Air Pollution and Control
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Lecture 12
Boundary Layer, Mixing Height, Stack Height and Plume Rise

Hello friends, today we will discuss about Boundary Layer, Atmospheric Boundary Layer and its Mixing Height, Stack Height and Plume Rise because they are interrelated to each other, when we talk about dispersion of pollutants or dilution of the pollutants when it is emitted from a particular stack or point source.

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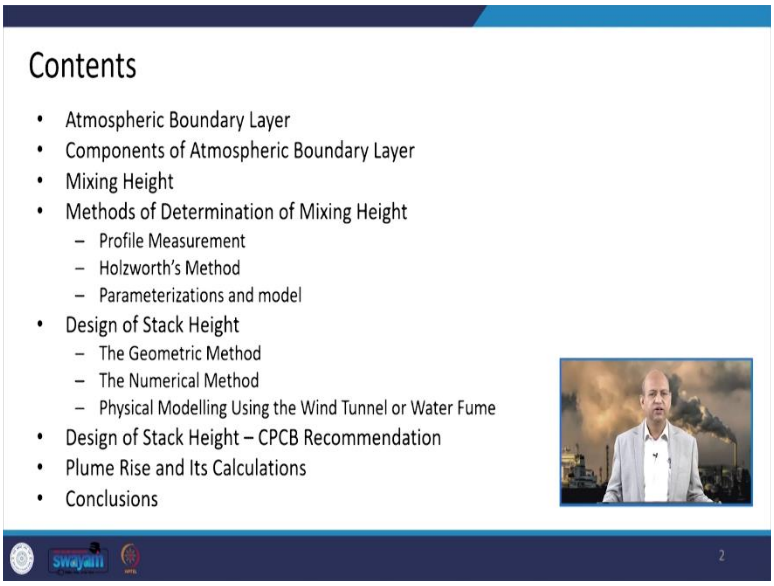

So, the contents of today's lecture is like first of all we will discuss atmospheric boundary layer what is the boundary layer, how it is defined how it is approximated then different components of the boundary layer and then the concept of mixing height and methods of determination of mixing height by different methods like Profile measurement, Holdsworth method is there and Parameterizations and model based calculations are also there.

Then we would talk about the stack height design. So, again there are different methods to design the stack height like geometric method, numerical methods or even by physical modelling in the wind tunnel or water fumes and some recommended, equations or relationships are there by CPCB (Central Pollution Control Board) some minimum heights maxima might those kinds of things are there.

And then the plume rise and its calculations we will discuss because plume rise is also important in the sense because it is added into the physical stack height when we calculate effectively stack height. So, that is also very important when we talk about stack height and then we will conclude.

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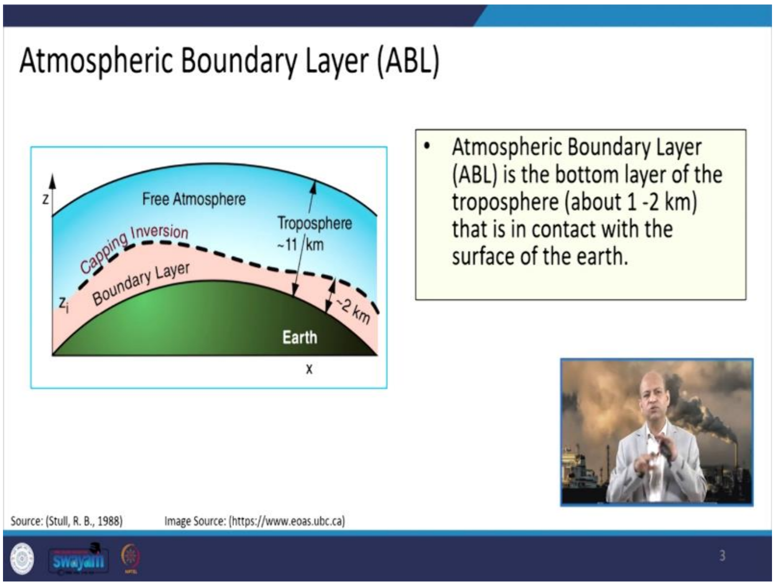

So, when we discuss about atmospheric boundary layer basically it is nothing but the bottom layer of the troposphere. You can you assume like 1 to 2 kilometre from the Earth's surface and because topography varies it is not overall smooth somewhere it is mountains or hilly areas, undulations, water bodies etc, so the height is not constant it can vary from 1 to 2 kilometre depending upon the surface nature of the Earth's surface nature of the Earth's surface.

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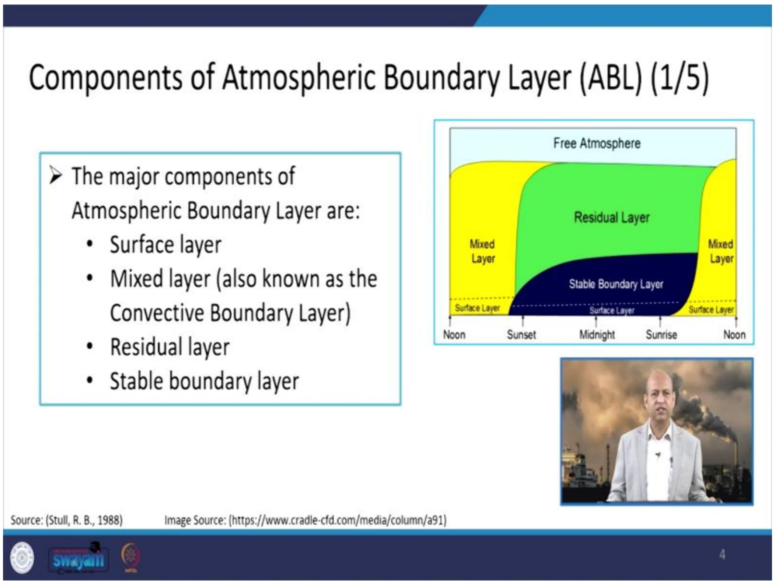

Well the different components of the boundary layer or atmospheric boundary layer are you know defined or they are given some nomenclature like surface layer or mixed layer then residual layer and stable boundary layer those kinds of names are there and how they are defined let us see.

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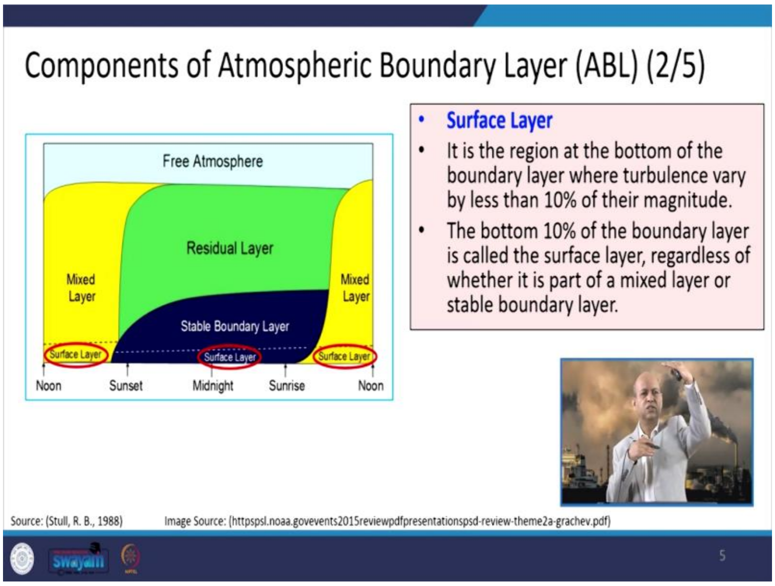

So, the surface layer is basically nothing but the, this is the region at the bottom of the boundary layer you can see here this is the surface layer very thin layer within the boundary layer or the troposphere the lowest one the nearer to the Earth's surface. So, this is the region at the bottom of the boundary layer where turbulence you know varies by less than 10 percent of their magnitude, we will see the turbulence what is turbulence basically.

And the bottom 10 percent of the boundary layer if you assume 100 units you know height of the boundary layer, then the bottom 10 percent of the boundary layer is called the surface layer regardless whether it is part of the mixed layer or the stable boundary layer, because there are other components also the boundary layer but means the bottom part the 10 percent of the total boundary layer or height of the atmospheric boundary we consider as the surface layer.

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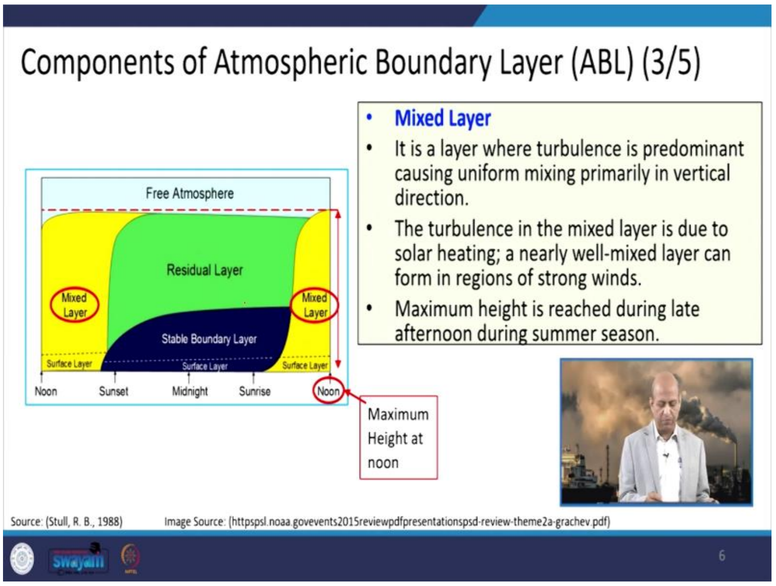

Then when we talk about the mixed layer basically it is the layer where turbulence is predominant. Again, as I said we will see what is the turbulence it is you know churning of the air lot of mixing takes place. So, this causes uniform mixing primarily in vertical direction because of turbulence, in the mixed layer is due to solar heating nearly well mixed layer can form in the regions very strong winds are also occurring. So, maximum height is reached during the late afternoon during summer seasons because of high solar insulation and these high Eddies or turbulence this happens.

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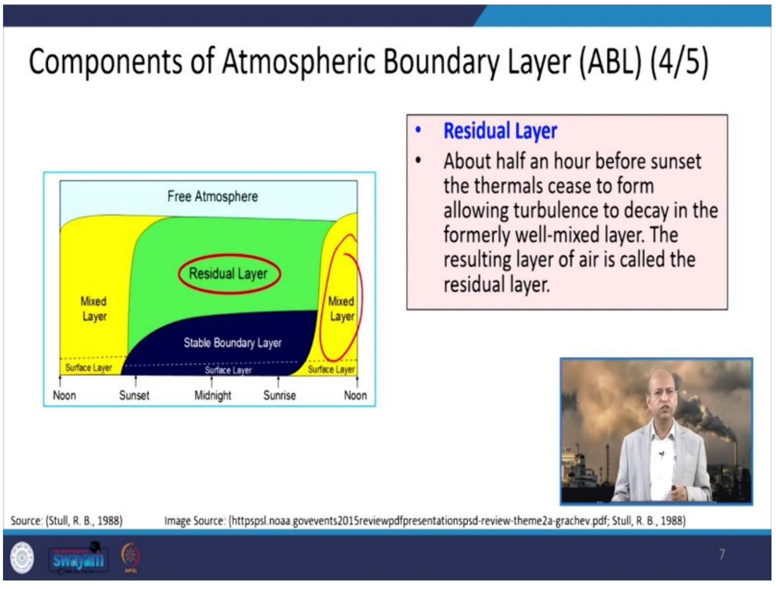

Well, when we talk about the Residual Layer, mixed layer was this one and it could go up to the boundary layer. So, the residual layer is the upper part you can see this is nothing but about the layer which is like about half an hour before the sunset when thermals cease to exist. And they allow like turbulence to decay slows down in the formerly well next layer.

So, the well mixed layer like this one reduces into these kind of two parts, stable layer the residual layer. So, the residual layer is the upper part because this is kind of you know the difference between the stable boundary layer where stability classification will be applied the concept of instability classification. So, the remaining layer above the stable layer is basically the residual layer.

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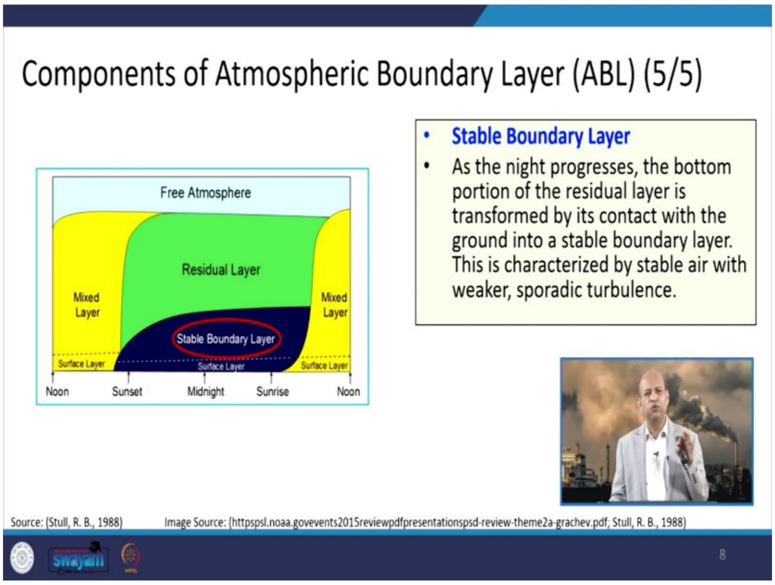

And what is the stable layer? When we talk about this then this is like when evening occurs and night progresses, then the bottom part of the residual layer is transformed into in the contact of the ground and it becomes like a stable boundary layer because of certain instability classification related temperature profile. So, this is characterised by a stable air with weaker or sporadic turbulence very less very negligible kind of thing.

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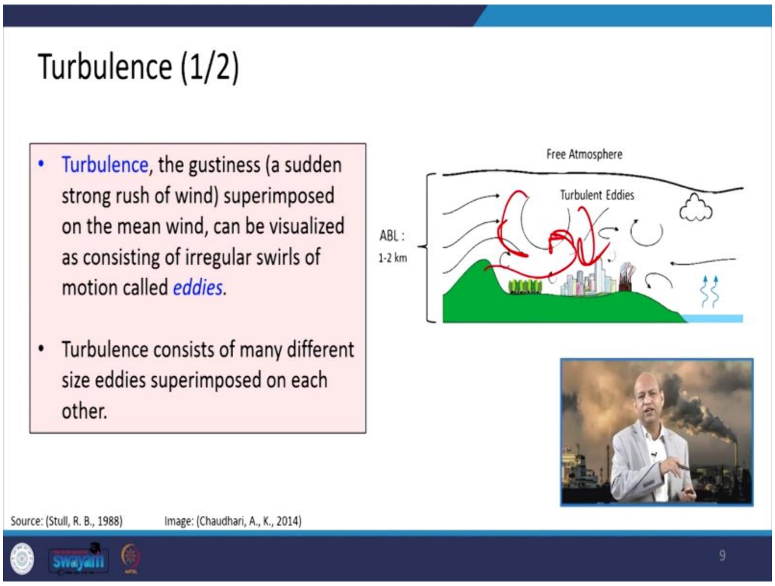

When we talk about the turbulence basically you see the air does not move in a very smooth single direction. It goes up and down depending upon churning and the solar insulation, topographical undulations all those. So, here goes like this it will go up, then come down mixing takes place those kinds of things occur.

So, this is the gustiness a certain strong rush of the wind superimposed on the mean wind direction and you can visualise it as a consistent of regular swirls of the motion which are called as Eddies. So, the turbulence consists of many different sized Eddies smaller, larger those kinds of and they are superimposed on each other. So, lot of mixing takes place in a mixture also you takes a lot of currents go, on one direction other direction those kinds of things happen.

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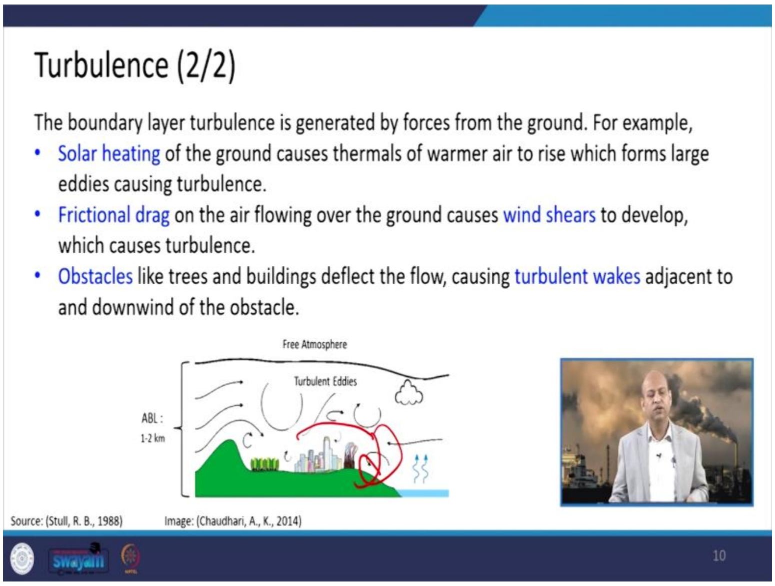

Well, so the boundary layer the turbulence which is generated by forces from the ground in the bottom part of the like solar heating of the ground causes thermals of the warmer air which rises from the ground and it forms large Eddies causing a lot of turbulence. Then there are frictional dread because air is flowing it is touching with the ground lot of friction is there. So, this wind shears develop, which causes the turbulence also because of this drag force.

Then, obstacle also like trees or buildings or undulated the terrain is there that also causes turbulence some weeks, because building is there, then some wake formation occurs. So, again it will be forced like air will come down. So, that is why you know, neither buildings we do not want stacks because when plume comes then there is tendency that it will go down because of this wake formation, those are issues maybe we will discuss later on also in detail.

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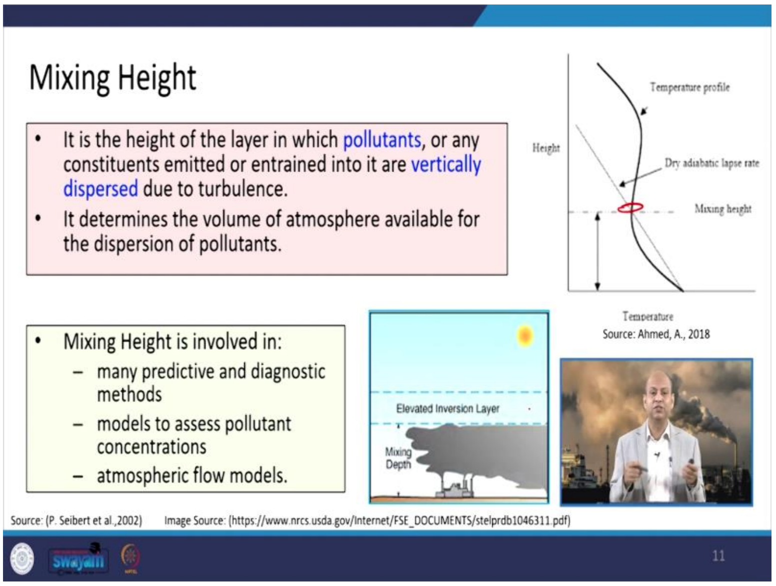

Well, the mixing height basically when we talk about in the boundary layer up to what height a lot of mixing will take place. So, that is also defined because of atmospheric characteristics, and normally we, get it by intersection of adiabatic lapse rate from the maximum temperature at the surface and whatever temperature profile is there like this one and then this intersection occur so, this is the mixing height.

But in theory you can see like, this is the height of the layer in which a lot of pollutants or any constituents of the atmosphere vertically disperses due to turbulence, vertical dispersion occurs, because of this, within this mixing height. So, larger mixing height, lot of volume is available for mixing, dilution of the pollutants, and if it is lower than higher concentration, we will be there because volume will be low.

Mixing height is involved in like many predictive and diagnostic methods which are related to air pollution, then models to assess the pollutant concentration at a particular place or atmospheric plume model. So, this is mixing is very important concept like you can see the whole this mixing height is there where all the pollutants disperse. The more mixing height, more dilution, more dispersion those kinds of things, then how to determine?

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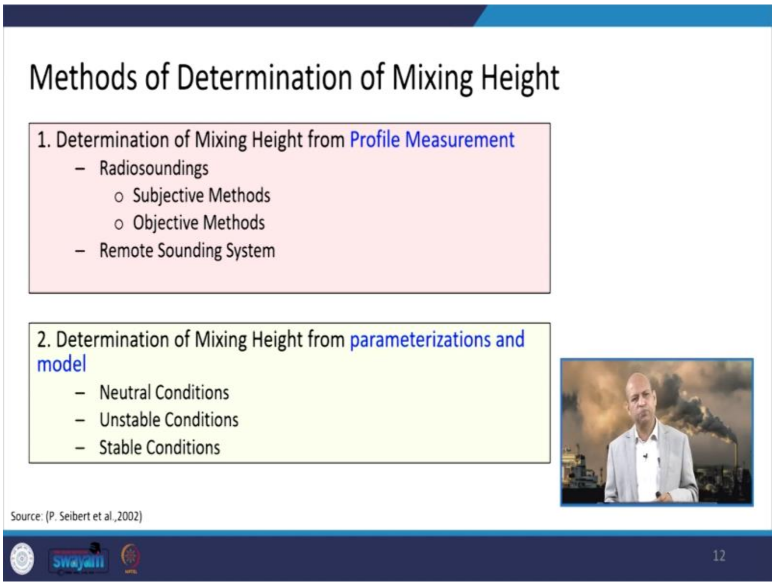

So, there are methods to determine the mixing height, like because your profile measurement you can measure it like radiosounding or subjective methods within the radiosounding objective methods, subjective methods or their, remote sounding system is also there, then you can determine mixing height by parameterization and model which are again divided like neutral conditions, what will happen to mixing height or there are empirical equations also, which uses these kinds of conditions or unstable condition, stable condition those kinds of things are there.

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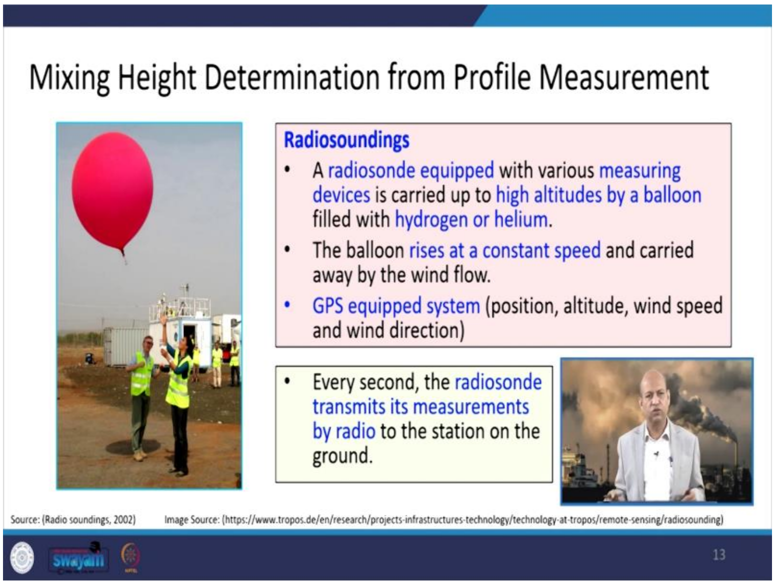

So, when we talk about radio sounding you use, we use the balloons and some instruments are hanging to that, when you know balloon rises, then at different heights, those sensor based equipment's, give us the reading. So, GPS equipped system is there which gives the position and the altitude and wind speed, wind direction all those data are collected at the ground level that system and every second this radio sound transmits its measurements by radio to the station on the ground.

So, but as this balloon goes wherever depending upon the wind direction flew etc, those data we get, it is not of our choice that we wanted this particular vertical column that is not possible in this that case.

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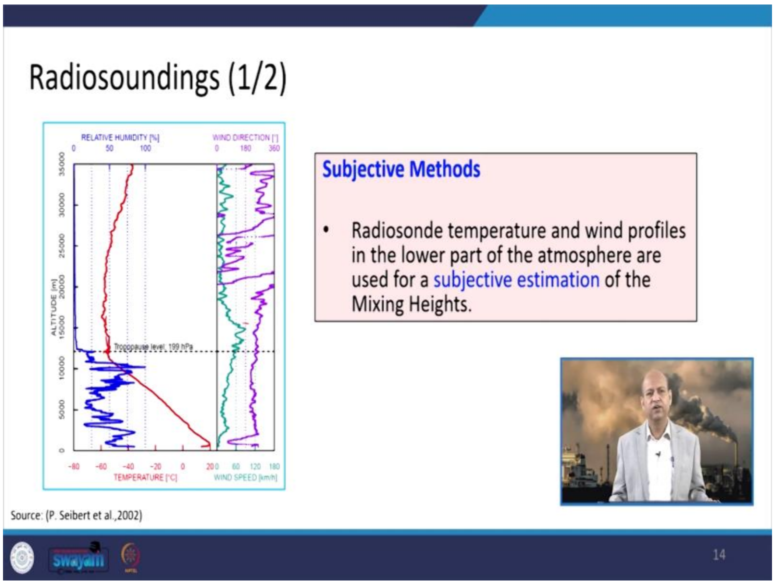

Then, within that subjective method is there because we have the profile we have temperature profile all those wind velocity etc. So, depending upon the expertise when wherever you know this profile is changing like this you can see the variation with the altitude this temperature decreases and at this height, temperature then rather than decrease it remains almost constant.

So, up to this one can expert can say, this is the mixing height after that this mixing it stops to work. So, through the subjective method you can get the because of this relationship with the wind profile also you can see it changes here up to this, increases the wind speed and then you know it start decreasing. So, the combination of these wind direction wind profile, temperature profile and expert can easily find out where up to which height the mixing it is there. So, this is known as the subjective method.

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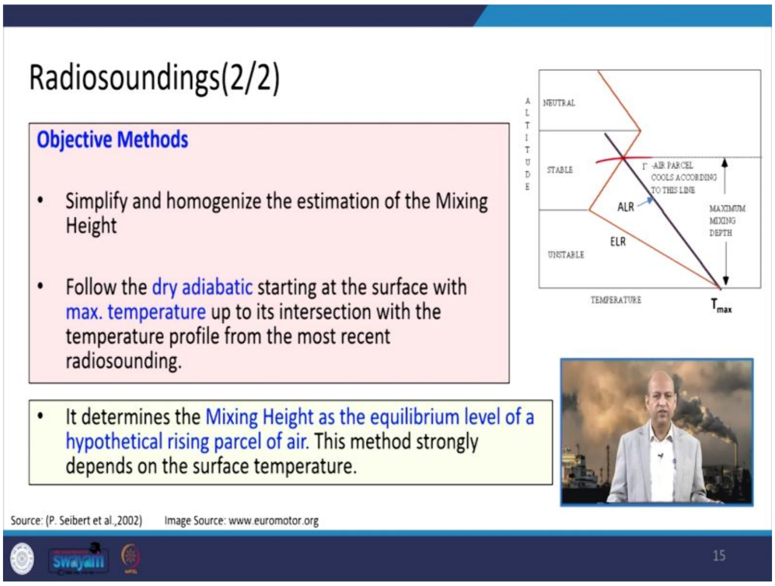

Objective method is also there, where you plot the profile as well as you know, see what is the maximum temperature during that observation and from there you know intersect this adiabatic lapse rate. So, wherever this is intersecting up to that, the mixing height or maximum mixing height is known. So, that is also one method this is objective, because, some value will come because of these plots and also.

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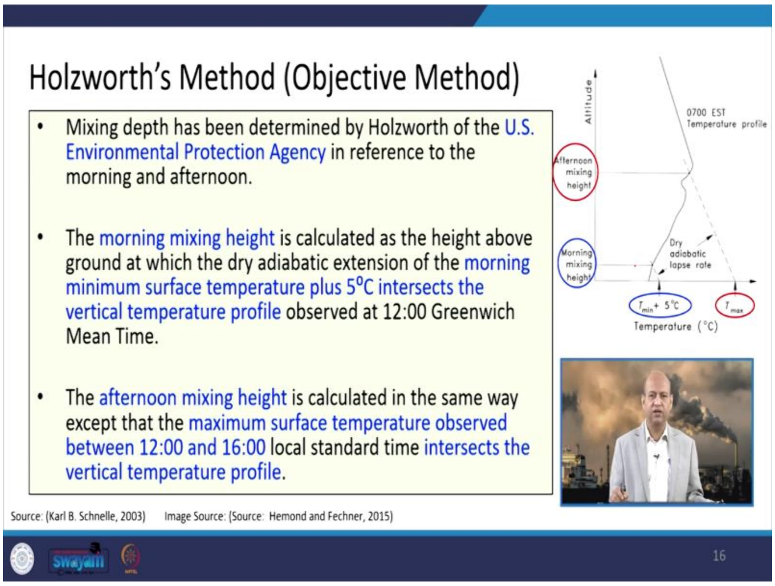

Then, there are other methods like this Holzworth's method which is the again objective method which gives readings about like morning mixing height or afternoon mixing height depending upon the time of the day. So, like this morning mixing height the minimum the minimum temperature at the plus 5 percent, there you can have this dry adiabatic lapse rate.

Then from T maximum you have the dry adiabatic lapse rate that gives the afternoon mixing height and the morning mixing height is known when we plot the adiabatic lapse rate from the T minimum plus 5 degrees Celsius. So, those methods are there and you can easily calculate those mixing heights.

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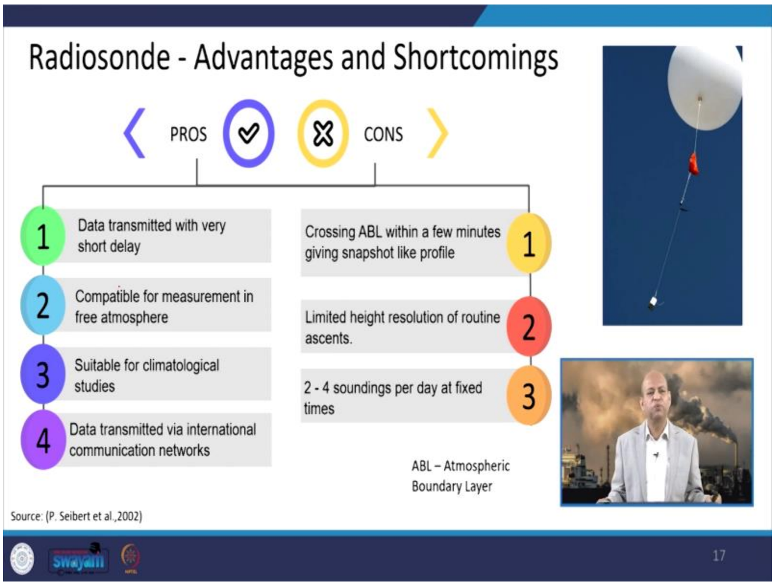

Then there are certain plus or minus, pros and cons depending upon their nature by when we are knowing these data from different methods. So, the reduced sound advantage and shortcomings are also there like you know data transmitted with very short delay so, this is good point for that it is compatible for measurement in the free atmosphere. And then, the suitable for climatological studies, because it needs lot of data then data transmitted via international communication networks.

So, you have huge amount of data and you can play with those to get different kinds of insights about the atmosphere mixing etc. But there are shortcomings also like, there are limitations you can’t go beyond 2-4 soundings per day at mixed limited height is their resolution depending upon this wind and the crossing of the atmospheric boundary layer within a few minutes given this snapshot kind of profile. So, there are these shortcomings you can see.

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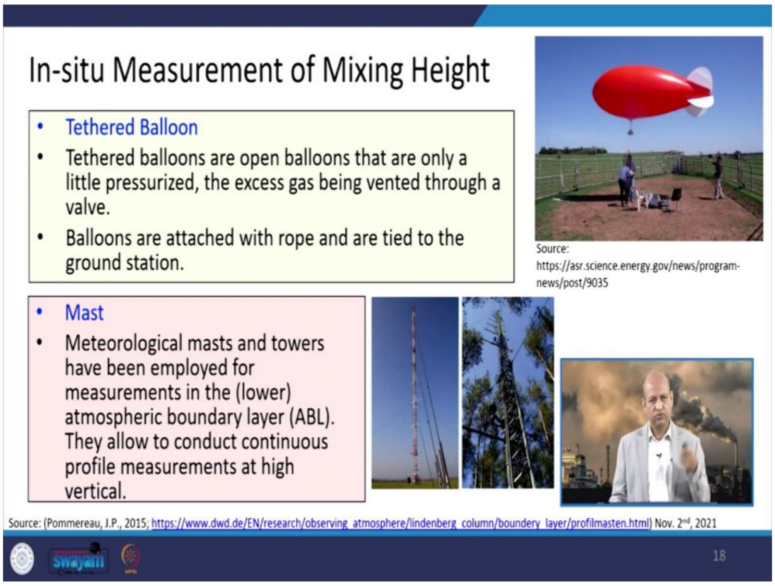

Then, we go for in-situ measurements of the mixing height where you can have this kind of balloon tied with a rope. So, up to certain height you can have the those profile related measurements. Then you can have the mast where you can have this kind of tower very tall and you can install different instruments at different heights and you can have these observations related to wind velocity temperature profile everything. So, you can have the data in the column.

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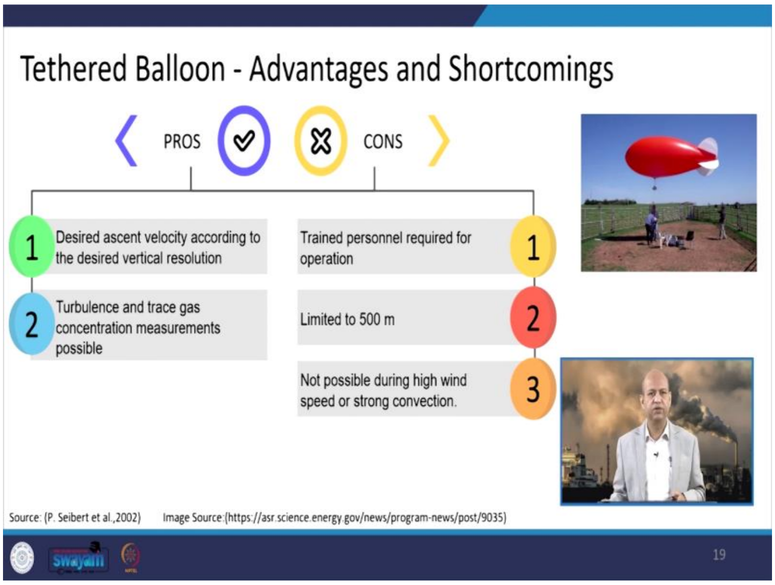

Well again, there are some pros and cons like there are this tethered balloon where it is tied to the rope. So, plus point is like desired ascent velocity according to the desired vertical resolution that we can maintain. Then the turbulence and trace gases concentration measurements are possible in this particular way.

But it requires a lot of skill, skilled person required to handle it, and then it can't go beyond 500 metres. So, that is the limitation and it is not possible during very high wind speed or during strong convection where a lot of vertical movements happen. So, it can be damaged because of those high winds etc we cannot have better results.

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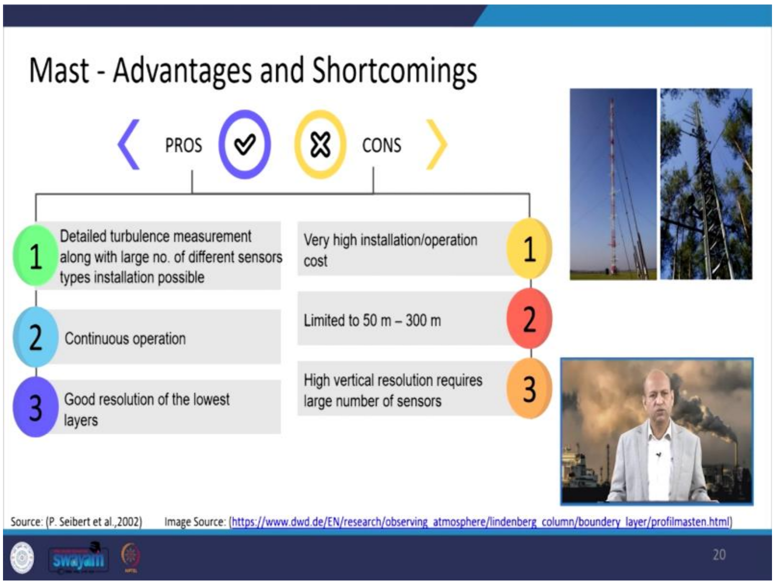

Similarly, in Mast also there are certain plus point like it can give detailed turbulence measurements along with the large number of different sensors which are installed on the tower this installation. Then continuous operation is possible good resolution of the lowest layer is very much possible you can do whatever height, you want to install those instruments, but it is very high installation cost is needed because of this infrastructure which are needed.

Then limitation like 50 to 300 metre only beyond that, it is not cost effective and high vertical resolution requires large number of sensors. So, again it adds into the cons. So, operational cost also increases.

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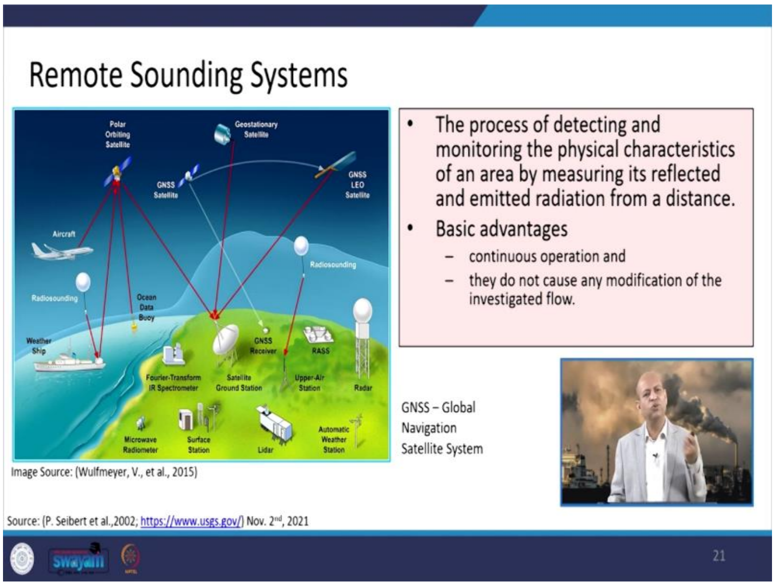

When we talk about remote sounding systems, then from the distance you can have some observations. So, basic advantages are like continuous operation can be maintained, and they do not cause any modifications of the investigated flow because whenever you are having a tower or balloon, so it is a little bit changing that particular location related flow metrics, but in this this is sensor based on some raise. So, there are no obstacles at all in this particular method.

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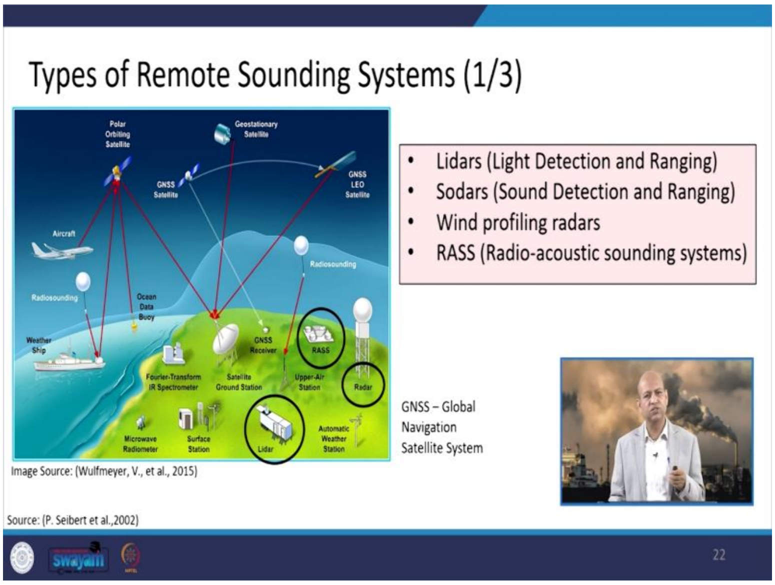

Well types of remote sensing sounding systems or there like light detection and ranging, which is known as LIDARS, then sound detection and ranging or SODARS, then when profile radars are also there, then Radio Acoustic Sounding Systems (RASS) is also there.

And the Global Navigation Satellite System (GNSS) can easily be used for these kinds of measurements.

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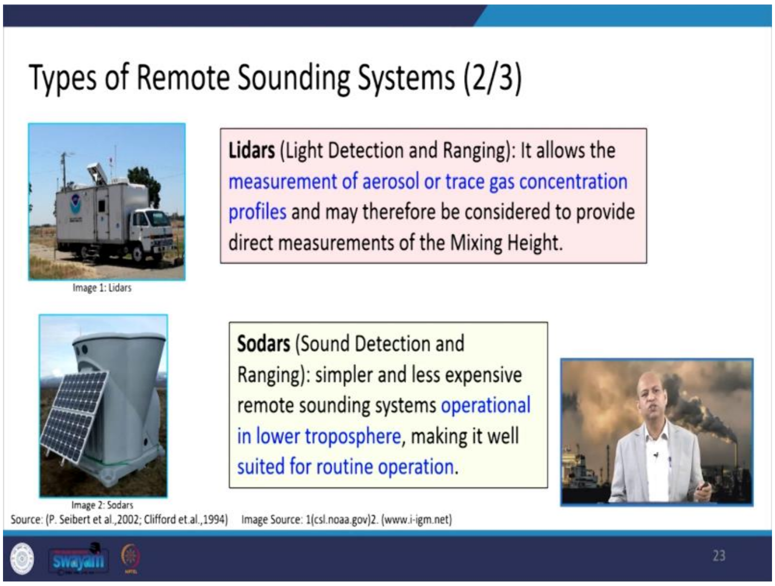

Well, these LIDARS you can use for measurements of the aerosols and trace gases concentration also. So, this is very much considered to provide direct measurement of the mixing height. And then, the SODAR is also very simple, less expensive, remote sounding system and operational in lower troposphere, which can make, very much suited for routine operations in that sense.

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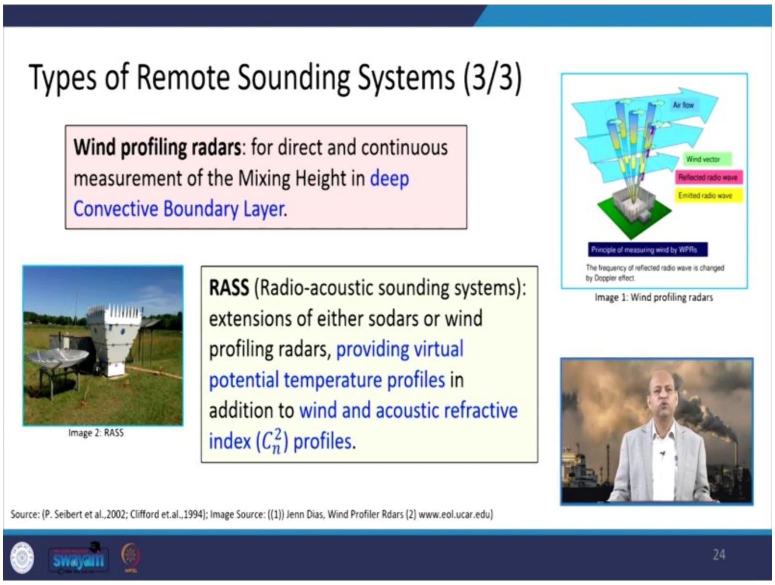

Then wind profile radars are also there, which are for direct continuous measurements of the mixing height in deep convective boundary layer, otherwise other systems may not give realistic data. And then when we talk about RASS Radio Acoustic Sounding System so, this is an extension of either SODARs or wind profile and it provides virtual potential temperature provide in addition to the wind and acoustic related these refractive indices profiles.

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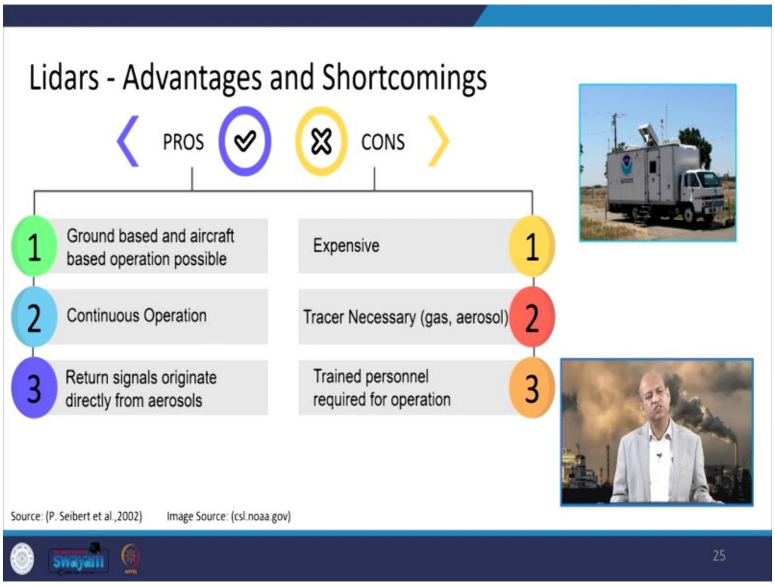

So, these are again pros and cons like for LIDARs, then ground based and aircraft based operation possible in case of LIDARs and the continuous operation is also possible then, return signal this originated directly from the aerosols. And but it is expensive the negative part or shortcoming. And the tracer necessary like gas or aerosol, some tracer must be there, because without that, it is difficult, to take those readings and then the trained personnel required for the operation. So, a skilled person is required.

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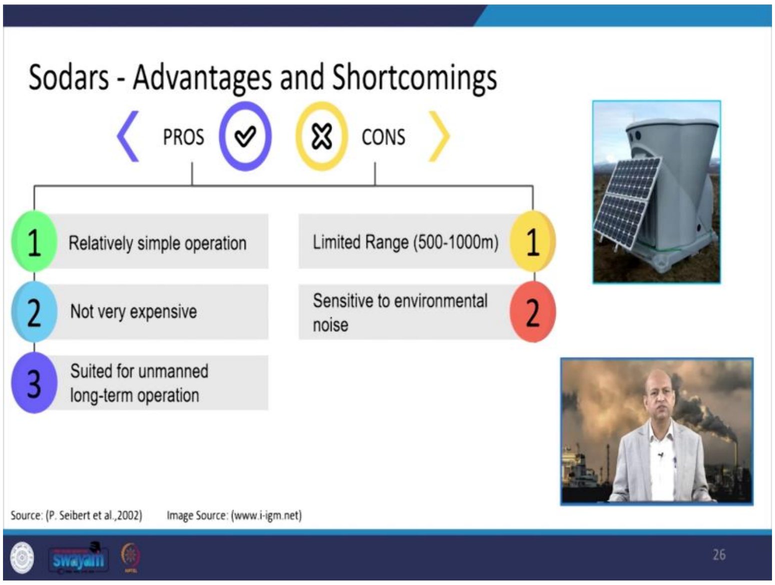

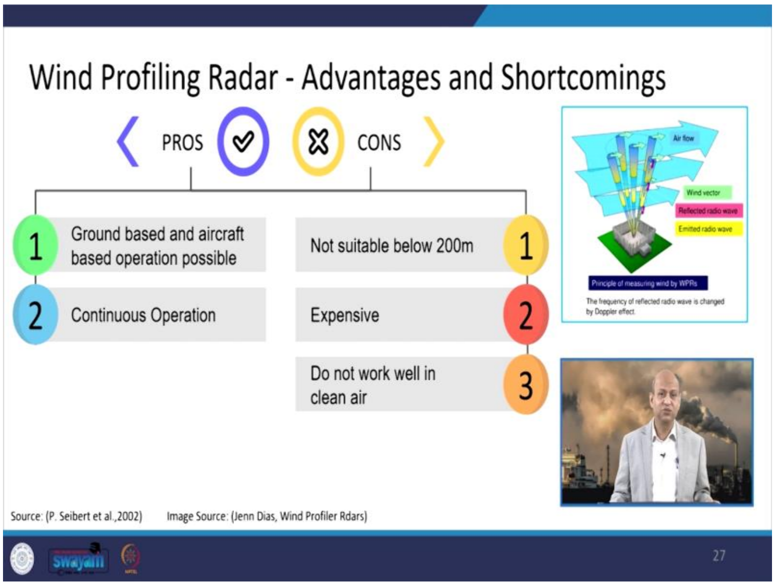

When we talk about the SODARs. So, the good point is like relatively simple operation, not very expensive and it is suited for even unmanned long term operation automatic operations are also possible, but then the range is limited. So, the shortcoming is like 500 to 1000 metre only this gives the reading good reading and sensitive to the environmental noise, then readings may be disturbed, so, that we have to again process after you know observations.

So, when we talk about wind profiling radar, so again good points like continuous operation is possible, ground based and aircraft-based operation possible. But you know shortcomings are like not stable below 200 metre, only beyond 200 metre, it is good and expensive it does not work well in clean air. So, again there are limitations of this particular issue.

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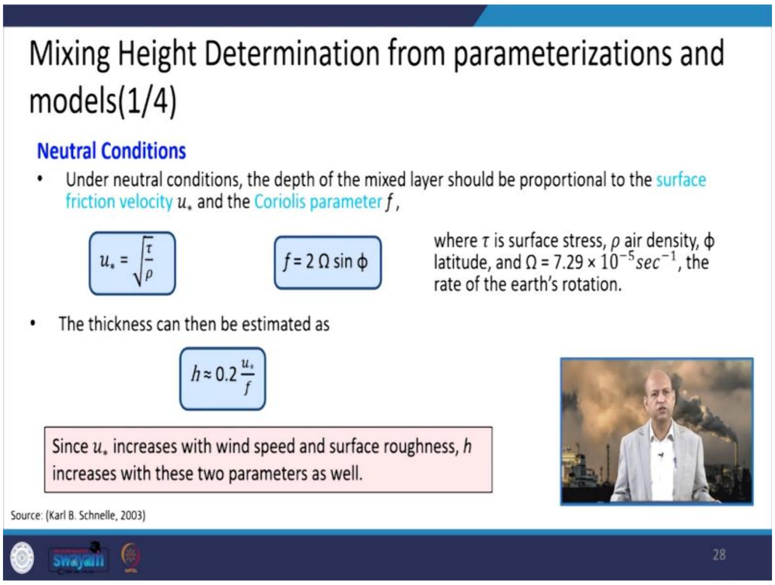

Then when we talk about mixing high determination, so depending upon stability classification neutral condition those kinds of different equations you can use to, these are the empirical relationships which can you use for determination of the mixing height.

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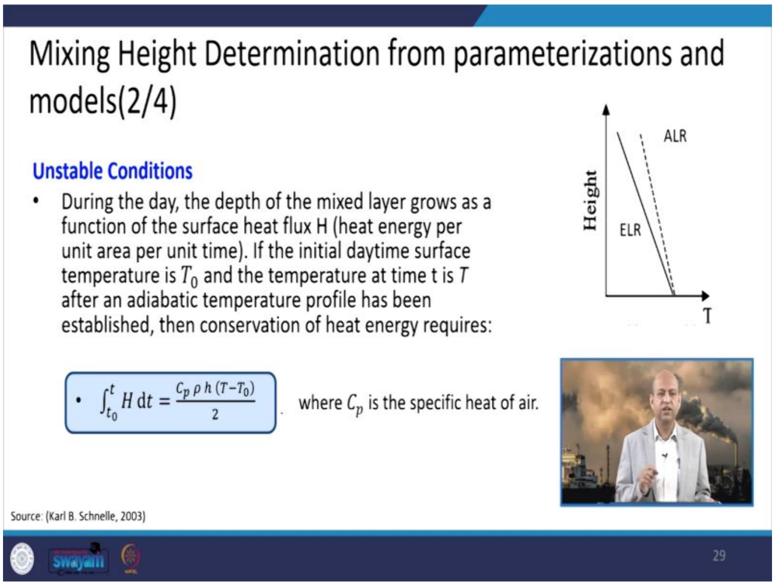

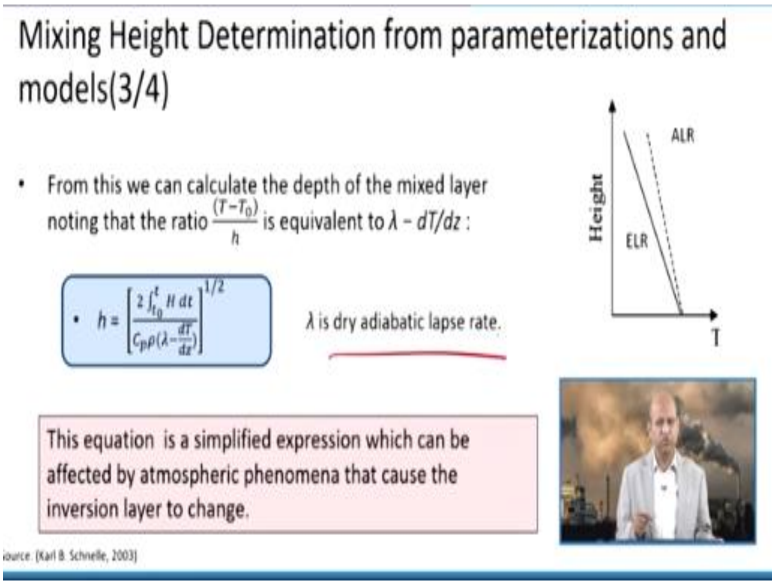

Well, this environmental lapse rate they are used and unstable conditions when we are talking about them another equation or relationship is there. And when we talk about these like calculation of mixing height by parameterization and models, then again there are certain empirical relationships, where these temperature differences is there and gradient of the environmental lapse rate, they all these things are used and dry adiabatic lapse rate is also used for calculation.

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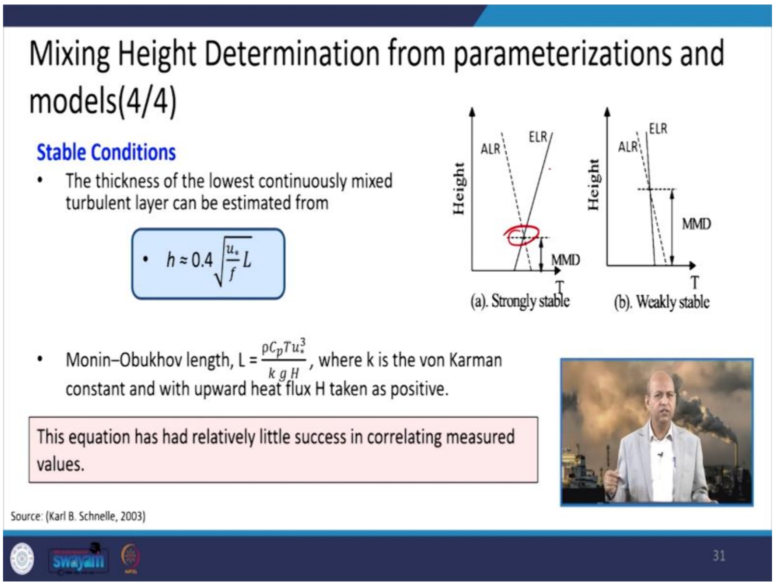

Similarly, in this case also like strongly stable when so, maximum mixing depth in stable conditions you can get here, see the adiabatic lapse rate is crossing even inversion is there. So, mixing is possible. So, I mean to say like when we talk about inversion, we say that it acts like the cap, but because of this relationship a little bit, it can go inside even inversion layer sometimes. Then maximum mixing depth is calculated in weekly stable atmosphere and this is strongly stable. So, again wherever this intersection is there, so, that kind of mixing depth can be calculated.

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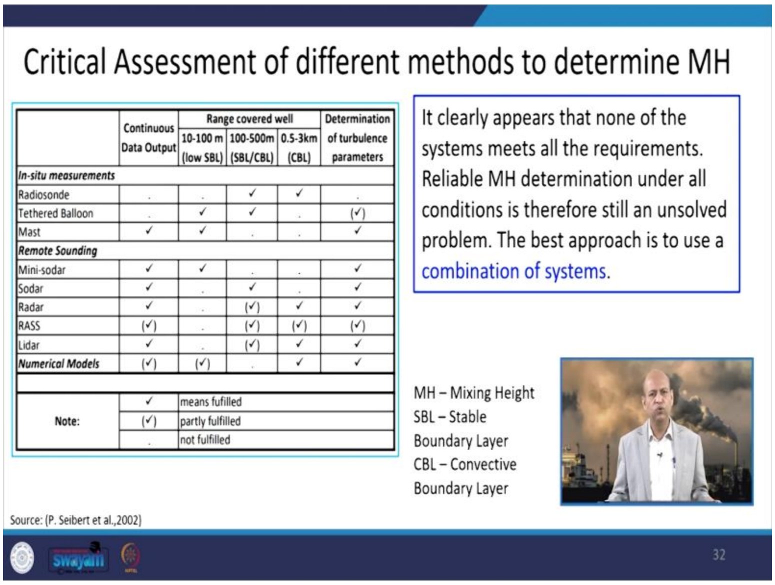

	Continuous Data Output	Range covered well: 10-100 m (low SBL)	100-500m (SBL/CBL)	0.5-3km (CBL)	Determination of turbulence parameters
In-situ measurements					
Radiosonde	.	.	✓	✓	.
Tethered Balloon	.	✓	✓	.	(✓)
Mast	✓	✓	.	.	✓
Remote Sounding					
Mini-sodar	✓	✓	.	.	✓
Sodar	✓	.	✓	.	✓
Radar	✓	.	(✓)	✓	✓
RASS	(✓)	.	(✓)	(✓)	(✓)
Lidar	✓	.	(✓)	✓	✓
Numerical Models	(✓)	(✓)	.	✓	✓
Note:	✓	means fufilled			
	(✓)	partly fulfilled			
	.	not fulfilled			

When we talk about critical assessment of different methods to determine mixing height. So, if we go for different methodologies, no single methodology is perfect. So, the combination of different ways we need to go for determining a good assessment.

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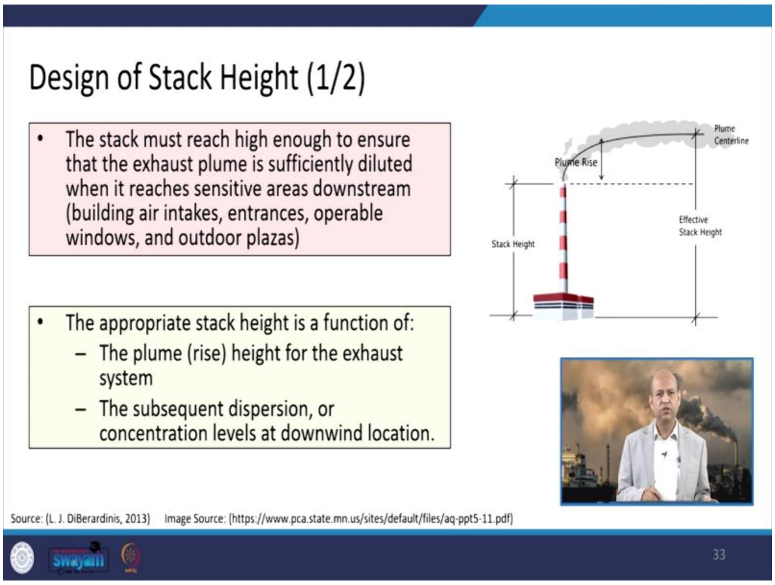

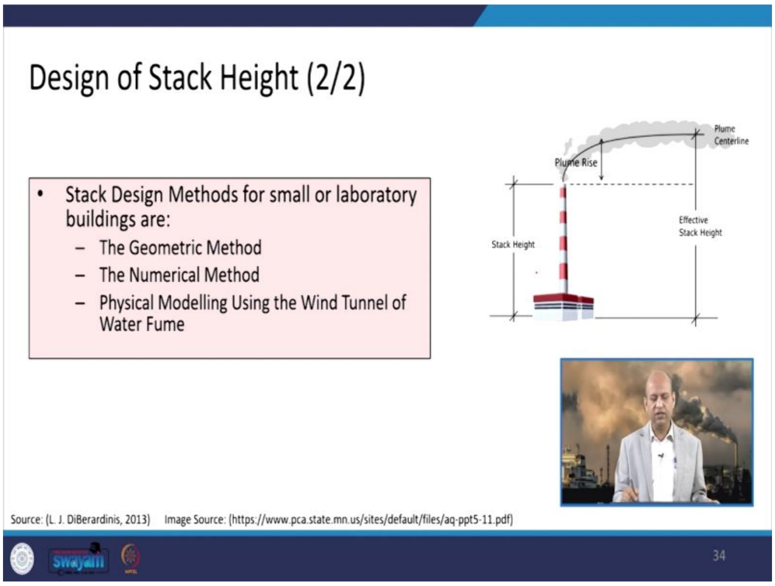

When we talk about design of a stack height. So, again there are many empirical relationships to design the stack height like geometric method is there numerical method is there, physical modelling can also be therefore for determining the stack height.

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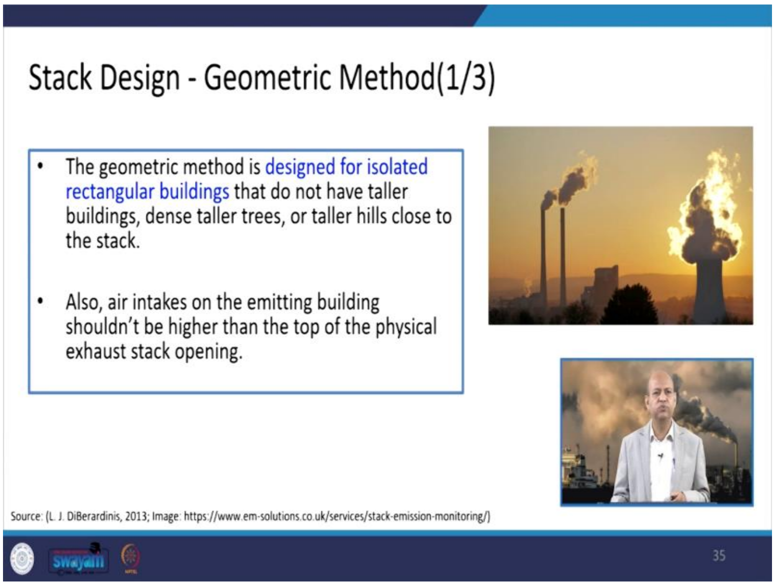

So, you can see like geometric method has certain parameters for isolated rectangular buildings that do not have taller buildings or dense taller trees, those kinds of conditions we have to see before calculation.

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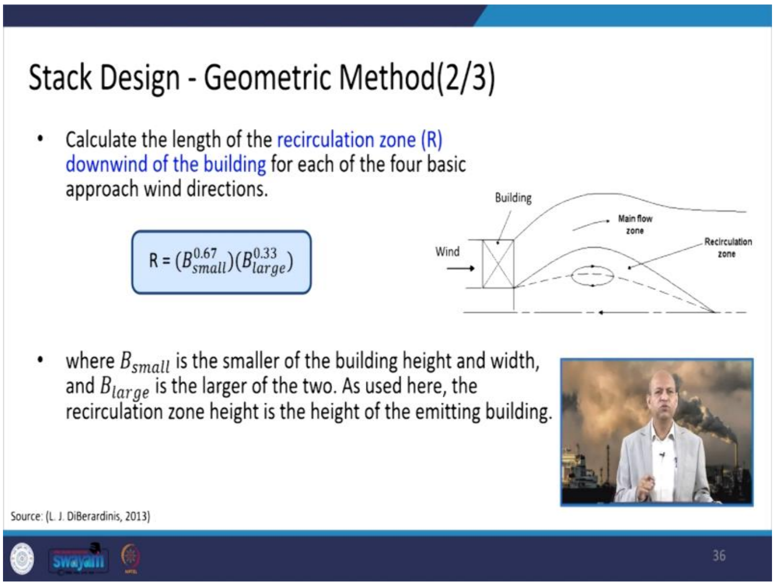

So, these are the you know relationships which gives us the particular parameters which are used for designing the stack.

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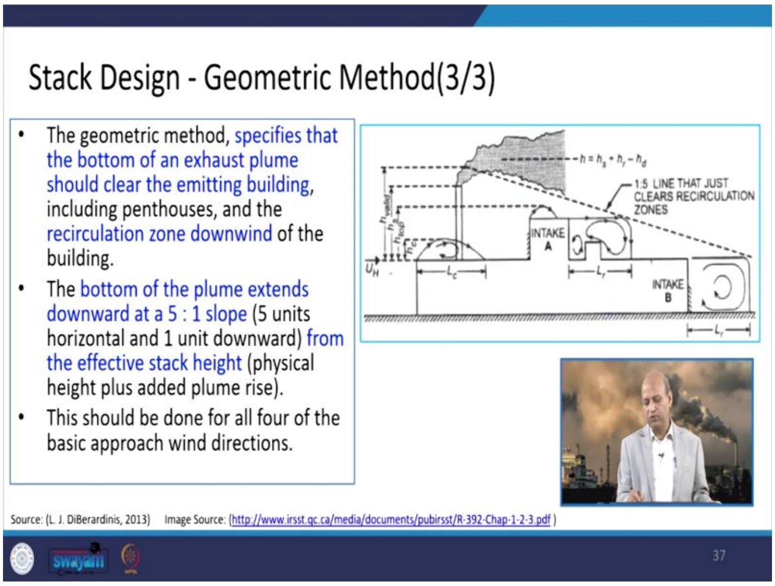

So, you can see here you know this plume is going this side so, the bottom of the plume extend downwind like 5 to 1, 5 horizontal 1 vertical. So, we have to take care that this should not come into the height where wind is intake in the buildings, the wind is going inside the buildings or some wave formation is there that is should be avoided. So, those things are to be observed and it should be ensured that the height of the stack must be sufficient so that plume does not come in this particular range.

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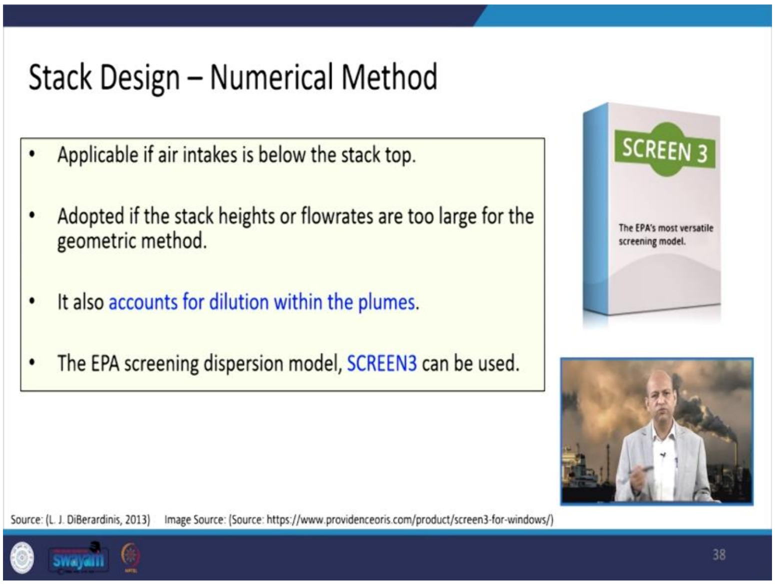

When we talk about numerical methods. So, you see different models are also available like EPA has designed one SCREEN3 model which can give the stack height related calculations.

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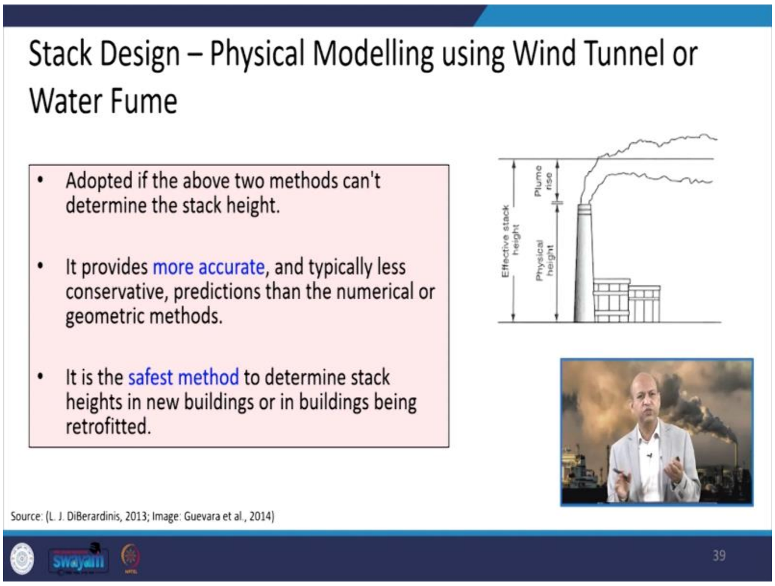

You can see here stack design based on physical modelling for by using wind tunnel or water fume. So, that is very accurate kind of method, but again it requires a lot of skilled manpower and some infrastructure which is very kind of sophisticated. So, that we also you can calculate by studying in those models.

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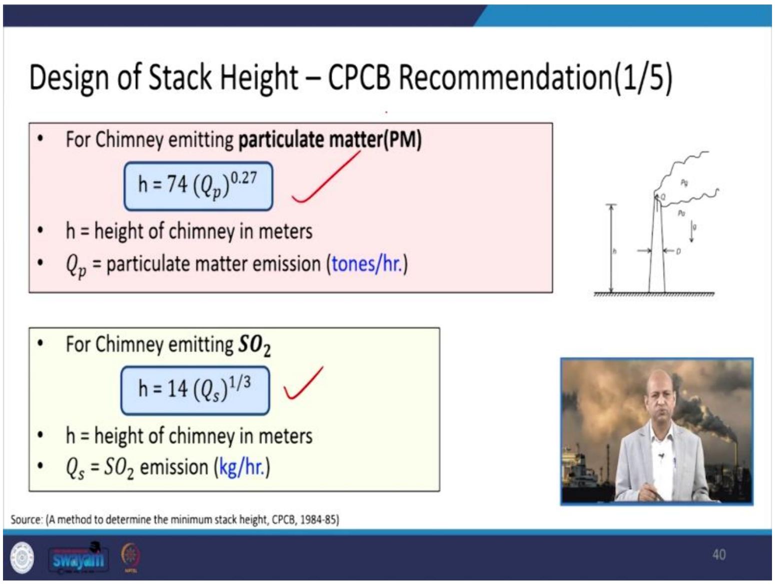

Then there are some empirical relationships like you can have this for particulate matter, central pollution control board is it recommended certain heights, similarly SO_2 related some estimated height can be taken from this particular relationship. So, these are empirical relationships, you calculate and then you take the maximum one.

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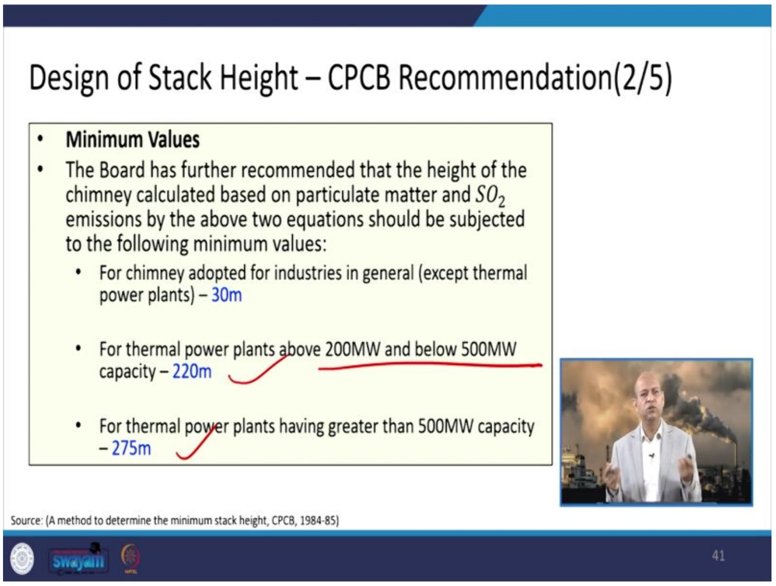

And then the minimum values are also recommended that whatever calculation is there it should not be less than 30 metre in case of this chimney which is in industries accepting thermal power plants, for thermal power plants depending upon their capacity they have recommended like 220 or 275 whether this you know power plant is of 200 megawatt and below 500 megawatt and then beyond 500 megawatt this is the height minimum height that should be taken.

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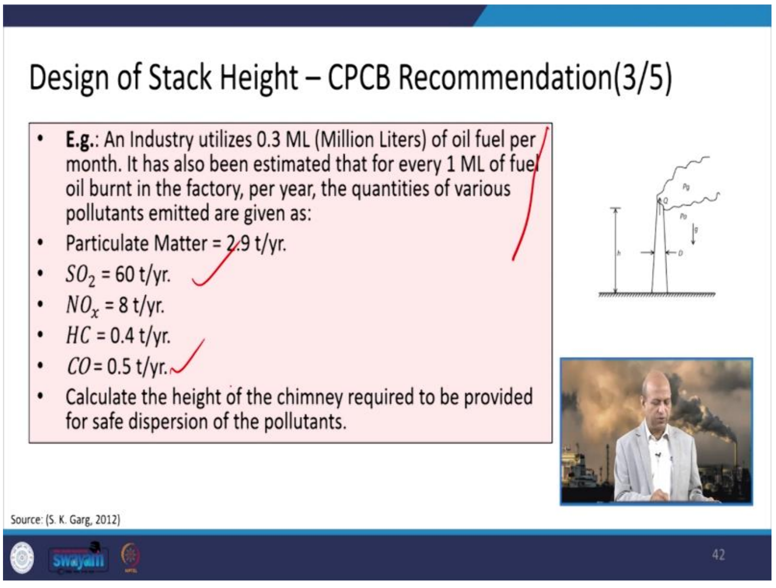

So, when we go for an example like there are certain input parameters, you take those equations and these values you can use, SO_2 say particulate matter etc.

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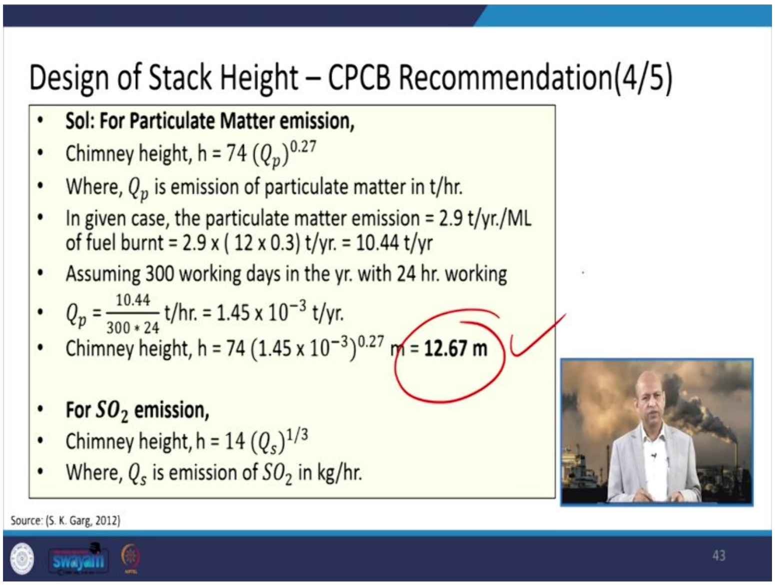

And you put in those equations values and you get calculations like for particulate matter the calculation is coming around 13 metre.

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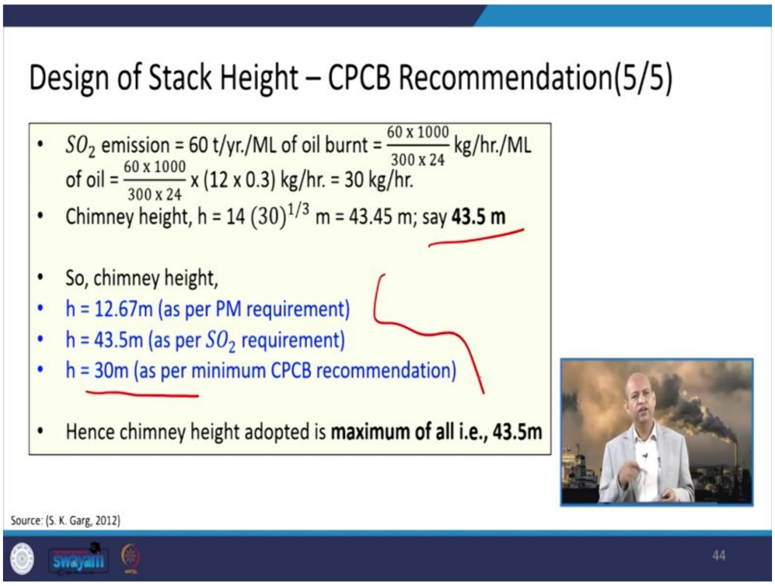

For SO_2 is coming around you know this 43.5 or 44 metre. So, you go for the maximum one out of this because this recommended minimum value is also lower than 43.5 it is 30 metre. So, these three values are there and you go for the maximum one.

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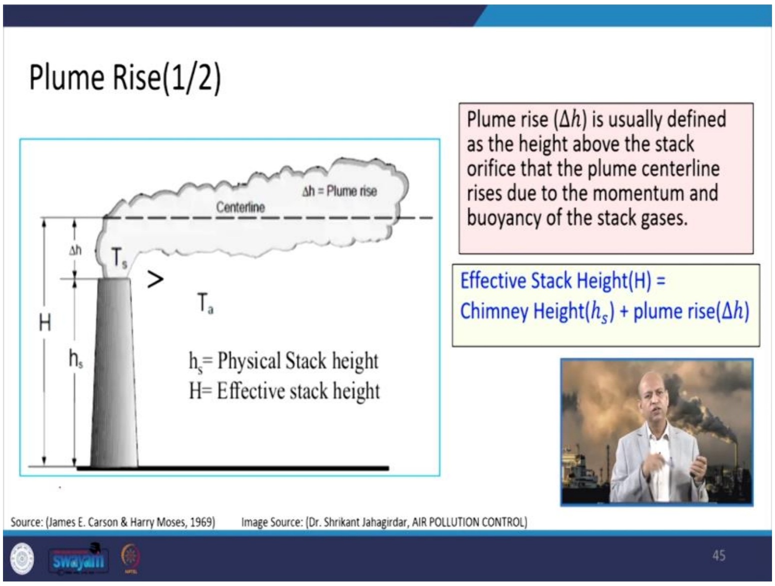

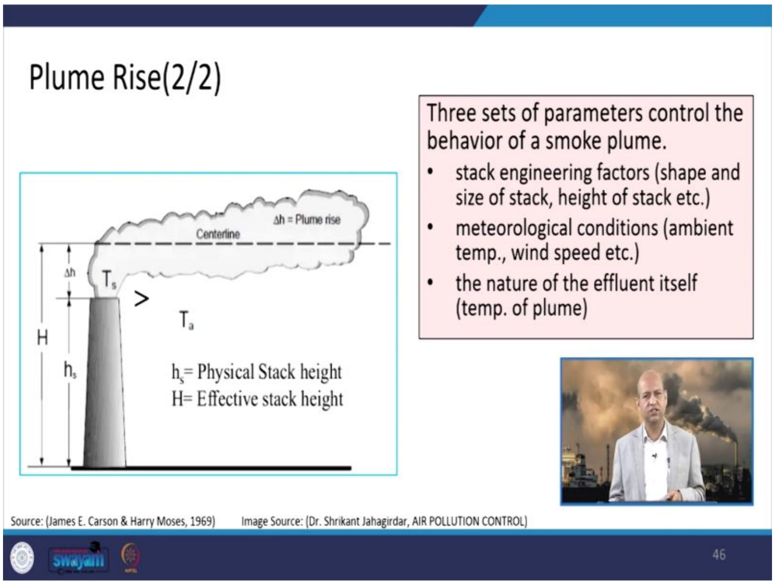

When we talk about plume rise because we discussed earlier also like plume rises because of you know momentum and the buoyancy, because of temperature difference, momentum because of exhaust velocity. So, these two components really helped us to get the plume rise. And plume rise this delta h is added into physical stack height to calculate the effective stack height which is used in model calculations when we go for dispersion models etc.

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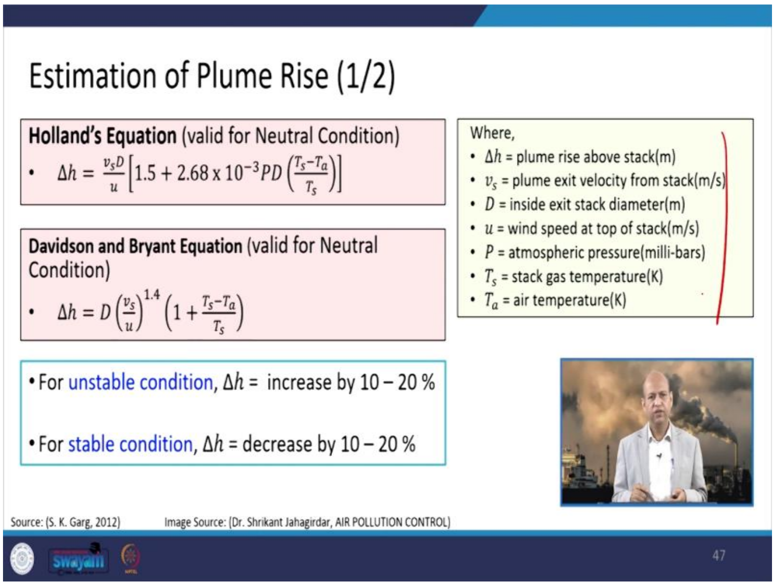

So, you can see here like these are the empirical equations recommended by different researchers like Holland's equation is there. So, they are taking into account this momentum the velocity and the temperature different that is the buoyancy part. So, different combinations are there and different combinations are because of those conditions only unstable condition, stable conditions these are the parameters you can see which are given in these equations.

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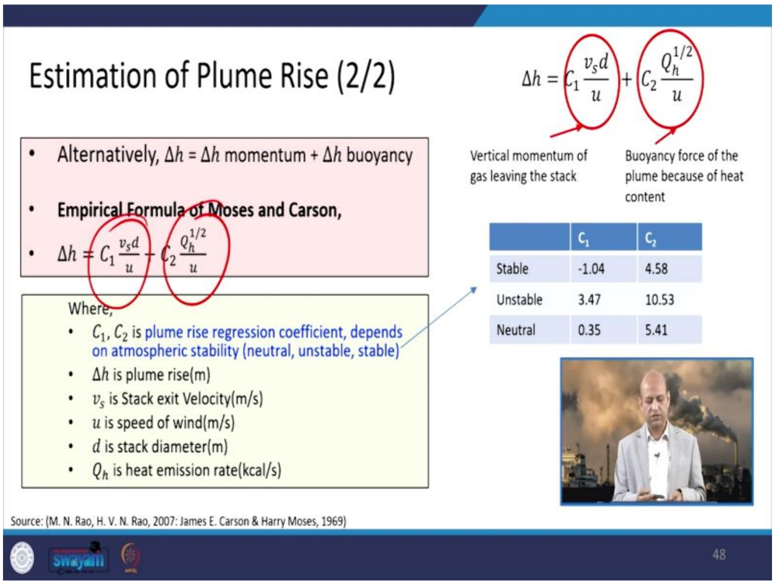

Then when we talk about like empirical relationship which is given by Moses or Carson. So, momentum and buoyancy factor as I said. This is the momentum related, this is the bouncy related, these are the different nomenclatures of those parameters which are used for calculation purpose.

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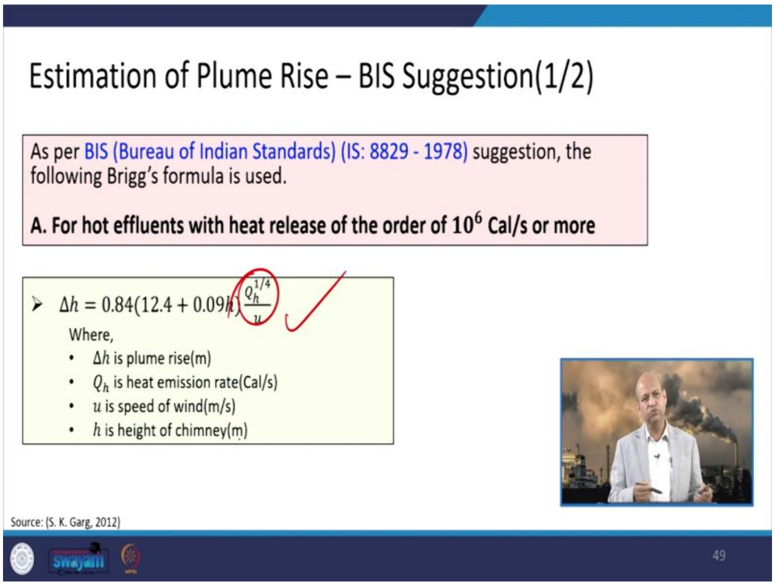

This Bureau of Indian Standards this recommended the BIS formula for estimating plume rise which is quite popular. So, again this Q part energy part or heat emission this takes care of the buoyancy. So, delta is calculated by this particular formula u is the, this wind speed h is the height of the chimney. So, according to that this plume rise can be calculated.

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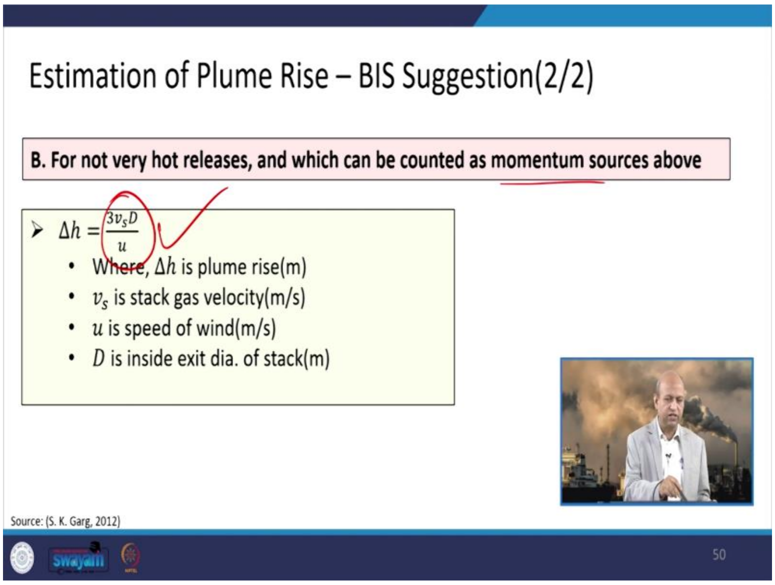

Then for hot releases then this is the relationship which is by this velocity of the exhaust emissions. So, these are two parts basically A part is heat release related that is the buoyancy related and this is because of momentum related wind speed is u but this is the Vs, is the exhaust velocity that is taken into account for momentum calculations.

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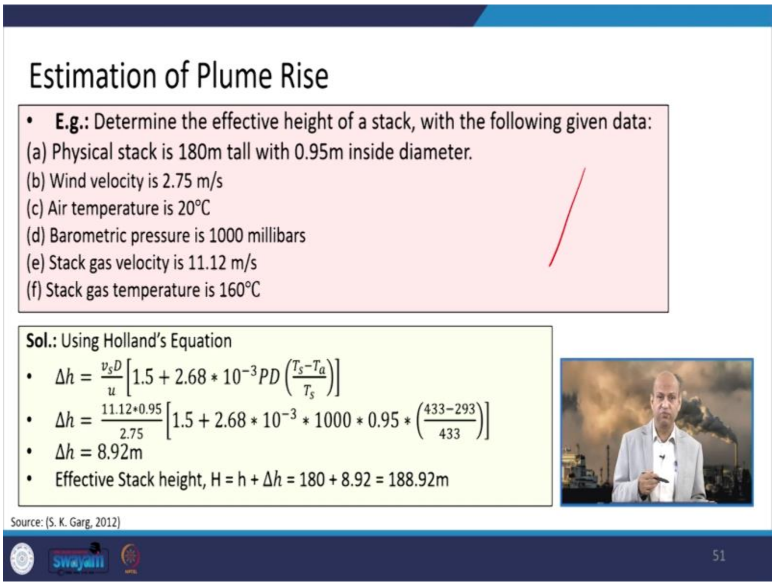

This numerical example is given for practice purpose. So, you can use these empirical relationships you can calculate the plume rise and see which is the maximum one which is the minimum one, why they are coming that way you can go for those simple calculations.

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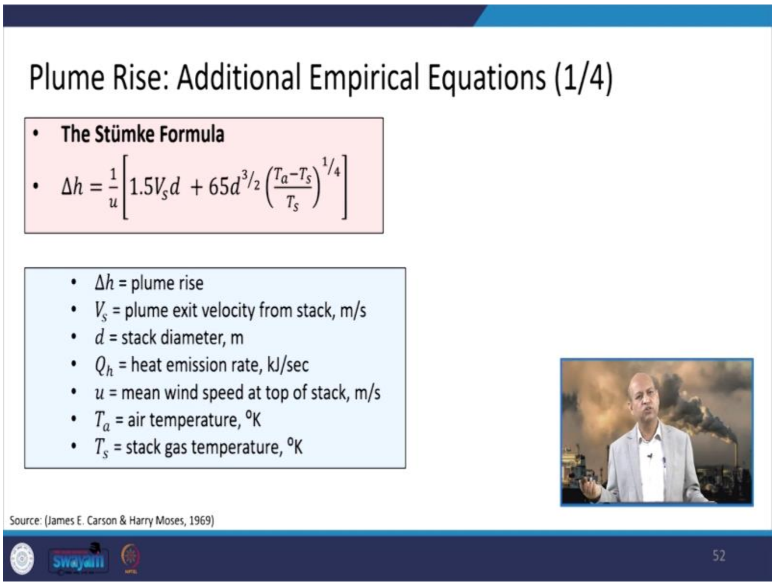

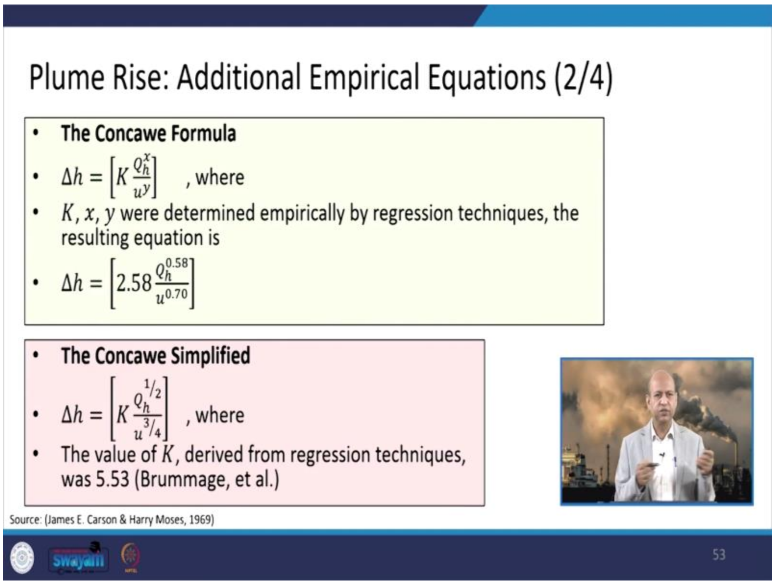

Then there are additional empirical relationships by different researchers depending upon what is the stability classification, temperature difference those kinds of things are there.

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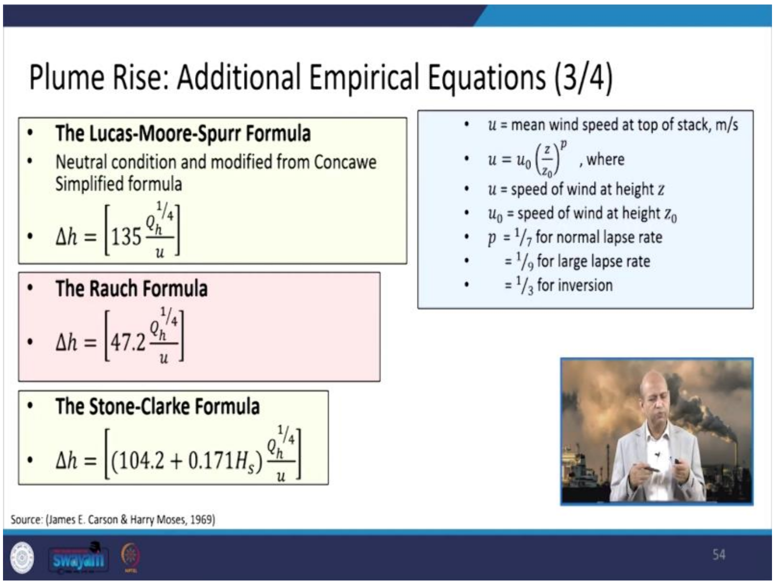

So, many researchers have recommended different you know formula or equations for calculating plume rise in different conditions.

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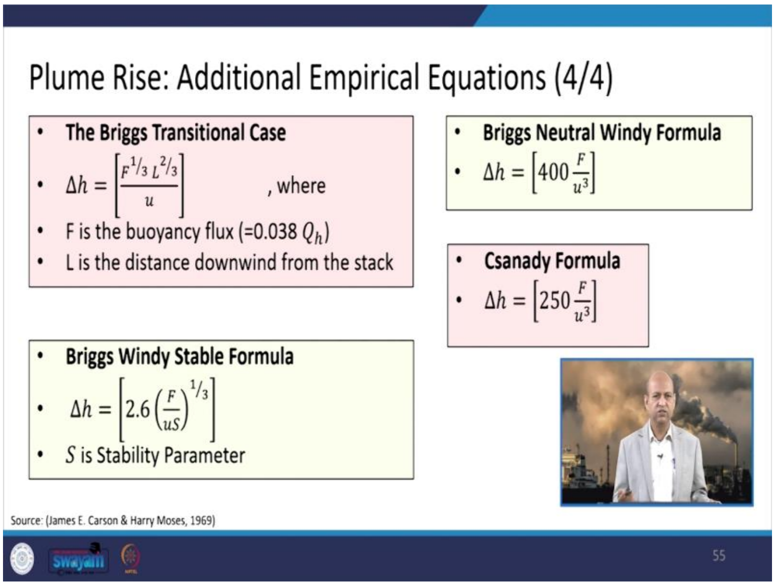

Well, you can see here delta h is being calculated by buoyancy factor or momentum.

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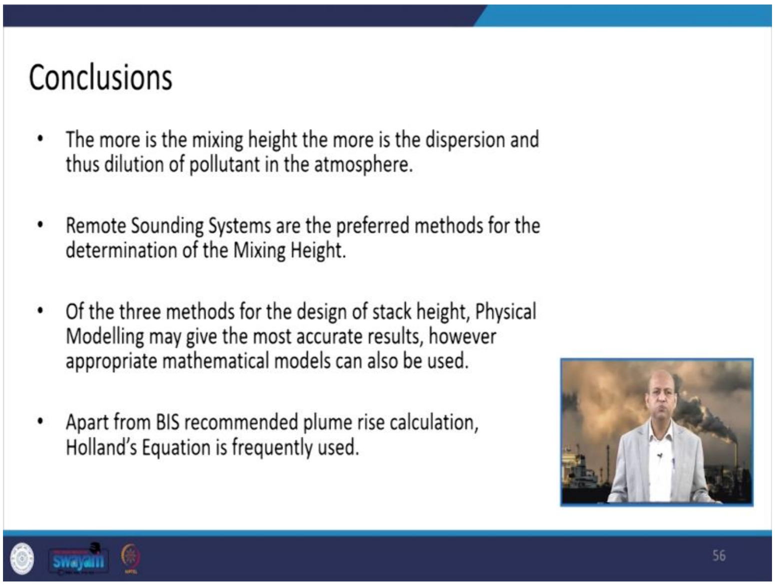

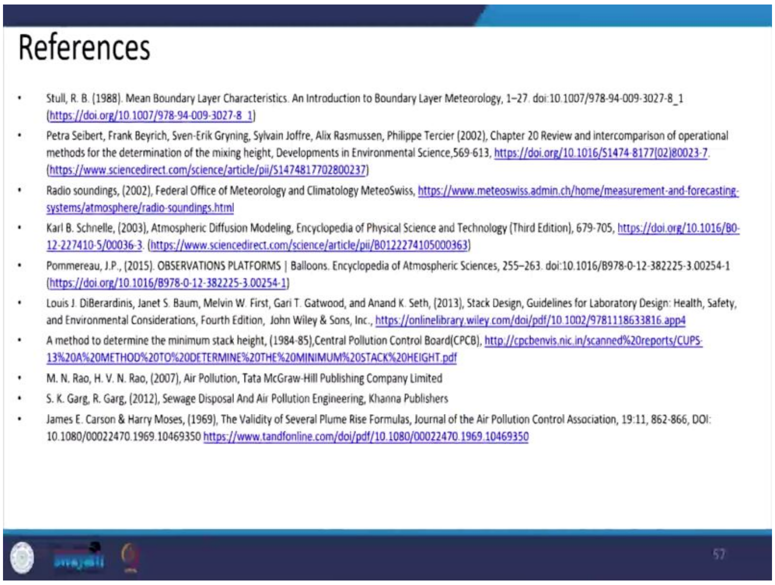

So, in conclusion, we can say that this this mixing height when it is more than more volume is available for dispersion and for dilution of the pollutants and remote sounding systems are preferred methods for determination of the mixing height they give good realistic values. When we talk about like different three methods for the design of the stack height, then physical modelling may give a more accurate result, but it has limitations as I said infrastructure is needed for that all those, but there are mathematical models also we they can also give some values and we can choose out of those different recommended values.

Then, if we talk about like BIS recommended plume rise calculations, then Holland's equation is also popular. And these Briggs formula recommended by BIS is also very much popular. So, this is all for today and these are the references for additional information. So, thank you for your kind attention. See you in the next lecture. Thanks.