the French physicist and Pascal is defined so that 1 millibar is 100 pascals or 1 hecta pascal so the pressure that supports a column of 76 centimeters that is the whole of the atmosphere is close to 1000 hpa.

Now we have all seen this is cool the parameter with the mercury column of about 76 centimeters being supported by the atmosphere and this is the pressure of the surface of the earth and this is around 1000 hpa the corresponding weight of the whole atmosphere is only 1 kilogram per centimeter square, so you can see how light air is.

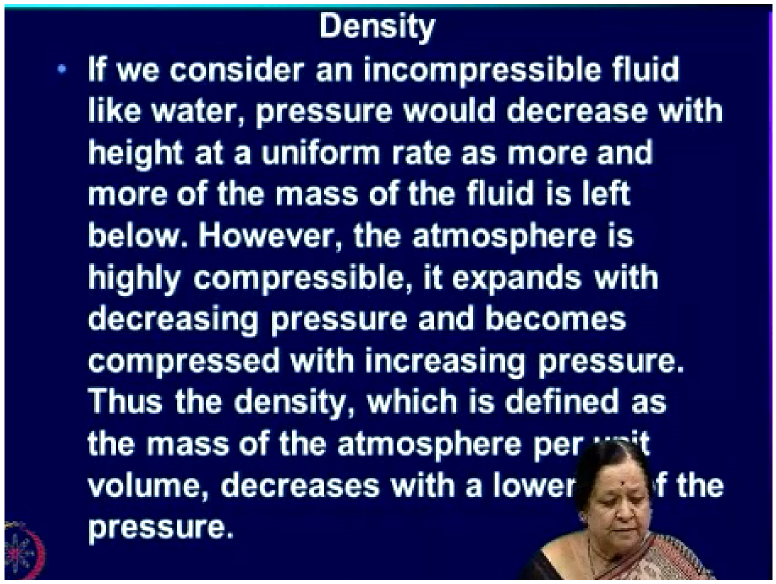
(Refer Slide Time: 05:41)



Okay now how does the pressure vary with height the atmosphere is almost in hydrostatic balance what does that mean this means that the pressure at any point is actually simply given by the weight of the air column above that point okay It is simply the weight of the air column above the point so naturally as we go higher and higher the height of the air column above decreases and so the pressure decreases.

So this is how the pressure varies with height and for your reference you can see Mt Everest is around here and there is a rapid decrease in pressure and we will in fact often come across various levels of pressure so that 850 is around 1.5 kilometers and so on and so forth and 500 millibar or hpa is around 6 kilometers or so about the atmosphere and this is the mid-troposphere above this is the upper troposphere now this is how pressure varies with height.

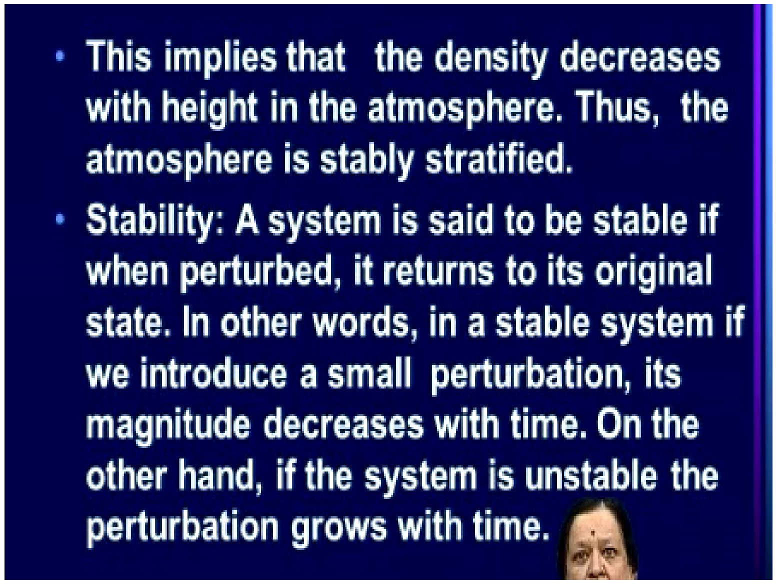
(Refer Slide Time: 06:48)



Now we have to consider density now if we had a incompressible fluid like water and this is relevant for the ocean then the pressure would decrease with height at a uniform rate why is that because the density is the same so as above you will get less and less fluid left so it will just decrease at a uniform rate however the atmosphere is highly compressible so it expands or decreasing pressure and becomes compressed with increasing pressure.

What does that mean that density which is defined as the mass of the atmosphere per unit volume therefore decreases with the loading of the pressure okay so as you go higher the pressure is lower and which means the density is also less okay, so this means that the density decreases with the height in the atmosphere.

(Refer Slide Time: 07:37)



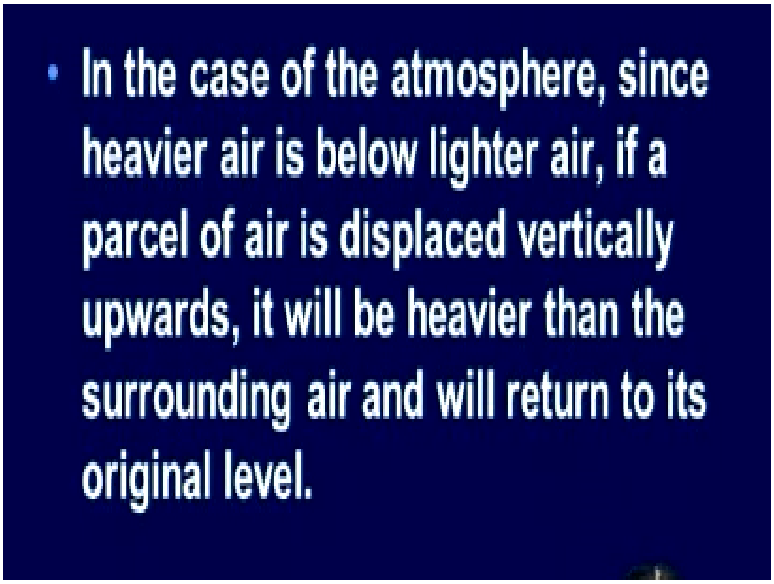
Thus, the atmosphere that is stably stratified now this concept of stability is going to come again and again. In this set of lectures because the spatial features of atmospheric weather is that many of the processes we are interested in you know that cloud systems that give us rain such as depression hurricane and so on and even the systems that give rain in the mid-latitudes system what is called weather are often the product of instability in the atmosphere.

So, it is important to have under our belt the concept of stability. So I will come to this again and again but right now let me just define stability for you a system is said to be stable if when perturbed it returns to its original state okay so you create a small perturbation it returns to its original state so we used to have a toy when we were small which used to be a doll with a very heavy bottom and no matter how much you pushed it it will always stand up vertical again.

I do not remember the English word for it and there is no point in telling you the Marathi word for it so this is a example of a very stable system that you can give perturbations to it but the but the perturbations die out in time and the system returns to its original state on the other hand I did that had considered an egg standing on its head you touch it a little bit and it will immediately fall this is an unstable system.

So, any perturbation you give to an unstable system actually will grow with time okay now why do I say that the atmosphere is stably stratified.

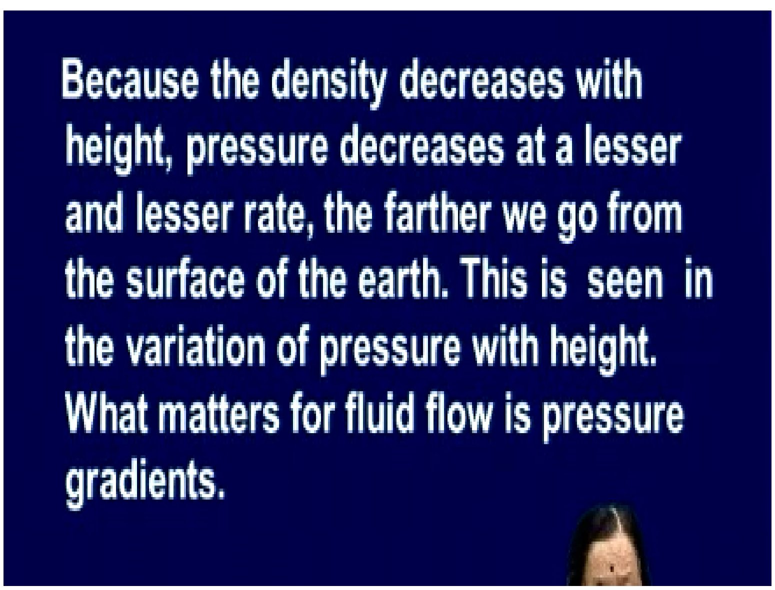
(Refer Slide Time: 09:15)



Because we have what does it mean we have said that density decreases as you go higher and higher that means heavy air is below light air that means even if you create some perturbations it is not going to turn upside down right because the perturbations are going to die because if your display a parcel of air vertically upward what example it is going to find itself in a surrounding in which the air is less dense around it and this particle is more dense.

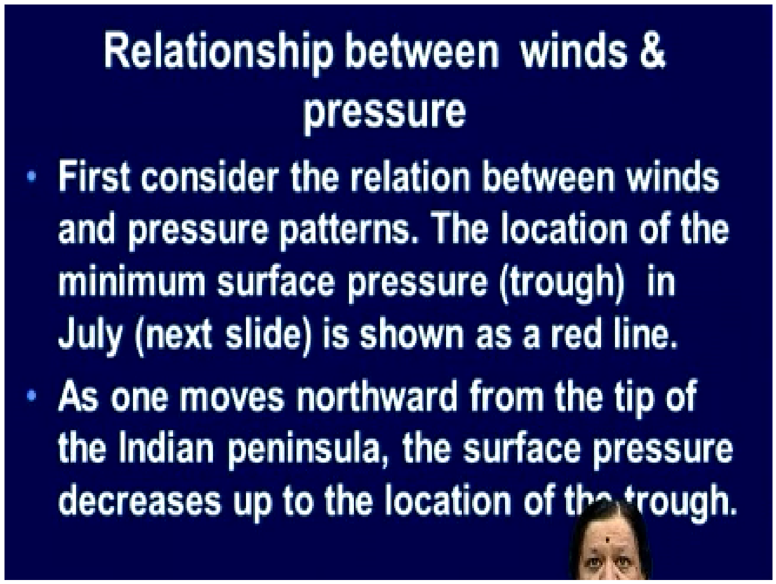
So, buoyancy forces will imply that it goes back to it original position so perturbations to such an atmosphere will die and therefore we consider the atmosphere is stably stratified.

(Refer Slide Time: 10:00)



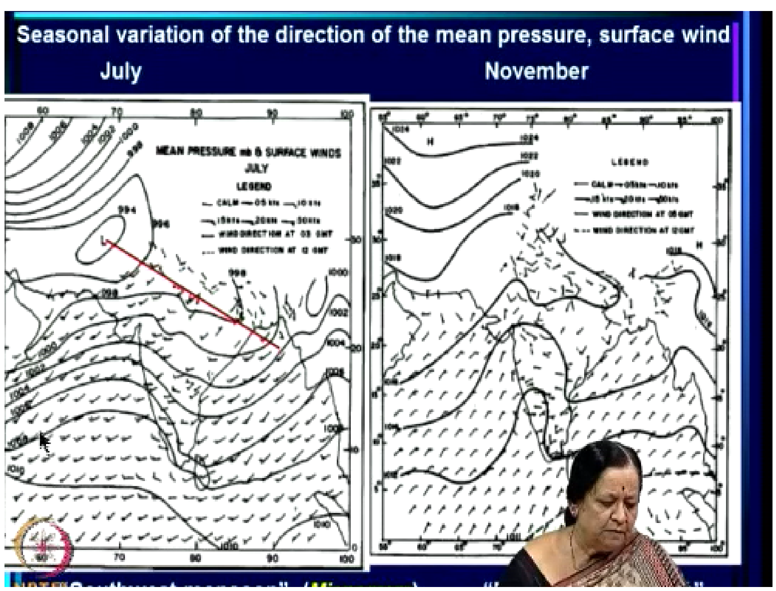
Okay now because the density decreases with height pressure decreases at a lesser and lesser rate the farther we go from the surface of the earth why is that because the amount of air in that column decreases because the density decreases. So, the weight of the air above also decreases and so the pressure decreases at a lesser and lesser rate farther we go and in fact we could have seen it in the earlier slide here see it is decreasing more and more slowly as we go here.

(Refer Slide Time: 10:35)



Okay now we are interested in relationship between winds and pressure okay so let us consider first the relationship between winds and pressure patterns.

(Refer Slide Time: 10:47)

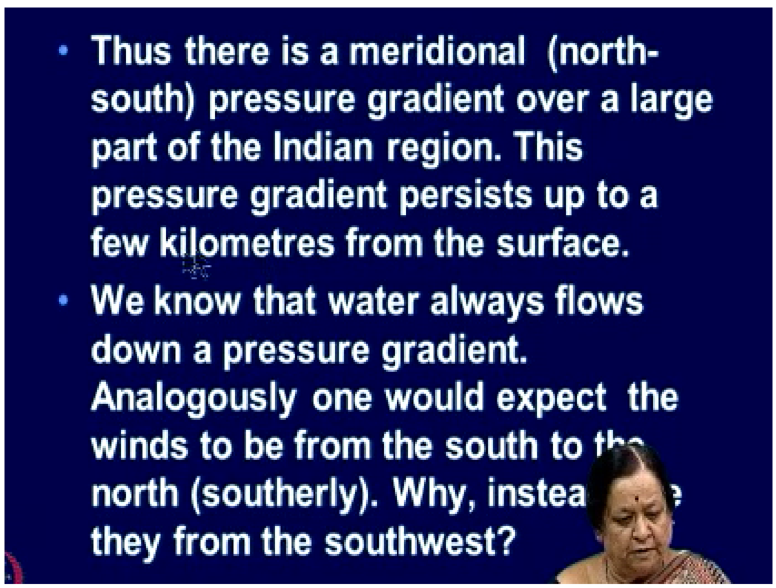


Let us see what we have seen earlier already these are the mean pressure and surface winds for

July and these are the mean pressure and surface winds for November and remember I explained last time that the winds are southwesterly that is coming from the southwest in July what does the pressure look like you can see that the pressure is decreasing from south to north this is the lowest pressure region here.

Okay and these are what we call isobars, isobars are lines of constant pressure so these are isobars, isobars are more or less east west and as you go from south to north the pressure is decreasing as you can see from these isobars so we have a pressure gradient which is such that high pressure is here and low pressure is here and yet the winds are not going from here to here right.

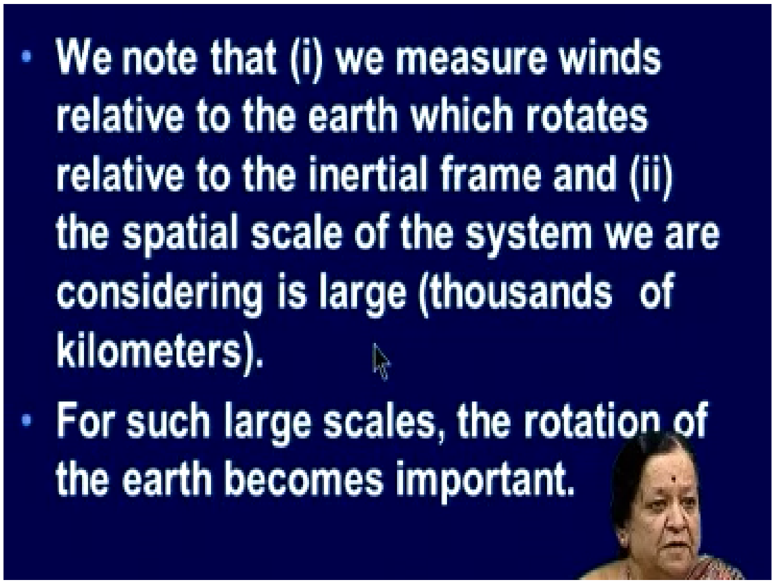
(Refer Slide Time: 11:47)



So, as I mentioned as one moves northward from the tip of Indian peninsula the surface pressure deceases till the attitude of the trough this region where the pressure is minimum is called a trough okay, so the pressure actually decreases as we go so there is a north-south pressure gradient over a large part of the Indian region and this pressure gradient in fact persists up to a few kilometers from the surface.

Now we know that water always slows down a pressure gradient right so in the kind of fluids we experience it in a laboratory for example we would expect that if there is a pressure gradient in the north-south direction right so that as you move northward the pressure is decreasing you would have expected the flow to be from south to north right towards the low pressure while instead out of the winds from the southwest.

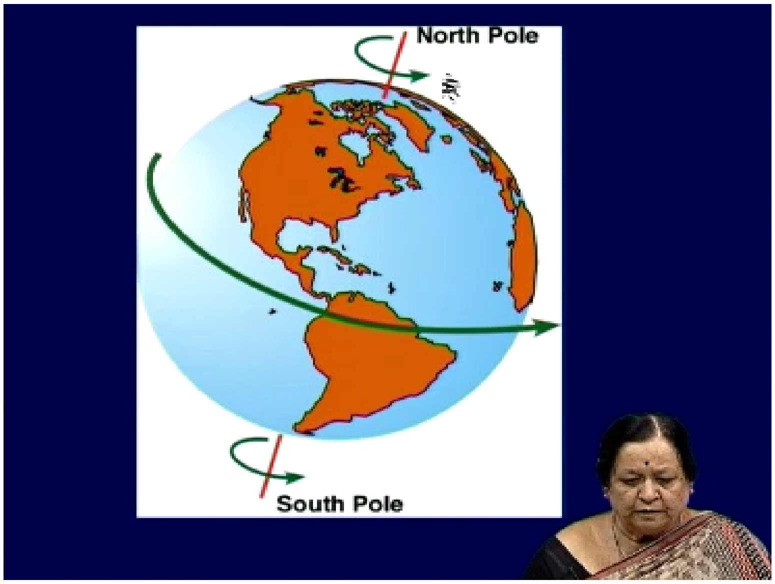
(Refer Slide Time: 12:42)



Now to understand this we have to know 2 things first of all the winds we measure here are relative to the earth relative to the surface of the earth and the earth it itself rotating with reference to the inertial frame of the fixed does so we are measuring velocities of winds a current relative to a rotating system okay and we also known that the spacious scale of the system involved is very large for example this is 70 degrees this is an 80 degrees.

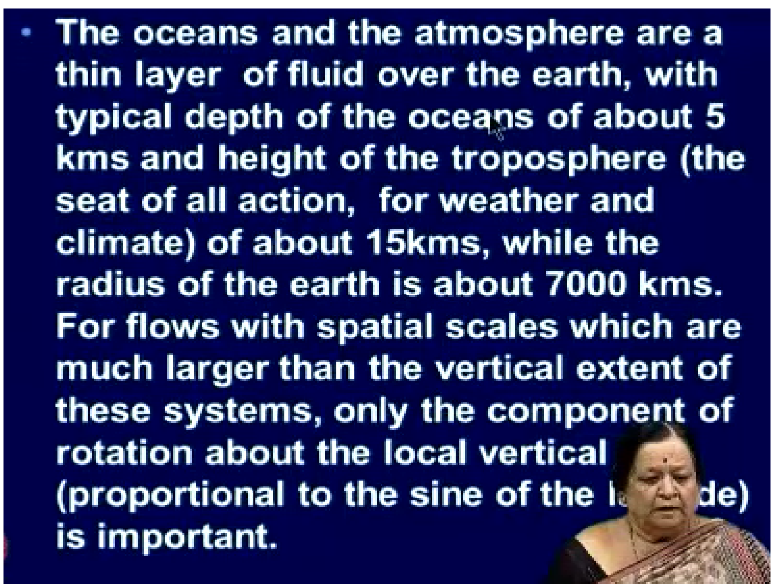
So, this is about 100 each degree is about 100 kilometer this is 10 degrees so this is about a 1000 kilometers so this is a system which is characterized by a spatial scale of 1000 of kilometers very very large-scale okay so when we have systems with spatial scale which is very large then the fact that we are measuring these winds relative to a rotating earth makes a difference okay rotation of the earth becomes important.

(Refer Slide Time: 13:46)



Now how is the earth rotating we all know that the earth rotates about an axis across from south Pole to north pole in this direction.

(Refer Slide Time: 14:01)

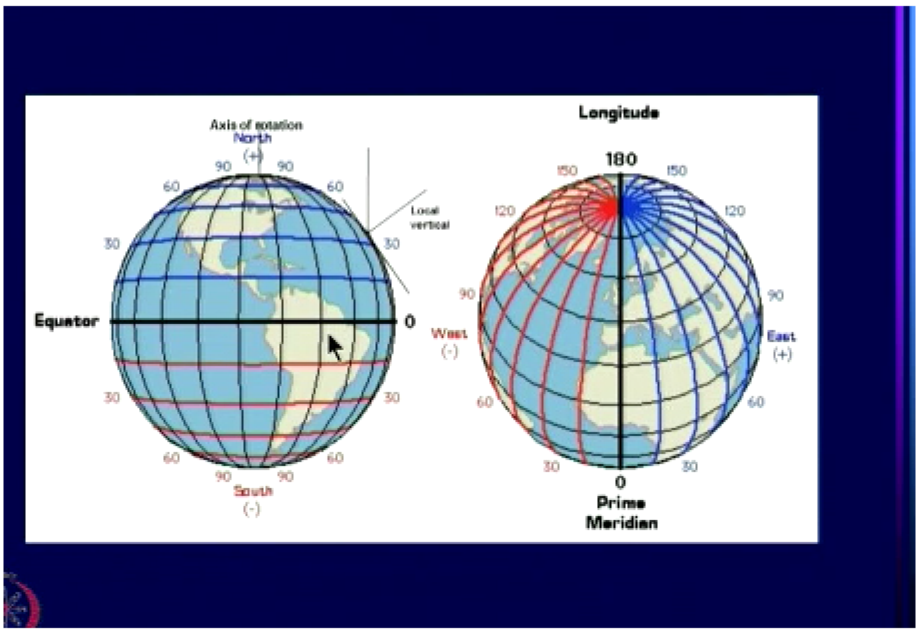


Okay now another thing we have to notice is the following that the oceans and the atmosphere are a thin layer of fluid over the earth with typical depth of the oceans of about only about 5 kilometers okay and you saw the troposphere is typically up to about 16 kilometers or so 15 or 16 kilometers or so while the radius of the earth is about 7000 kilometers so while the radius is 7000 kilometers.

So you can see that the radius of the earth is about 7000 on that there is a very thin layer of the atmosphere which is only 16 kilometers so you can say 16 versus 7000 so it is an extremely thin layer that we have and similarly oceans level flows with spatial scales which are much larger than the vertical extent of these systems that is to say for flows which are spatial scales much larger then few kilometers which is most of the systems.

We are interested in the monsoon system or the depressions and so on that we talked about only the component of rotation about the local vertical is important.

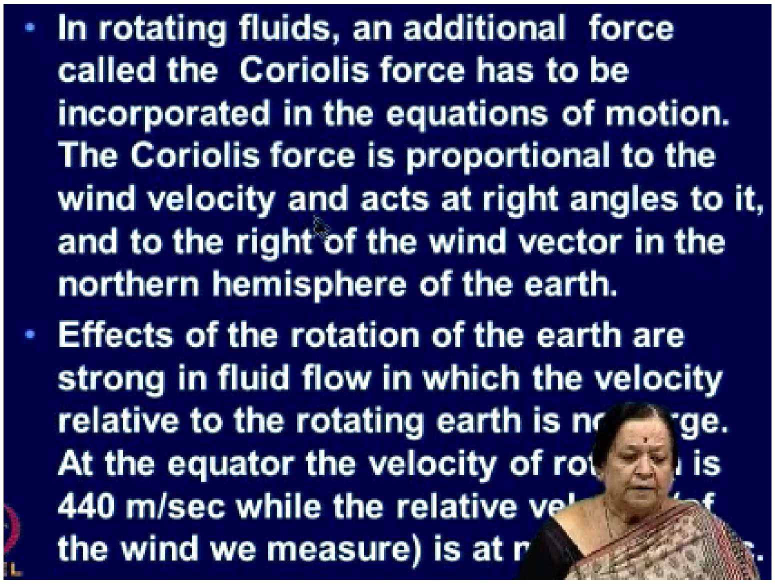
(Refer Slide Time: 15:06)



And this is something that I am not going to get into at this point this is something that we can look at and show by looking at the equations of motion governing a fluid which is on a rotating earth okay but what matters the main result is the following so suppose you are at this latitude okay and this is a tangential plane and this is local vertical okay whereas this is the axis of rotation of the earth.

So, what really matters are what the projection of this on the local vertical that is what is relevant when we are looking at the flow of a thin fluid over the earth okay.

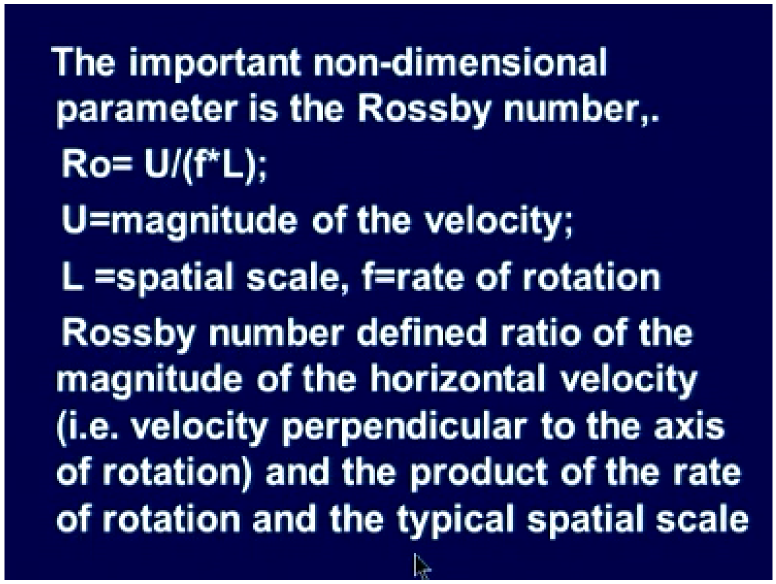
(Refer Slide Time: 15:50)



Okay now in rotating fluids an additional force called the Coriolis force has to be incorporated in the equations of motion. Coriolis force is proportional to the wind velocity and acts at right angles to it and furthermore which way it acts right angles could have been to the right or to the left of the wind but which way it acts depends on the how the system is rotating so for the earth in the northern hemisphere the Coriolis force is to the right of the wind vector.

Now effects of rotation of the earth are strong in fluid flow in which the velocity that led to the rotating earth is not large which means most of the flow is we are interest in it because at the equator the velocity of rotation is 440 meter per second okay it is huge this is the basic rotation of the earth while the relative velocity of the wind we measure is at most 40 so certainly the relative velocity.

(Refer Slide Time: 16:54)

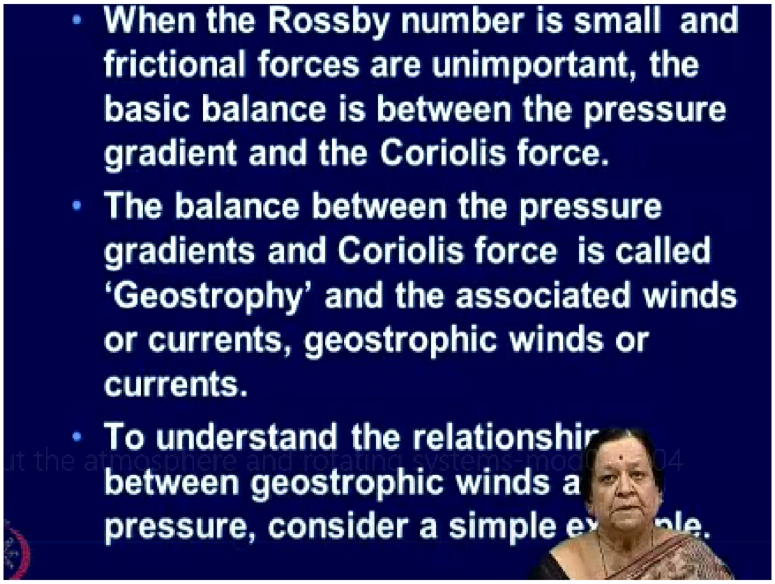


And order of magnitude smaller than the basic velocity now the parameter and this is again something we will run into again and again then we are trying to assess which of the many terms in the equation are important for a specific phenomenon are which of the forces are really dominating that phenomena what we do is to assess how large the different terms are so if you want to assess how large the friction try and assess.

How large is the friction we surveyed the acceleration and so on and so forth so in this case the important and the way by taking those ratios you formed non-dimensional parameters and it is how large these non-dimensional parameters are which will determine which flow regime we are in, is it a regime in which rotation is important is it regime in which friction is important and so on and so forth so for rotation the critical parameter is what is call it as Ross by number.

Which is the wind/rate of rotation * the spatial scale, you can just see that it is non dimensional because wind has dimensions of say meters per second and rate of rotation is one over something over second and length is again that so length over a second in this case and this is also length over second so it is actually a non-dimensional parameter and Rossby number defined as this this is the definition of the Rossby number.

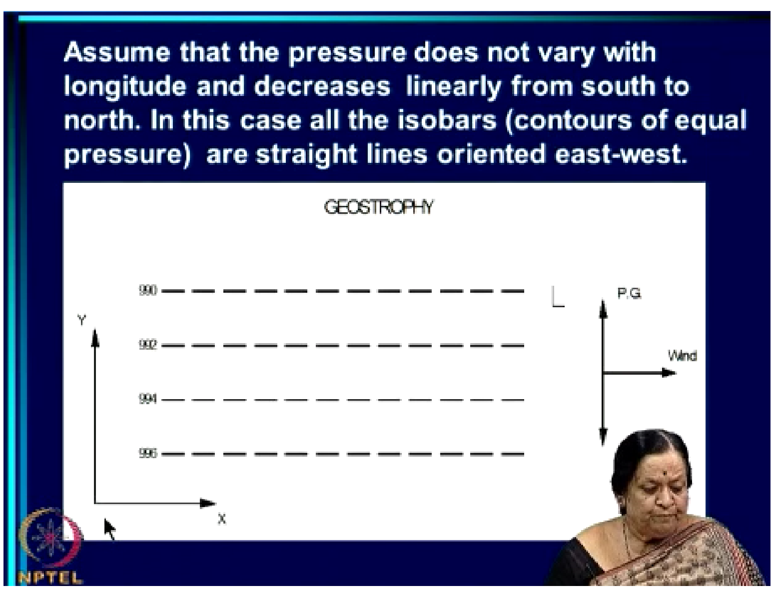
(Refer Slide Time: 18:23)



Now when they must be numbered is small and when friction and force is unimportant it is the rotation which is the most important term and then the basic balance is a bit in the pressure gradient and Coriolis force look at it another way that when we write down the full equations which we may we will do it much later on there that acceleration terms in the laws of motion which involve conservation of momentum there are acceleration terms that involve U.

And then there is the Coriolis term which involves F and when Rossby number is small it is the Coriolis term which dominates the local acceleration this is why.

(Refer Slide Time: 19:04)



This is way when the Rossby number is small basic balances between pressure gradient and

Coriolis force now this balance is called geostrophy and the associate winds or current are called geostrophic winds or current. Now let us understand what it is the relationship between pressure patterns and winds when you have a geostrophic balance okay and to do so I am going to consider it a very simple example.

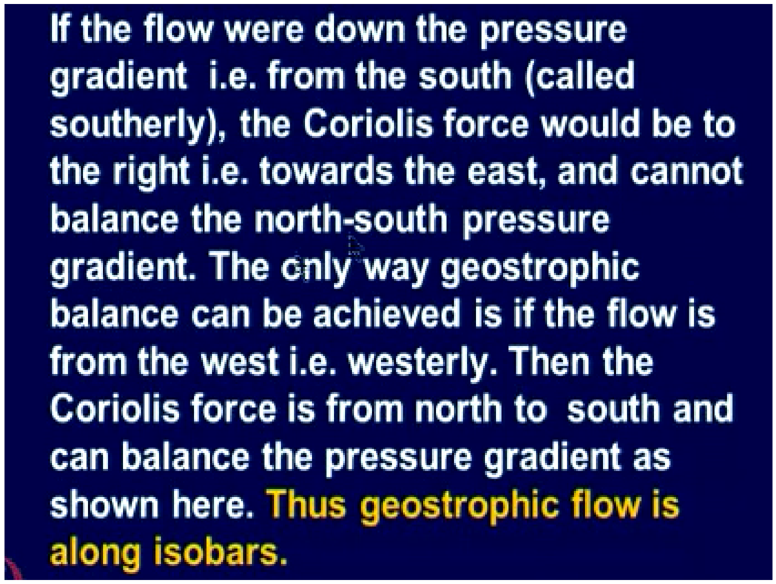
Let us assume that actually all the isobars are along the longitude circles if you wish I consider this as a longitude and this as a latitude so this is increasing latitude this is longitude and they are independent of longitude in other words, we have actually pressure decreasing from 996, 994, 992 to 990 so we have a steady linear decrease of pressure from here to here and we want to know how the wind would be in a non-rotating system.

Of course the wind would be simply coming from south to north now if you assume that the wind was the same in this rotating system what would happen if the wind were to go from south to north okay then the Coriolis force is to its right so it would be this way right and the pressure they gradient is this way so the Coriolis force cannot balance the pressure gradient so the only way the 2 can be balanced is if we have this kind of a situation.

We have wind, vectors parallel to the isobars okay wind blowing this way then what will happen then the Coriolis force as I said is to the right in the northern hemisphere so it is this way and the pressure gradient is this way so when you have wind like this it is possible for the pressure gradient to be balanced by Coriolis force in other words when rotating when we considered rotating systems in which rotation is very very important.

That is to say the spatial scales are large in those systems in fact you get a balance between pressure gradient and Coriolis force and in those systems, you do not expect flow of winds to be down the pressure gradient but rather along the isobars now this is a very striking difference between rotating and non-rotating systems.

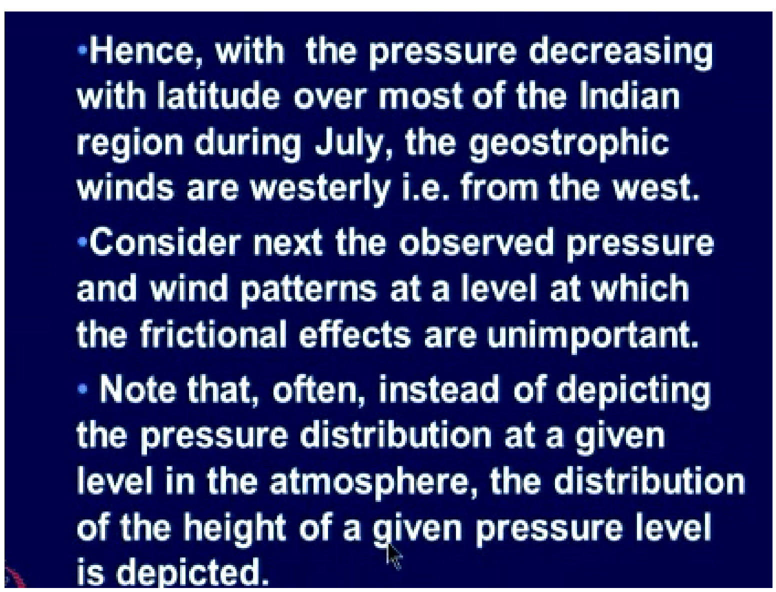
(Refer Slide Time: 21:29)



So as a explained here earlier if the flow were down the pressure gradient then the Coriolis force to the right cannot be balanced by the pressure gradient the only way geostrophic balance can be achieved is if the flow is from the west that is westerly meteorologist call flow from the south southerly and flow from the west as westerly and so on this is something that I will keep using then the Coriolis force is from north to south.

And I can balance the pressure gradient as we have seen thus geostrophic flow is along isobars hence with pressure decreasing with latitude over most of the Indian region during July which we saw the geostrophic winds are westerly from the west okay.

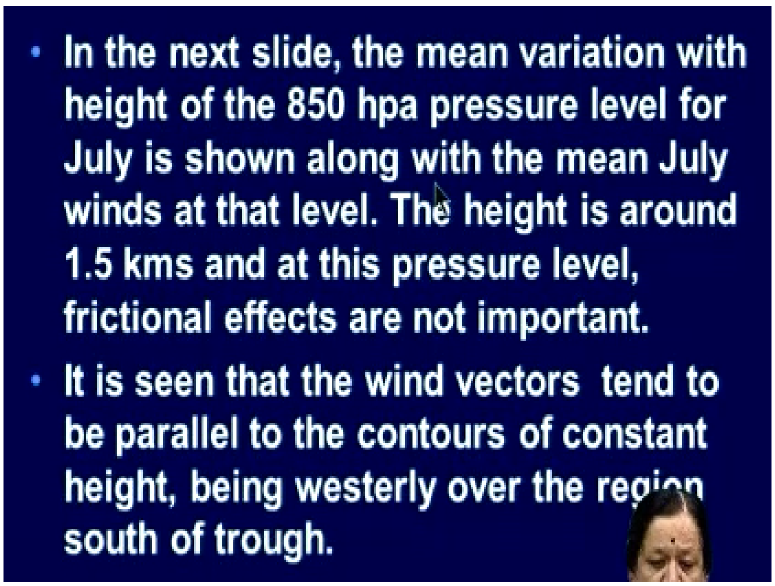
(Refer Slide Time: 22:21)



So what do we expect in terms of winds given that the pressure over Indian region during our summer monsoon decrease from south to north we expect winds to be westerly now let us consider but the problem is that the picture I showed you of the winds earlier were winds at the surface and as I will come to in a minute near the surface you know one more force becomes important.

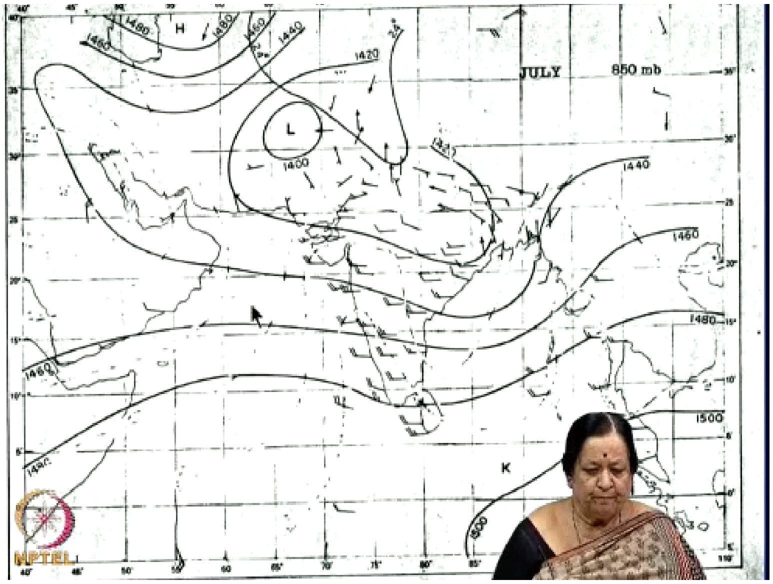
The frictional force here geostrophic balance occurs s away from boundaries that is to say away from regions in which the friction is important.

(Refer Slide Time: 22:51)



So, we should now look in fact I will show you the flow pattern over India at a height of 850 hpa which is about 1.5 kilometers about this is about the surface above the sea level now at this height frictional effects are not important okay.

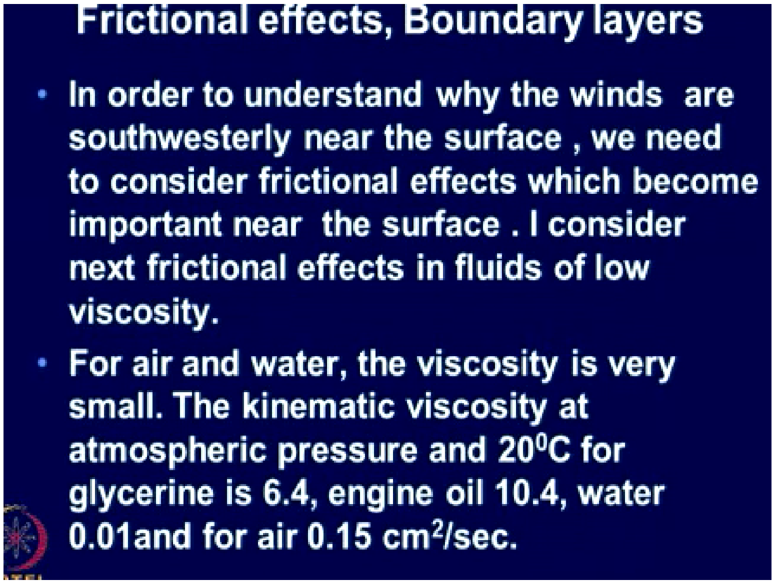
(Refer Slide Time: 23:14)



And what we find is that in fact these are you can consider these as isobars if you wish and you will find that in fact the arrows are essentially parallel to the isobars now I must also mention that these are not actually isobars because what actually shows is the level of the 850 millibar surface or 850 hpa surface so this is low level and this is higher level so rather than saying what is the pressure at specific level like.

We did in the simple example here we are asking the question what is the level of a certain pressure surface but it comes to the same thing these are lines of equal height for the pressure surface and we get a low pressure here and high pressure here and what you see is that indeed way above the place frictional where frictional effects are important in fact geostrophy prevails.

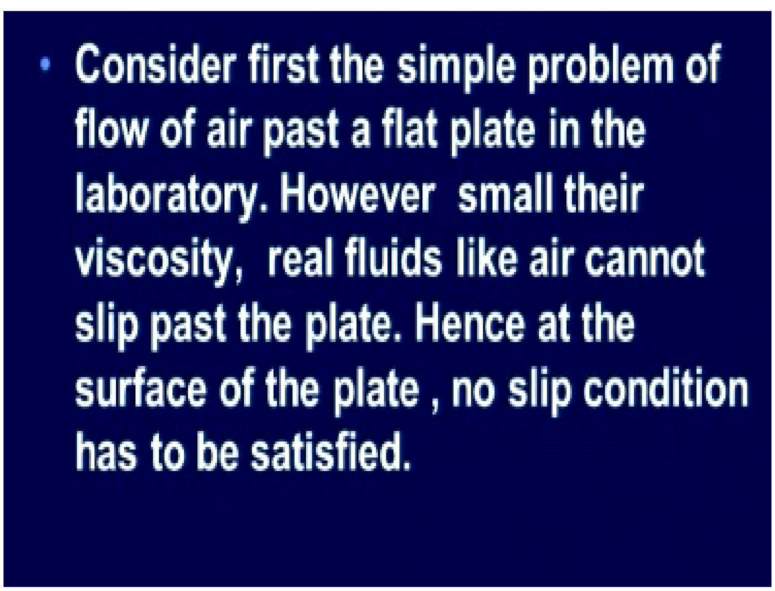
(Refer Slide Time: 24:13)



Okay now we have to see what happens near the surface of the earth now why do we have to worry about friction at all okay now we have to remember that actually air and water the viscosity is very small see water is very different from honey for example which is a very viscous fluid okay air and water the viscosity is very small the kinematic viscosity atmospheric pressure in a number.

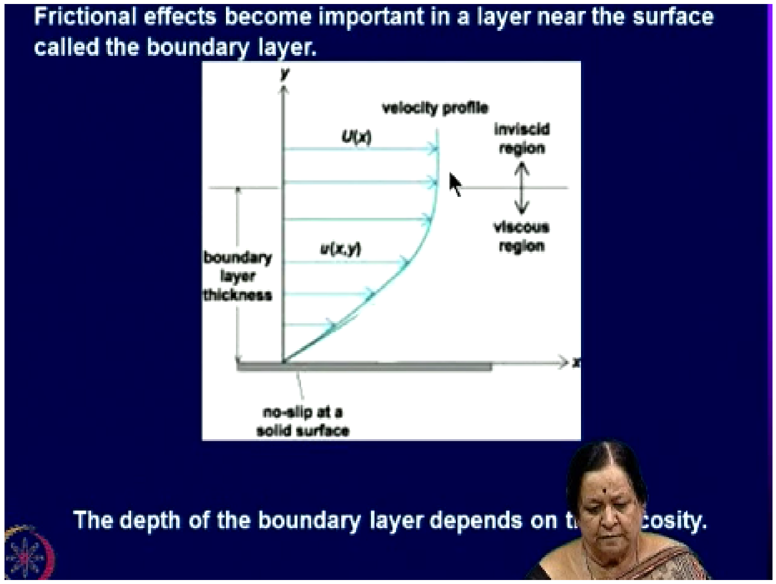
20 degrees centigrade for glycerin is 6.4 engine oil much more viscosity 10.4 water at 0.01 air is 0.15 centimeters square per second this is just to give you a feel for how viscous area is.

(Refer Slide Time: 24:57)



So now let us consider the simple problem of flow past a flat plate why do I say flow of air because I want to consider a fluid with low viscosity now however small their viscosity real fluid like air cannot slip pass the plate right.

(Refer Slide Time: 25:22)

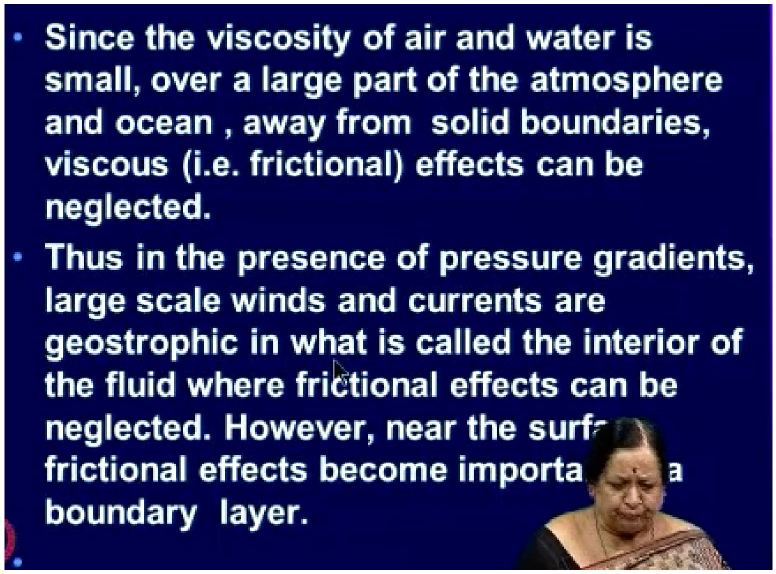


If you have a plate here and you have a flow like this okay this is the wind if you wish and this is the surface of the flat plate, then add the surface of the earth surely the air cannot go past it the there cannot be a slip so the boundary condition here is of no slip okay and frictional effects become important in a layer near the surface called a boundary layer and the whole purpose of the boundary layer is to satisfy the conditions at the surface of no slip.

So we within the boundary layer the velocity in fact decreases from what it was well above the boundary layer to the no slip or 0 velocity at the surface so how thick this boundary layer is depending on how viscous the fluid is this is the region in which viscosity viscous effects become important and this is the region there viscous effects are not important okay the velocity has increased slowly and has in fact may come to the free flow velocity around here.

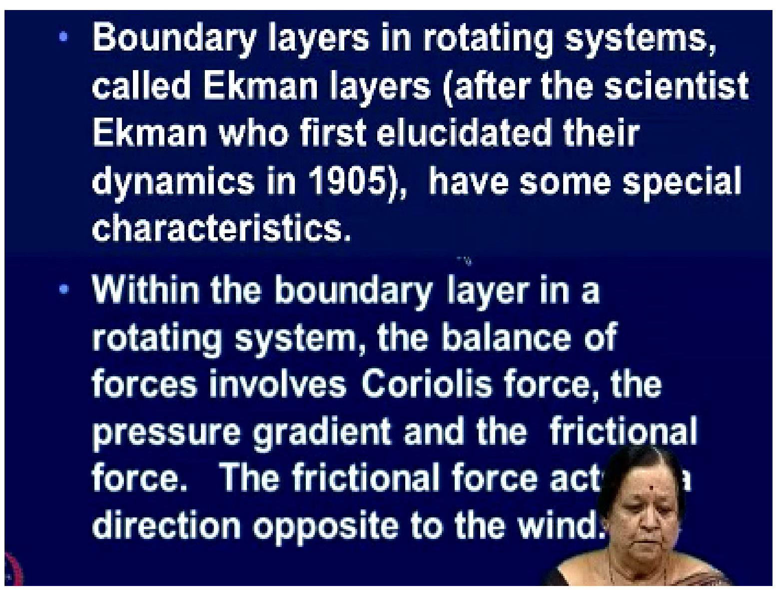
Now note this is a picture of what happens in the lab in a non-rotating fluid so in a non-rotating fluid friction becomes important in a layer whose thickness depends on the viscosity and above the friction is not important and within that friction a layer the velocity rapidly decreases with distance from the plate to become 0 at the plate.

(Refer Slide Time: 26:47)



Okay now since the viscosity of air and water is small over the large part of the atmosphere and ocean away from solid boundaries viscous that this frictional effects can be neglected thus in the presence of pressure gradients large-scale winds and currents are geostrophic in what is called the interior of the fluid where the frictional effects are neglected however near the surface frictional effects become important and they become important in the boundary layer.

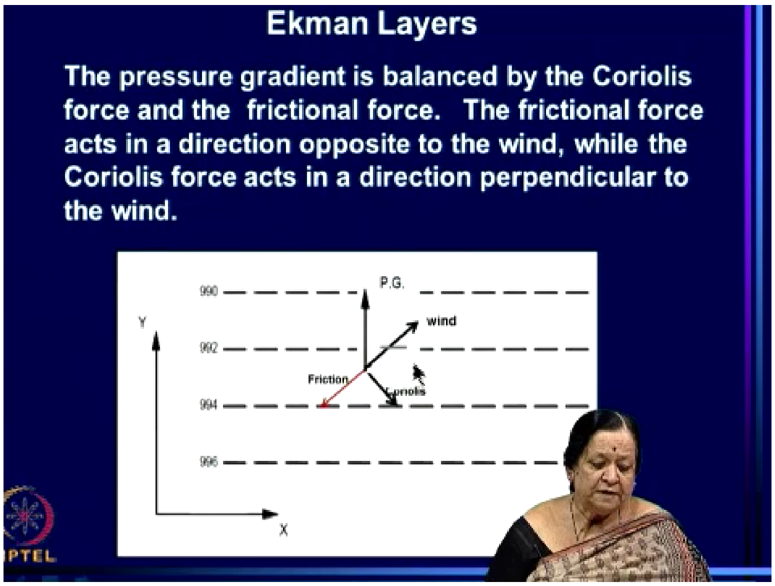
(Refer Slide Time: 27:19)



Now we already saw what a boundary layer in a non-rotating fluid looks like how do boundary layers in rotating fluids look now this is some work done way in the last century in the early as 1905 by Ekman and so these boundary layers are called Ekman layers after this great geo physical fluid dynamics Ekman now within the boundary layer of the rotating system the balance of forces involves Coriolis force pressure gradient.

Remember these 2 are important away from the boundary zone that is the geostrophic balance, so the Coriolis force is important pressure gradient is important and in addition frictional force comes into being now in which direction is the frictional force frictional force acts in a direction opposite to the wind.

(Refer Slide Time: 28:07)

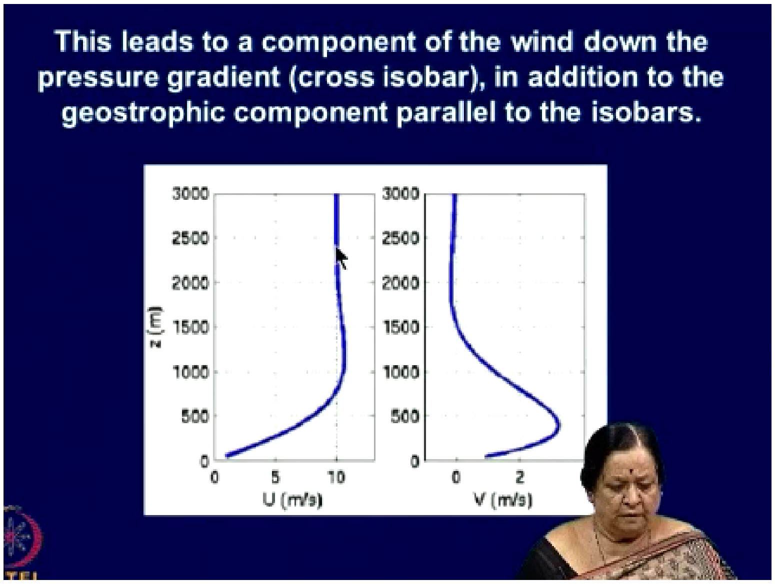


So what is the balance like the balance is supposed to go back to the old example right where the pressure decreases this way so that the pressure gradient is like this okay a earlier you remember if there was no wind in this direction and the Coriolis force would balance it now if the wind continued to be in this direction it would be slowed down by frictional force Okay so it cannot balance the pressure gradient term.

Therefore, what happens is you get a wind in a direction like this the Coriolis forces in this direction the friction is in this direction and the 2 together then can balance the pressure gradient okay so when you have frictional forces come into play the wind is no longer along isobars but you get another component which is down the pressure gradient this wind comprises a component along the isobars like a geostrophic component.

And also, one down the pressure gradient and is down the pressure gradient is called cross isobar component okay this cross-isobar component comes into play within the frictional boundary layer.

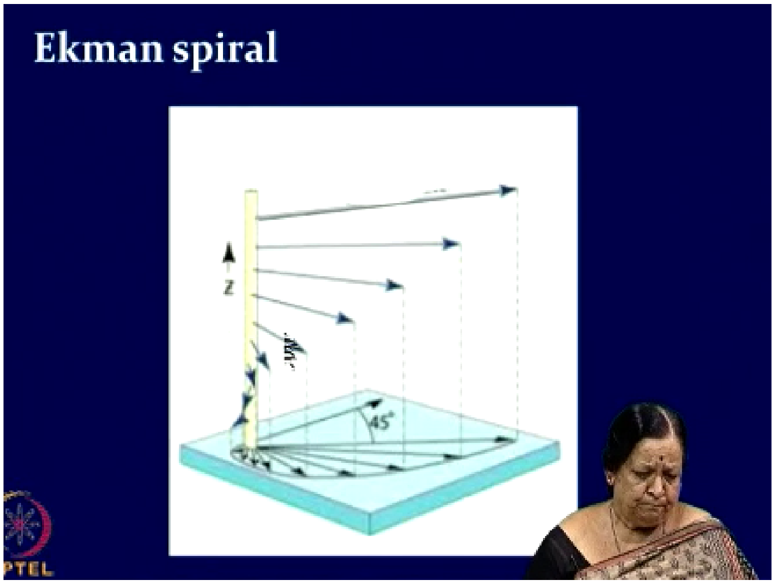
(Refer Slide Time: 29:19)



Okay and this is what you see here that you saw the profile earlier suppose this is the velocity way above the frictional boundary layer wind going this way then the velocity decreases within the boundary layer and here the boundary layer is taken to be about 1 kilometer a realistic assessment for the atmosphere and here the U velocity is going down but what you find is that V velocity comes up.

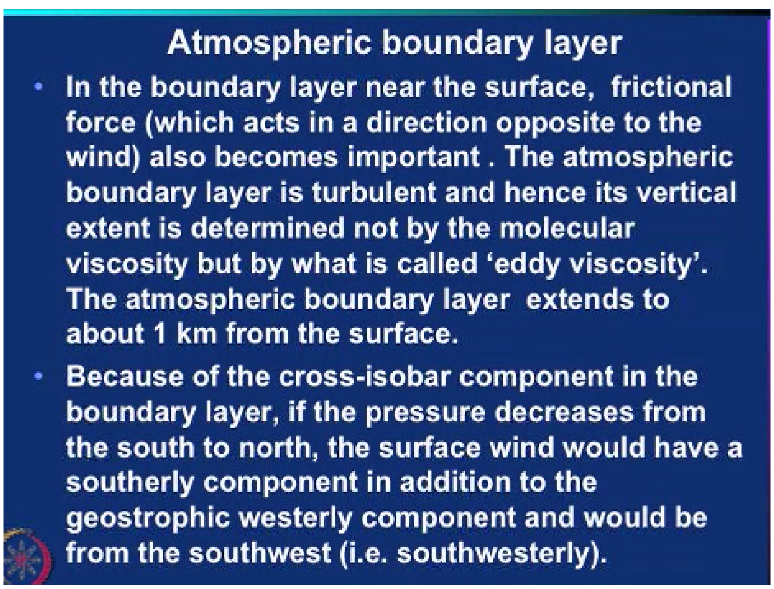
So this is exactly what I showed earlier that this wind now has a U component as well as a V Component right that is what you see here that both U and V go to 0 at the plate as they must at the plate but within the Ekman layer within the boundary layer in fact you see that there is a cross isobar flow as this is decreasing this is increasing okay this is increasing and it in fact peaks around half way through the layer and then decreases.

(Refer Slide Time: 30:30)



In fact, I will not have much time to go into it but that kind of thing layers to a very famous diagram called the Ekman spiral if you consider this as the window the free flow then it slowly spirals down and goes to 0 and it is very beautiful image here.

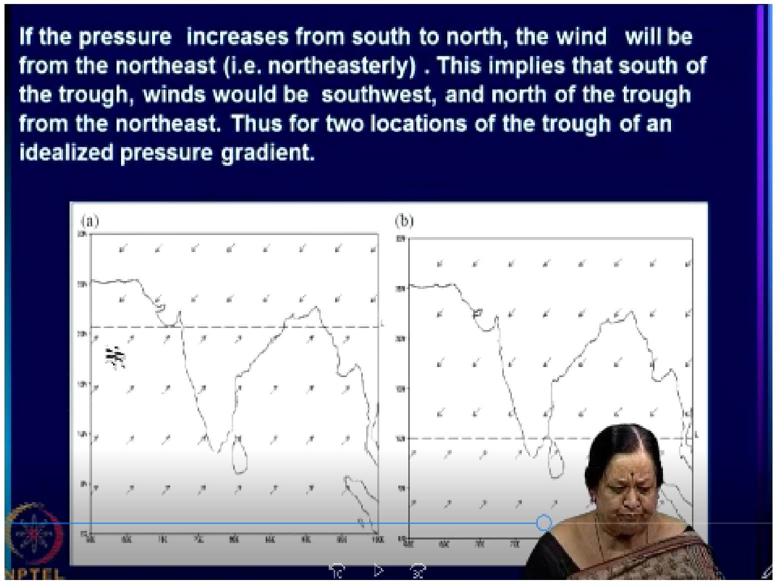
(Refer Slide Time: 30:49)



Now let us look at the atmospheric boundary layer so in the boundary many of the surface frictional force which acts as a direction opposite to wind also becomes important atmospheric boundary layer is turbulent and hence it is vertical layer is determined not by the molecular viscosity but by what is called Eddy viscosity the atmospheric boundary layer extends to about 1 kilometer from the surface.

Now because of the cross-isobar component the component of wind down the pressure gradient if the pressure decreases from south to north not only will you have a geostrophic component which goes from the west to the east in addition to that you will have a component which goes from south to north, so the wind becomes south westerly wind from the south west.

(Refer Slide Time: 31:33)



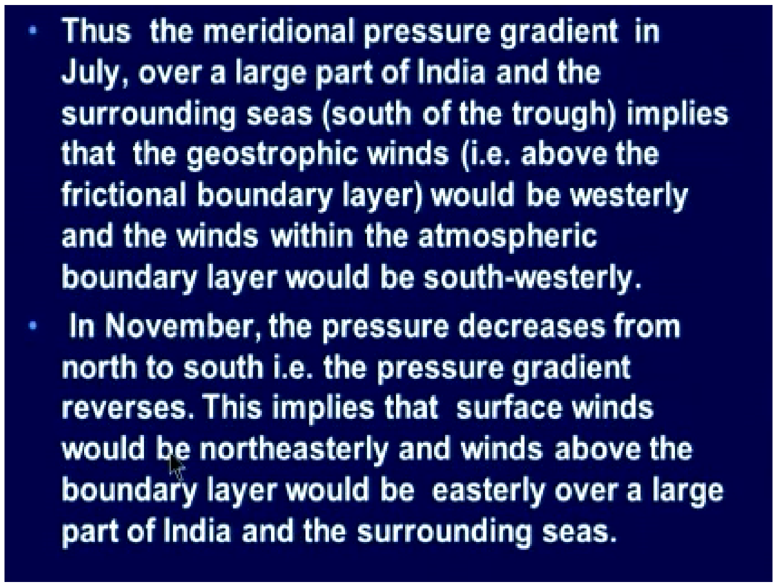
Okay So this is again an idealized picture suppose you had a trough year okay this is the line of minimum pressure so to the south of the trough the pressure is decreasing as you go this way, so the cross-isobar component is towards the north and you have a geostrophic component to the west, so you have southwest flow. But look at what happens north of the trough if you go to the north of the trough.

In fact, now here the pressure is decreasing from here to here so the cross isobar component is this way from north to south and the geostrophic component is from east to west so what you get here is north easterly winds and here south westerly winds okay now this is more or less what we see in July that you have a trough around here to the south out of south westerly winds to the north or north easterly winds in November.

When that trough has moved to here you will still have southwest winds to the south and north east winds to the north so actually that has not been a substantive change in the system itself what has happened is that the system is shifted and earlier only a little region of the north was under the sway of north east winds now this entire region has come under the sway of north east winds.

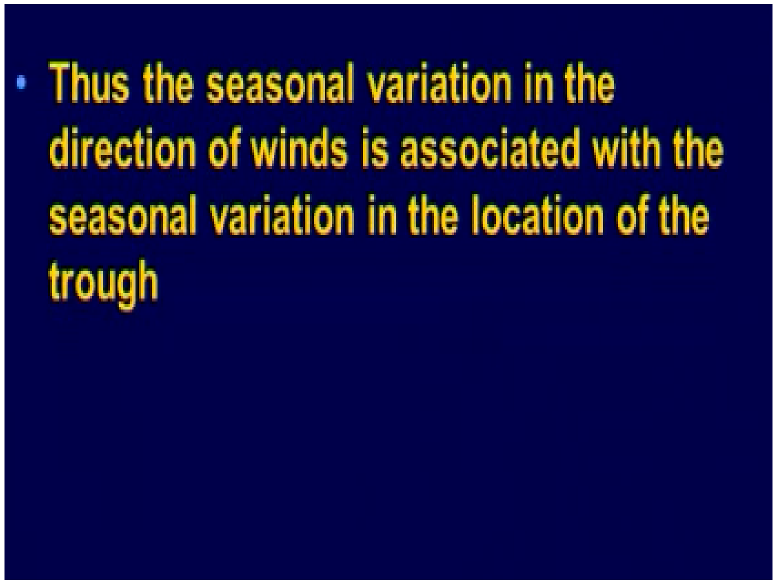
This is why I think that the name Southwest and north east for this are somewhat mis leading because they give the impression that the entire system has changed but that is actually just a movement of the system I will come back to this later.

(Refer Slide Time: 33:16)



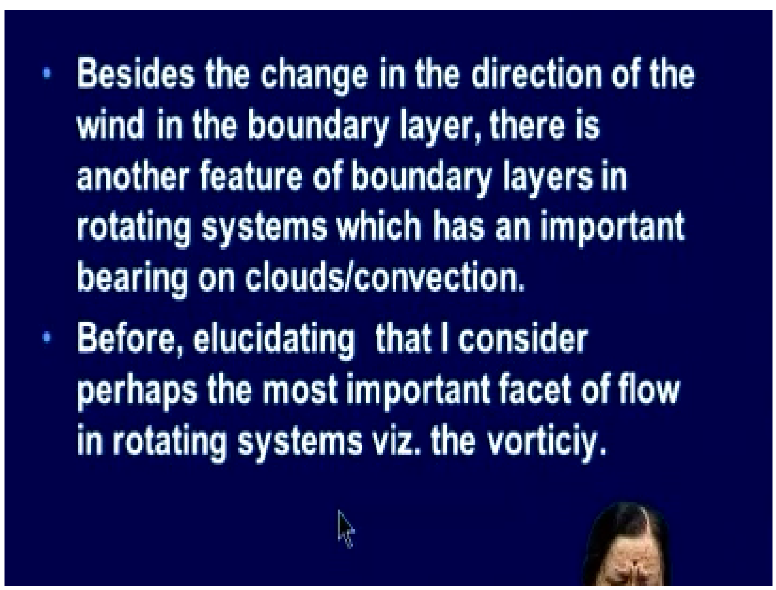
So then to summarize the meridian pressure gradient in July over the large part of India and surrounding seas the south of the trough implies that the geostrophic winds is above the frictional boundary layer would be westerly. And the winds within the boundary layer would be south westerly in November the pressure decreases from north up to south that this pressure gradient reverses this implies that the surface winds would be north easterly and winds above the boundary layer would be easterly over a large part of India.

(Refer Slide Time: 33:42)



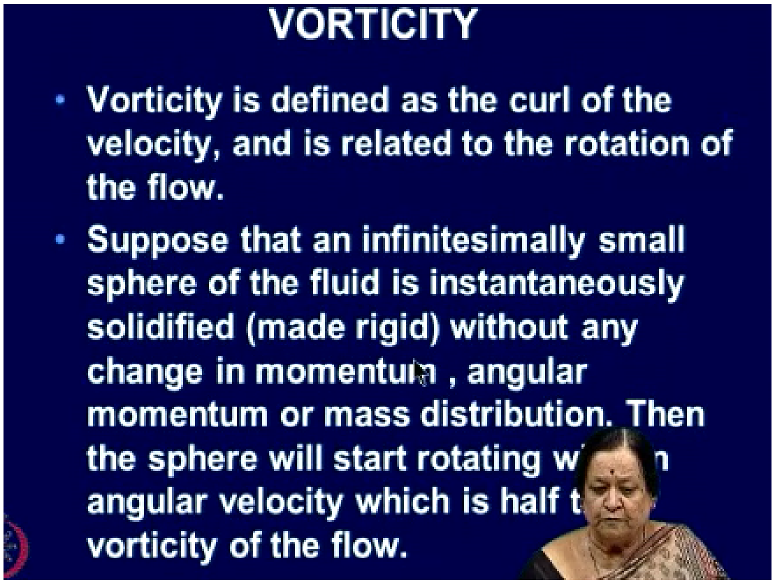
Thus the seasonal variation in the direction of winds is associated with the seasonal variation in the location of the trough trough being the region where the pressure is minimal okay so this is important to see so we have now understood why the wind direction is the way it it is but in a way all we are saying is it is that way because the trough moves so now the ball is in the court of what creates the movement of the trough which we will come to.

(Refer Slide Time: 34:13)



But there is another very important feature of boundary layers in rotating fluids which we have to understand, and this has very important implications for the genesis of clouds and so on and so forth so before I can consider that I have to introduce one of the most important facet of fluid flow in rotating system now this is something some of you may already know this is the vorticity.

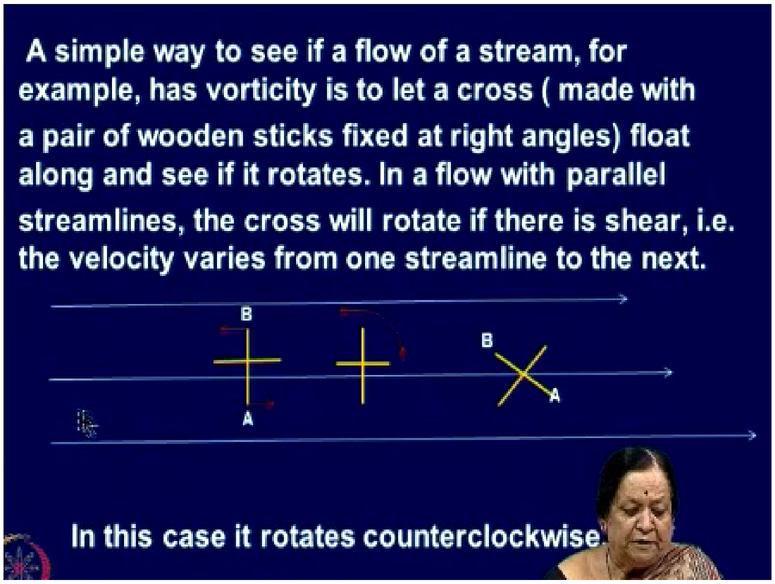
(Refer Slide Time: 34:42)



So what is the vorticity, Vorticity is defined as the curl of the velocity and is it related to the rotation of the flow it is del/v curl of the velocity not to get a physical feel for what is vorticity city suppose that an infinitesimally small sphere of fluid is instantaneously solidified made rigid without any change in momentum angular momentum or mass distribution okay as it is this is the third experiment as it is.

Suppose you solidify a sphere which was a fluid before without any change in momentum angular momentum or mass distribution then the sphere will start rotating with an angular velocity which is half the vorticity of the flow so if the flow has vorticity then such as sphere will start rotating and it will start rotating with an angular velocity which is half the vorticity of the flow.

(Refer Slide Time: 35:42)

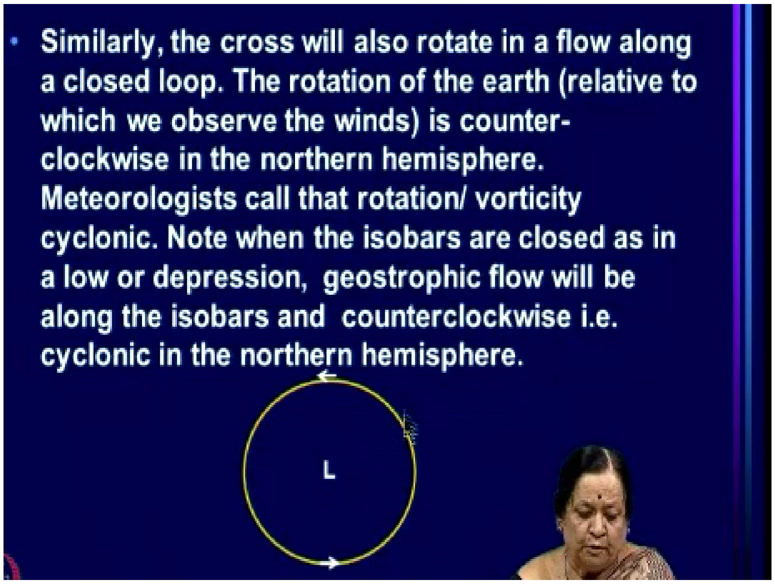


So you can see that vorticity is related that the basic rotation in the fluid ok now there is a very simple way of deciding that a particular flow has vorticity or not and that is suppose you take a cross and this can be done very easily with water flow for example in streams suppose you make a cross out of 2 wooden sticks okay so that it is at right angles to one another and let the cross flow with the stream okay.

Then suppose we have flow that is parallel and but velocity here is high velocity decreases velocity decreases here and this is called a shear flow right in such a case then what will happen to this cross as it proceeds along It will in fact rotate because you can see that A will go faster than B will so at this point of time for example A has come much further and B is lagging behind so what you see effectively is a rotation in the counter clockwise direction.

So, the cross will start rotating counterclockwise because that is how the shear flow is this is how the velocity pattern is so in this case it rotates clockwise and counter clockwise, so this means that such a flow does have vorticity and it is counterclockwise.

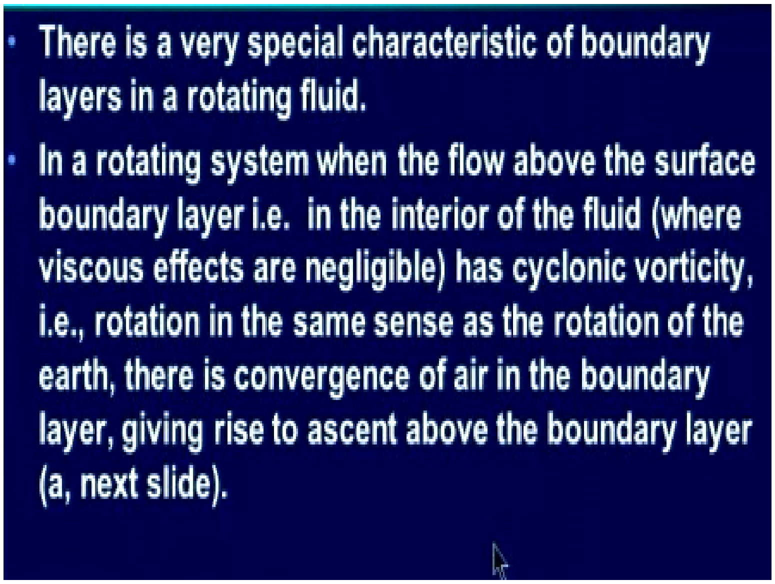
(Refer Slide Time: 37:00)



Now if you have a flow like I suppose you have a low pressure and you have a flow around like this then once I placed a crush here it will rotate with the flow in this direction so the rotation of the earth related to we observe it is counterclockwise in the northern hemisphere so me tell I just call that rotation/vorticity cyclonic okay so when the isobars are closed as in a lower depression so what happens when the isobars are closed lowest pressure is here.

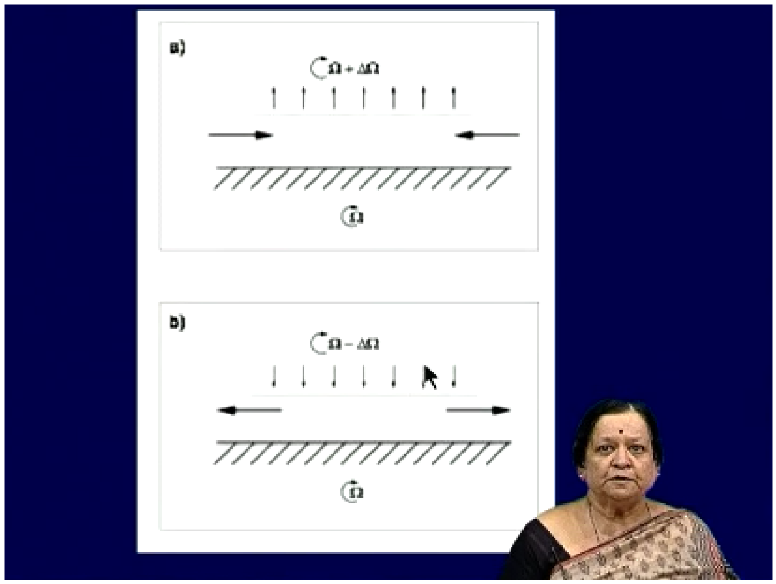
And this in the next isobar okay in that case geostrophic flow will be along the isobars like this and that means geostrophic flow will be counterclockwise that is to say it will be cyclonic okay, so this is the way of seeing of the flow has vorticity.

(Refer Slide Time: 37:53)



Now there is a very special characteristic of boundary layer in rotating fluid in a rotating system when the flow above the surface boundary layer that is in the interior of the fluid where viscous effects are negligible like say at 1.5 kilometers or so above the surface of the earth if the flow has cyclonic vorticity that is rotation is in the same sense of the earth then there is conversation of air in the boundary layer and ascent of layer above the boundary layer.

(Refer Slide Time: 38:11)

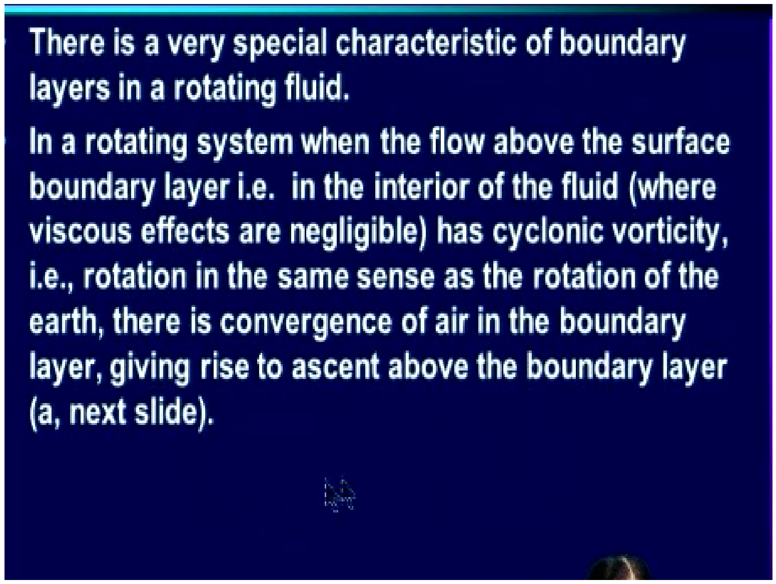


So let me just show this as an example imagine this is the earth okay this is rotating with a velocity omega angular velocity omega now above in the interior of the fluid you vorticity which is the same sign of as the earth so you will in effect if event of the inertial system this is rotating with the angular velocity of omega+delta omega this is what happens when you have a cyclonic vorticity above the frictional layer.

So in that case what is happening is this fluid is spinning faster than this one and this layers in fact to convergence of layer this is the surface layer and once it convergence it goes somewhere and it goes in fact in the interior of the flow now what happens when the vorticity is anti-cyclonic okay opposite side what happens when it is anti-cyclonic is that in fact you have divergence of air here okay.

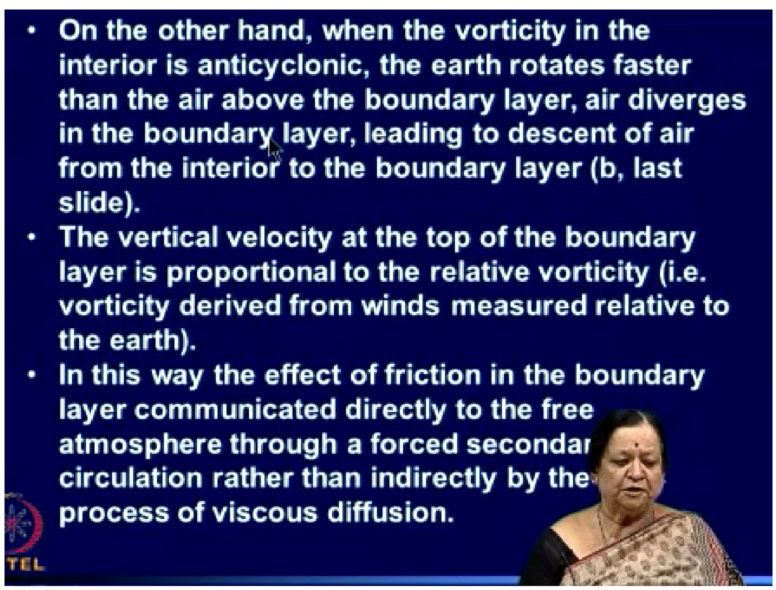
So, more and more air leaves this place and the continuity is maintained or conservation of mass is maintained by having descent of air from above.

(Refer Slide Time: 39:39)



So, what we have seen is when the air above the boundary layer is cyclonic vorticity there is convergence of air in the boundary layer giving rise to ascent about a boundary layer here.

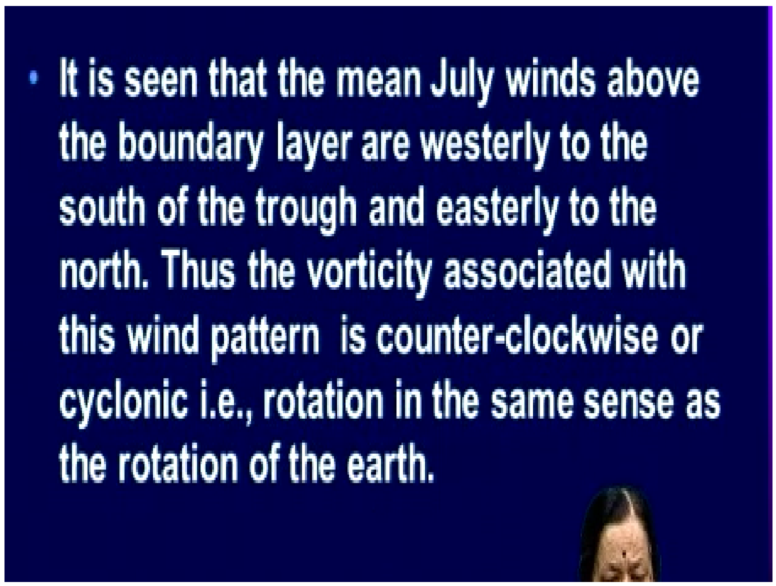
(Refer Slide Time: 39:52)



And on the other hand, when the vorticity in the interior is anti-cyclonic the earth rotates faster than the air above the boundary layer the air diverges in the boundary layer layering to descent of air from the interior to the boundary layer. So, the vertical velocity at the top of the boundary layer is proportional to the one can show this mathematically that the vertical velocity at the top of the layer is proportional to this relative vorticity okay derived from the winds measure related to the earth.

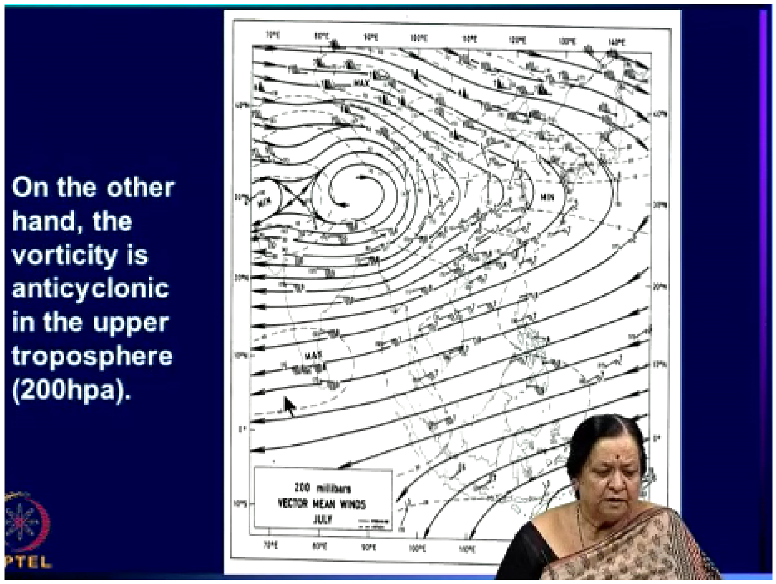
In this way, the effect of friction in the boundary layer is communicated directly to the free atmosphere through a forced secondary circulation rather than indirectly by slow process of viscous diffusion. Now, this is very important and because of this rotating fluid can spin up much faster than non-rotating ng fluids because of this dynamic if you wish dynamic boundary layer the boundary layer which communicates directly with the indeed of the fluid.

(Refer Slide Time: 40:59)



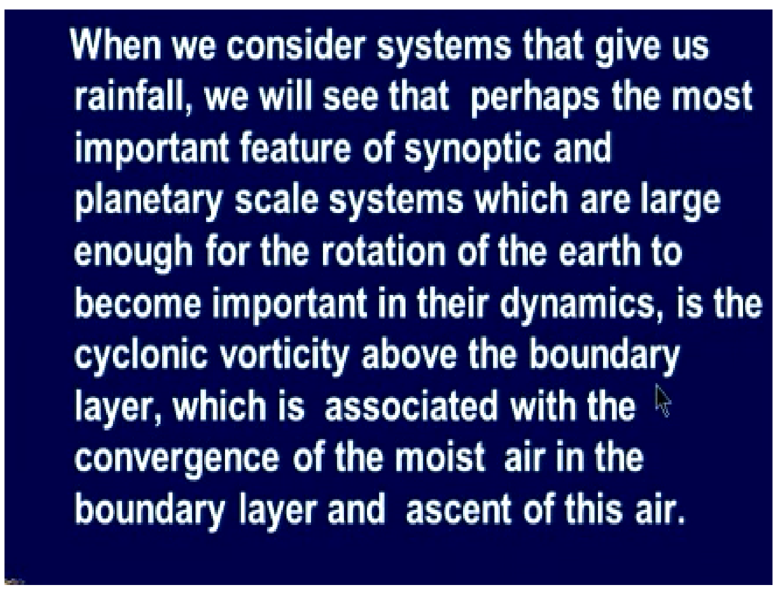
I am not going to go into it right now okay so now what have we seen we have seen that the mean winds above the boundary layer are in this direction westerly here and easterly here so this means the velocity is cyclonic it is anticlockwise or cyclonic okay so mean July winds above the boundary layer are westerly south of the trough an easterly north and the vorticity associated with this wind pattern is counter-clockwise a cyclonic okay.

(Refer Slide Time: 41:29)



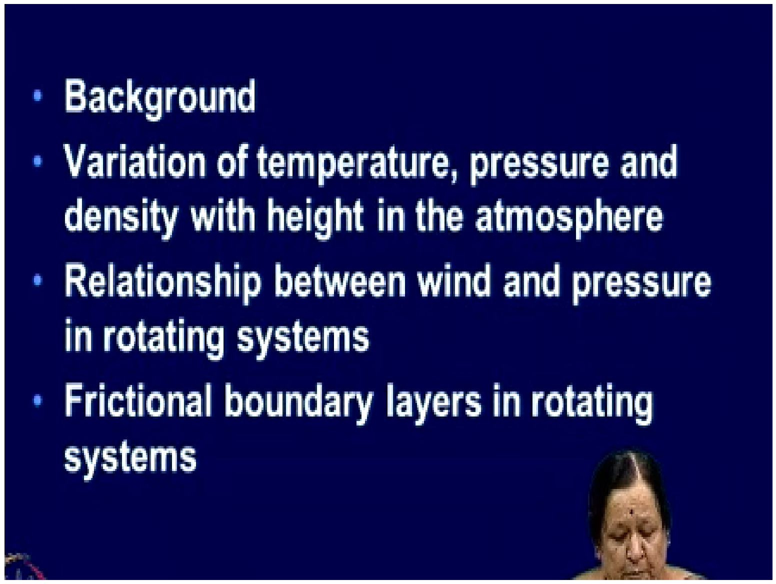
On the other hand, if we go away above to the upper troposphere 200hpa then what this is the winds are like this and you can see that this is clockwise. So, it is anti-cyclonic this has anti-cyclonic vorticity okay.

(Refer Slide Time: 41:43)



Now, when we consider the systems that give us rainfall we will see perhaps the most important feature of synoptic and planetary scale systems which are large enough for the rotation of the earth to become important in their dynamic is the cyclonic vorticity above the boundary layer which is associated with convergence of moist air near the surface.

(Refer Slide Time: 42:05)



So, we have now learned so far that because although the radiation although the atmospheric circulation in the main source of energy is solar radiation because most of it is observed at the surface of the earth the atmosphere is heated from the bottom because of that the temperature decreases with height and temperature decreases with height throughout the troposphere and above the tropopause begins the stratosphere.

In the stratosphere though the temperature increases with height because of ozone which absorbs ultraviolet radiation so temperature variation in the atmosphere involves decrease of temperature in the troposphere and increases in the stratosphere. How does the pressure vary pressure decreases as we go higher and higher basically because pressure just depends on the weight of the air column above that level okay?

Now it so happens that the density of the atmosphere also decreases with height so we say that atmosphere is stably stratified because we have light air over heavy layer then we came to the major difference between a rotating and a non-rotating system and that difference is in how in the relationship between wind and pressure gradient in a non-rotating system the wind will blow from high pressure to low pressure or the current will flow from high pressure to low pressure.

Water in our taps flows from high pressure to low pressure okay but in or not in a rotating system on spatial scales on which rotation is important that is large-scales of the earth which fill the earth rotation in fact what happens is Coriolis force is an important force that has to be incorporated but it then the basic balance is between the Coriolis force and the pressure gradient and in that situation what you get is flow along isobars along the lines of equal pressure.

Whereas in the non-rotating system the flow is essentially across isobar flow from high to low pressure in a rotating system the flow is along isobars provided the frictional effects are not important now where are frictional effects important see although air and water fluids a very low viscosity in comparison with things like honey or engine oil or something like that even then you see frictional effects become important because even though they have very low viscosity.

These fluids cannot slip past the surface so if you consider that a flow past a flat plate the flow has to become 0 at the plate because the fluid cannot slip over the plate so this no slip condition has to be satisfied and what this means is that frictional effects become very important in in a layer very near the surface where the boundary conditions have to be satisfied how thick the layer is depends on the viscosity.

So, in that layer frictional effects become important again we said that frictional effects lead to another dimension in that relationship between wind and pressure gradient whereas when frictional effects were not important in a rotating system we had flow along isobars once frictional effects become important we also get a cross isobars component to the wind and this leads to a very beautiful in spiraling wind in an idealistic case.

And this is the months spiral now even more important than the fact that this cross-isobar flow in fact implies convergence or divergence of air okay, so you have convergence or divergence of air in the frictional boundary layer and furthermore there is another important property of the boundary layers in rotating fluids that is something that depends on the vorticity of the flow and we defined what was vorticity of the flow.

If the flow in the interior is such that the vorticity which is cyclonic that is the same sign as the rotating earth beneath then it becomes a problem of a faster rotating fluid in the layer about a frictional layer and a slower rotating boundary namely the earth. In that case actually there is convergence in the boundary layer and these surface air ascents into the interior, so the boundary layer directly supplies moist surface air to the interior of the fluid.

Now these phenomena have very, very important impacts on the genesis of clouds and rainfall as we will see later if under that hand the vorticity in the interior happens to be anti-cyclonic then in fact that is divergence in the boundary layer and descent of air from the boundary layer to the interior. So, this is something that all these features have very, very important implications to clouds and rainfall and that is what I am going to consider in the next lecture. Thank you.