**Introduction to Atmospheric Science**
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**Lecture-07**
**The Earth system – Hydrological cycle contd ... and Carbon cycle**

Okay so, we will continue that discussion on the various commuters of the earth system. Yesterday's class we started looking at the hydrological cycle.

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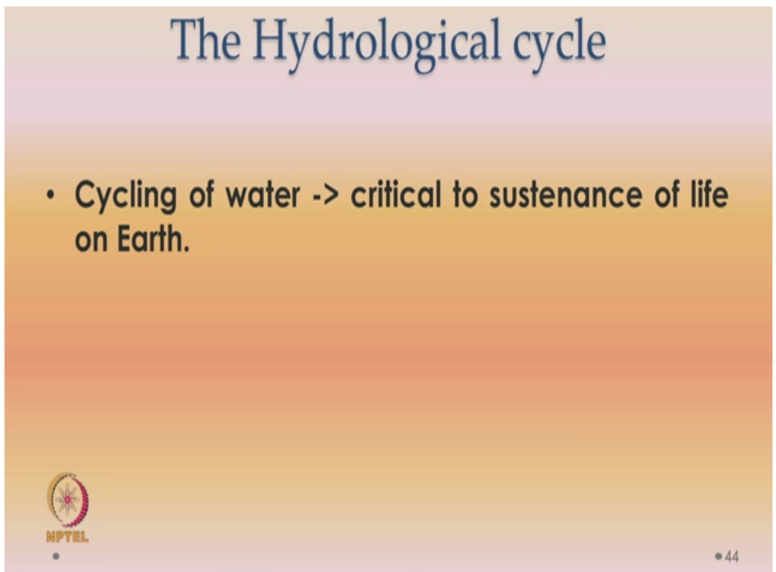


So, the hydrological cycle is very critical to the sustenance of life on Earth.

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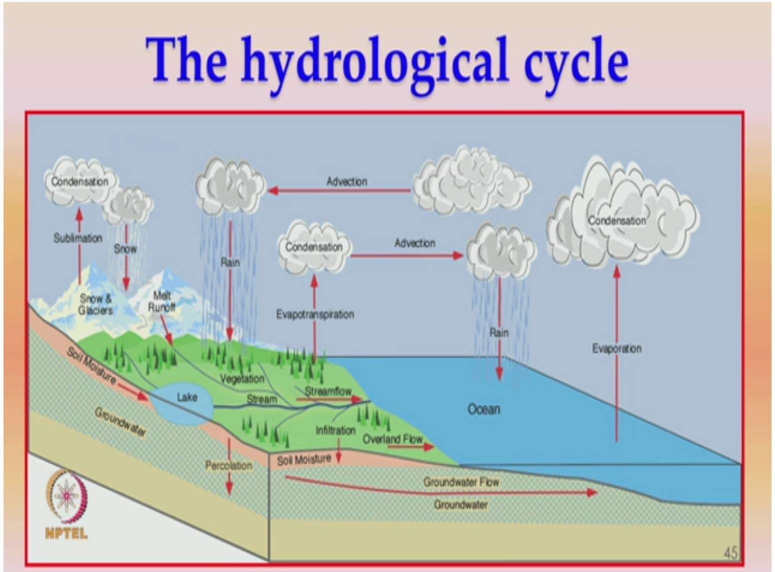


So, this is basically overview of the hydrological cycle. We already took a look at it in yesterday's class. The basic process of evaporation and condensation which are happening both from the terrestrial biosphere as well as from the oceans and then there is a lot of transport, horizontal transport, the winds that is advection and then you have got rainfall then, precipitation you have got flooding, you have got runoff.

And so, this is, this cycle is very critical for the sustenance of life and it is very important that we get rain over the continents. In fact, yesterday when we continued I told you that globally precipitation is =.

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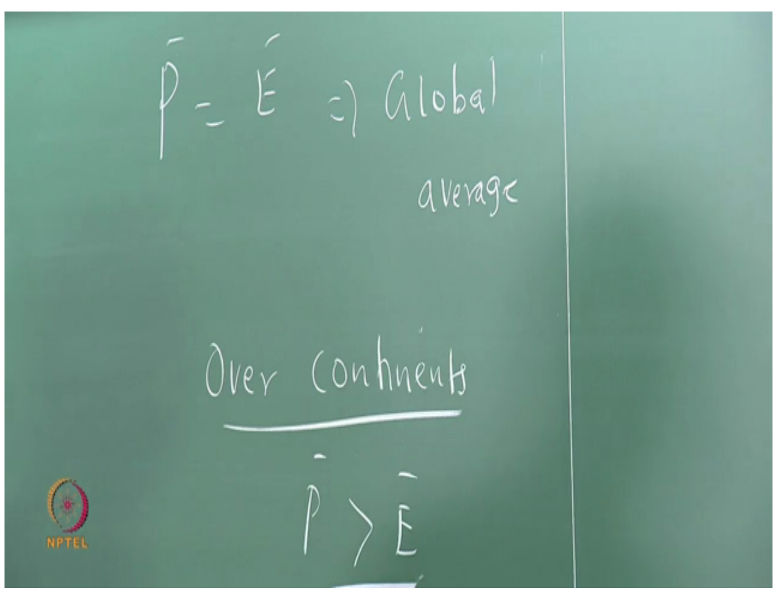

So, this is global average, okay. Over continents, there is good news. So, over the continents the precipitation is greater than the evaporation. So, there is positive the P - E is positive which is very good. But there can be places like deserts where E is much, much greater than the P the evaporation is more than the precipitation. And this water vapor will move towards the Intertropical Convergence zone that is towards equator or it will go towards the mid latitudes, ok.

Mid latitudes is typically 30, 40 or whatever Germany, UK and all that. And I think what will come on the southern hemisphere, Brazil or okay all these things will come, alright. So, this is very important to work on continents. P is greater than E.

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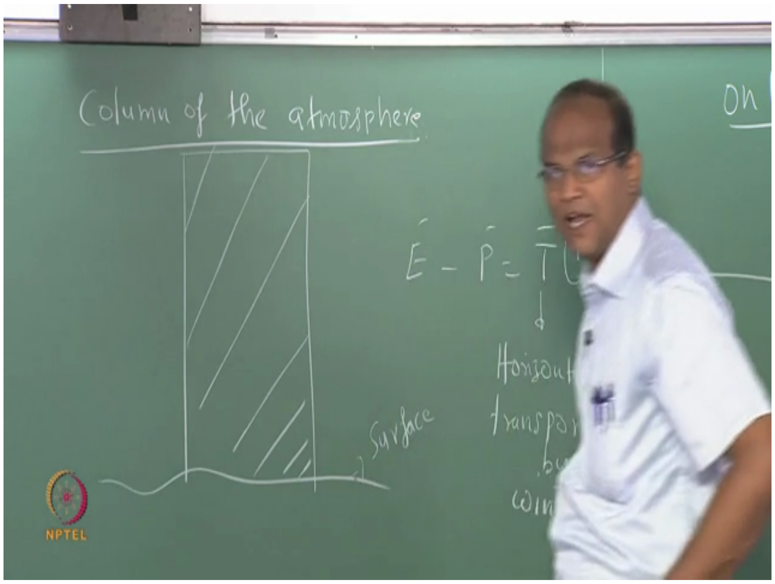


Now if you take a column, if you take a column of the atmosphere, what can you say about P and T. To take a column of the atmosphere E - P, I just wanted to check whether I am using P - E or E - P. So, shall we assign some equation numbers to this, for we will start with 1 or okay. So, what is at T. Please look at this figure. T is the horizontal transport by winds, okay. That is you take some column like this, okay. You take a column like this and do a one dimensional by a mass balance horizontal transport by wind.

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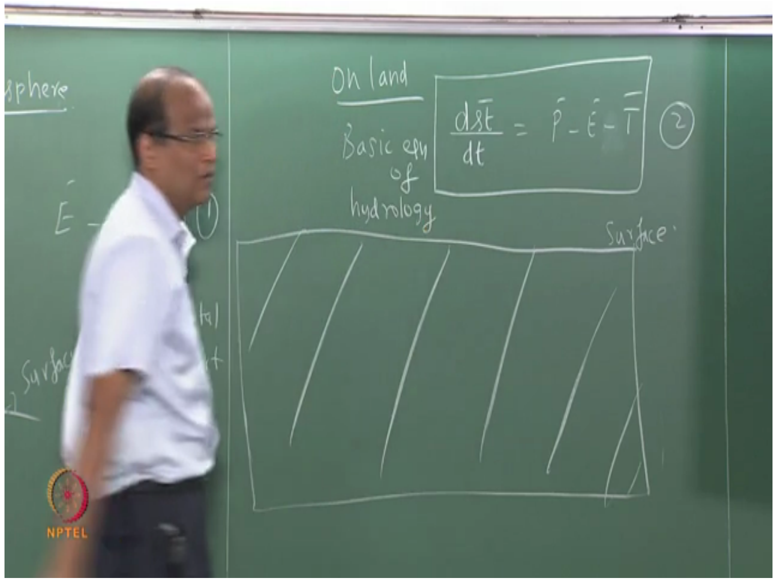


Now, let us look at on land. So, now this is the surface. So, this is a column of the atmosphere. This is the surface right this can be in ocean surface or a land surface. But no over land, you are looking at something like this. Look at something like this. So, you can write this. The rate of change of storage with time is = P - E - T or its okay. P - E or P - T + T, you are getting + T, okay. Is it correct?

It depends on how you define transport. But if you take it from this equation ds by dt, P - E + T. So, I am having a - here. We will have to flesh this out later. Anyway to make it correct let us keep it like this. So it depends on how you visit the influx of the efflux, okay depends on your okay so long as I account for it properly, the net change in the precipitation - evaporation, the horizontal transport.

If it is under steady state, there would not be any change of storage of water with time. Otherwise, this can increase or decrease which could happen to a lake, reservoir, pond or whatever, okay. So, this is basically a, the basic equation of hydrology. So, where st is the average storage of water and dst bar by dt is a rate of change of average storage of water for averaged over the basin or whatever.

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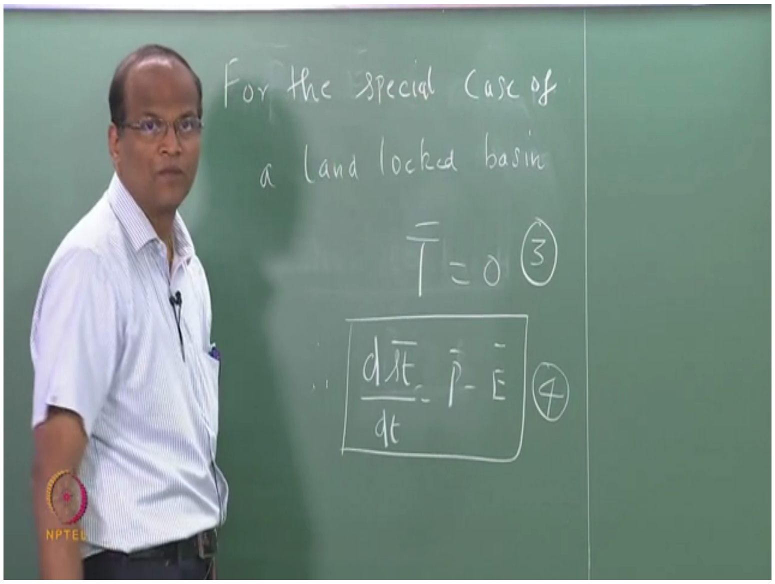


For the special case of a landlock basin, so the special case of a landlocked basin, landlocked there is nothing which is coming in and going on. Which of the terms is 0? Rainfall will be there, evaporation will be there, T is 0. So, in the case of land, what are those entities which contribute to the T, runoff, then from ground water runoff, from rivers, tributaries, whatever is going out and whatever is coming in and all these.

In the case of a landlocked basin, T is =0. No, we are talking about this, we are talking about the land it is not the atmosphere. They have already changed I already switched surface level I am ignoring. Surface level some good will be there but that we do not worry too much about that. Now, if you the beauty of this equation for is if you integrate it over a sufficiently long period of time P will be =E, okay.

But over shorter times P if P and E are different, then dst by dt will be non 0, okay. Suppose, there is no evaporation and continuously you get rain, so dst by dt must be positive or negative. Positive, does the equation confirm this, okay. There is no rainfall at all in Chennai for example Red Hills. Last 6 months there is no rainfall at all. There is only - E which is taking place then the height of the lake will decrease or increase. It will decrease.

So, this equation is consistent with our understanding; it is consistent with your common sense agreed, okay.

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| Reservoir of water | Mass x $10^{-3}$ kg/m$^2$ | Residence time |
|---|---|---|
| Atmosphere | 0.01 | Days |
| Fresh water(lakes and rivers) | 0.6 | Days to years |
| Fresh water (underground) | 15 | Up to hundreds of years |
| Alpine glaciers | 0.2 | Up to hundreds of years |
| Greenland ice sheets | 5 | 10,000 years |
| Antarctic ice sheet | 53 | 100,000 years |
| Ocean | 2,700 | |
| Crust and mantle | 20,000 | $10^{11}$ years |

We already looked at this in yesterday's class, right. So, the atmosphere has got a mass of 0.001 10 to the power of three kilogram per meter cube. We looked at the residence time. These are the basic reservoirs of water.

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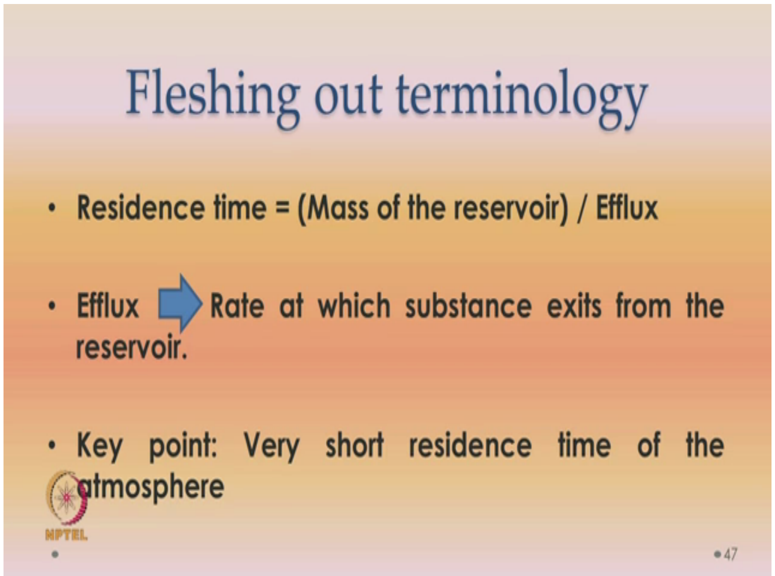


So, we looked at residence time which is the mass of the reservoir divided by efflux. Efflux is the rate at which substance that is water or water vapor exits from the reservoir. Key point is a very short residence time of the atmosphere which is the order of days. The mantle is about 10 to the power 11 years and so on, ok.

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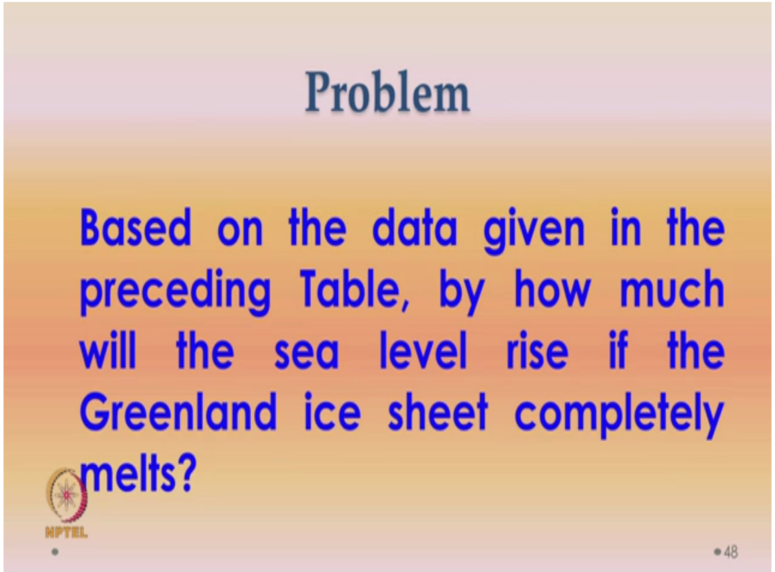


Problem number 7 please state now this is over, fine, 6.95 meters.

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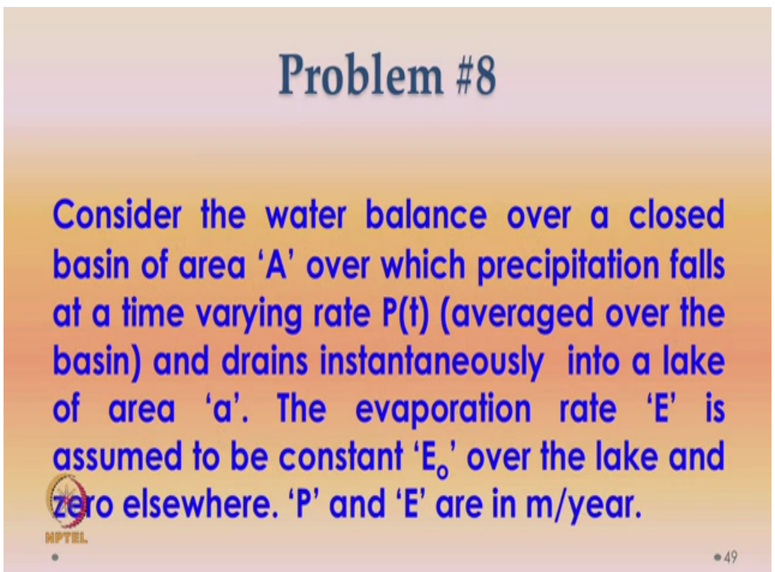


Problem number 8, okay, I will dictate it for the sake of completeness. You can either follow what I'm saying or you can directly take it from the board. Consider the water balance over a closed basin of area capital A, over which rain or precipitation consider the water balance over a closed basin of area A over which the precipitation or rain falls at a time varying rate P of T. So, the precipitation is a function of time.

But this is averaged over the basin, it is okay. Once you have taken upto basin, just hang on. What does it mean? Averaged over the basin mean? If the basin is sufficiently for example in the hostel you get rain and in the in gate you do not get rain or something, okay. So, we have to say what is this P? It is only P of T but P of XY is is =P are you getting the point?

So, for example, if it is so many kilometers, by so many kilometers, spatially rainfall this way the rainfall is highly variable spatially. But here we are ignoring that, okay. For starters we can ignore that. So, move on. So, drains instantaneously into a lake of area A.  Please note the difference between a basin and a lake. The basin is the catchment area, the place where is lot of rain will, rain will be likely there is a likelihood of more rain and then from all these catchment areas the rain water is fed into or diverted to the lake of areas small a.

The evaporation rate E is constant the evaporation rate is assumed to be constant at the rate of E sub script o E naught over the lake and is 0 elsewhere that means do not worry about the basin okay both P and E are in meters per year that is a normal listening okay what do you think is average rainfall in Chennai in meters per year take a guess 14 meters 1.4 meters it is about 1004 and millimeters per year.

So, western guards you may get 2, 3 or 4 meters per year a Bhagambay, for example in the Western Ghats how remains the Cheerapoonji South India, so how many people are from Karnataka, Bhagambay it gets up at 6, 7 meters having be using the Western Ghats. So, it is a cobra capital of India.
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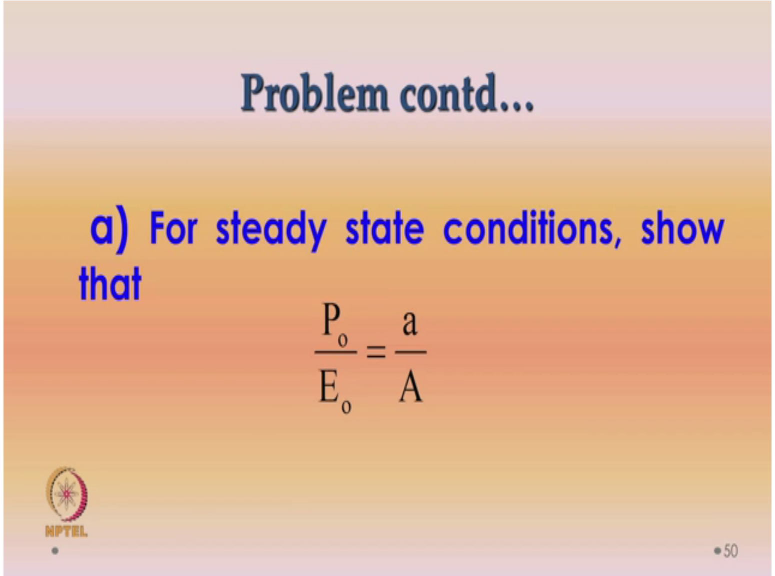


Now the problem is a for steady state conditions show that P naught by E naught =a by A part A show that for under steady state conditions P naught by E naught =a by A, please start solving this problem number 8 right.

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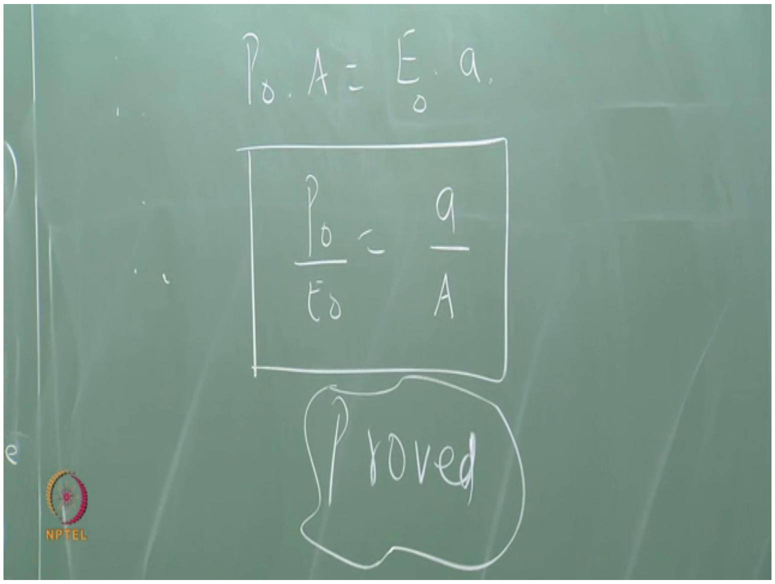


What is the first equation in apply what is the basic equation of play under steady state P bar equal D bar is a slightly difficult apply yes, you will be getting it 0 but basically it is in the integration and be sufficiently long. So, under steady state total precipitation is =total evaporation you start from that okay. Under steady state total precipitation =total evaporation how to evaluate the total precipitation okay.

So, agree so the total precipitation is a product of density into area into P naught into time. The time will be the same for both the precipitation evaporation or considering the same time okay Rho is going to be the same A is going to be the same sorry A is going to be different okay. So, this is the total precipitation. You still have the units of kg tons whatever kg will be very small does not matter okay.

We are not working with numbers total evaporation Rho very good, Rho small a E naught into time, now we will apply the condition of steady state under steady state therefore E naught fine this is pretty simple any doubts lets more to the part everybody through with this okay.

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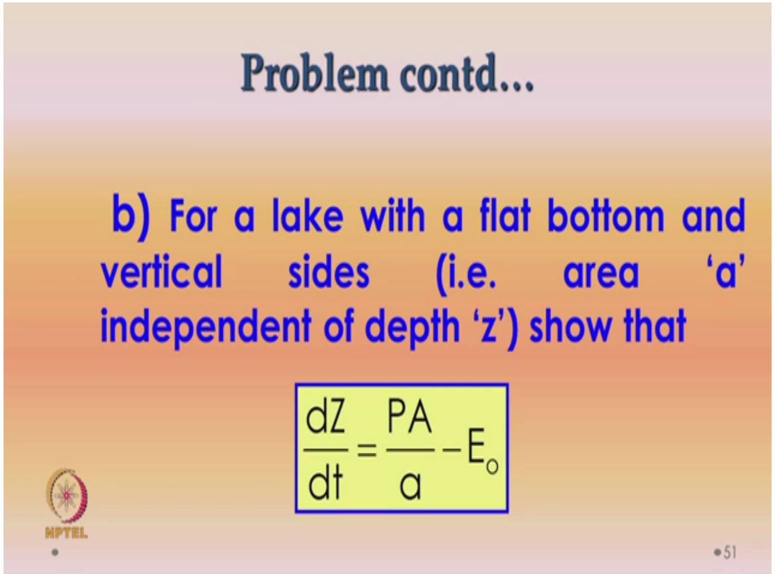


Now, we will have a lake which has got a flat bottom and vertical sides, okay. So, the lake is like this, okay.

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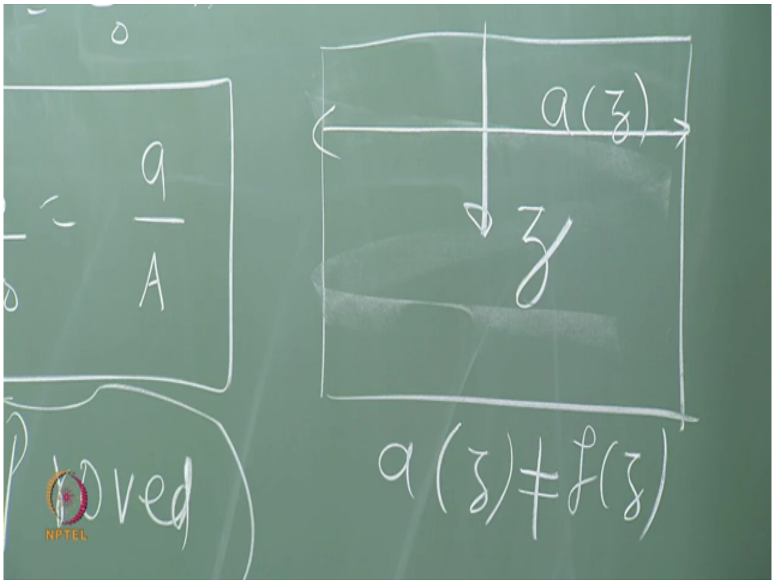


So, this is a of z now we have a lake where a of z is not a function of z. Some people may have a doubt. So, how come here a of z can be function of z, yes the lake can be like this right, for example.

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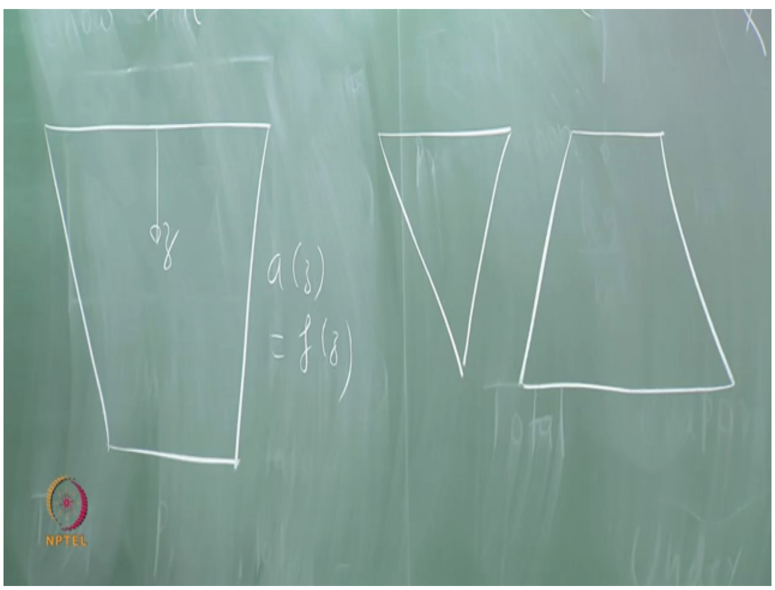


So, very special case could be like this. You have a case like this. Being an artificial lake it is left with the designer. We can have some fancy, civil engineers have to worry. So, you can have various shapes. Now, we are looking at a simple shape where a of z is a is not a function of z, so proceed. For a lake with the flat bottom and vertical sides that is the area is independent of the depth, z or z show that dZ by dt is PA by a minus E naught.

Now you have to consider a time interval dt. In a time interval dt, what is the total precipitation, which is coming in? What is the evaporation which is going out? The difference between these two must be = the rate of storage, okay. The dt will get cancelled throughout, it is a finite time and then, you will get this resulting equation. Please do this, got it?

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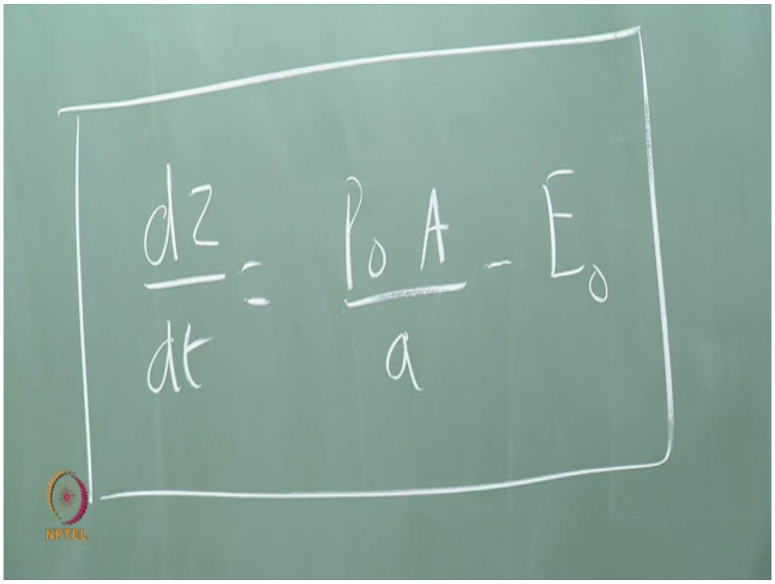


So, rate of inflow into the lake, P naught into which a? The inflow is coming from the basin the influence coming from the basin. So, do not ask, sir what happened though this thing plus small a into P naught into dt will also be there. What is the whole idea now? The a by A ratio is adjusted such that that this is more important for us, okay. Or we assume that there is no rain or the lake itself, okay. So, these are of this second order or higher order effects, okay. What is the rate of evaporation from, any doubts, okay?

E naught, E naught a, change in volume, Rho, Rho is already taken care know. Change in volume of the what are the units of this? Meter per year some meter per second, okay. Meter per second, second meter square meter cube, okay. So, rate of influence is volumetric, okay or you do this okay that will make it kg, alright. Now, what did he say? The change of volume, did you say that?

The change of volume of the lake, very good, small a, dZ, you, you can either use a small Z or whatever. Its 3, this equation is mass continuity law of conservation of mass, okay. Dividing by dt throughout with the condition that dt is not = 0, okay. Therefore, did we get what we want? This is the same as what is seen on the TV so thankfully we got the same result, okay fine.

So, this is the governing equation for the rate of change of height of the lake with time, okay. This very simple, very highly simplified equation, the K, the equation will get complicated the equation will get complicated under the following conditions. The precipitation is a function of time, the evaporation is a function of time, the area is a function of Z, okay. It is further complicated if there are incoming streams and some outgoing streams.

If you model this with all these complications, you are becoming a hydrologist, okay. Multiple n any incoming streams n outgoing streams and all these and varying flow rates and this thing so our equation you get very, very messy. How many civil engineers are there, here, okay? So, you must have studied some basics of this. So then, you can make it very then, you can study the hydrology in Madhya Pradesh, this Lake this river basin in Narmada basin, in Godavari Basin.

It will all become research problems, okay. Now, please take down part C. It is interesting, right? But we will ditch hydrology in today's class. And tomorrow we will go on to the get down to the carbon cycle, we will finish the carbon cycle and the oxygen cycle and get down to thermodynamics, okay. Part C based on the equation derived in B, based on the equation derived in b, describe in general how the level of the lake varies with time?

How the level of the lake varies with time as a function of P naught and E naught? Describe in general, how the level of the lake varies with time as a function of P naught and E naught? In simple English, I am asking you to solve the first order equation, okay. Some initial condition you have to assume. What is the initial condition? Time T = 0, Z = ZI. That is the initial level of the lake, okay.

And please think of some analogy in physics, no, after you work out. The after you work out the solution. See, whether you have. Is the question clear, okay?

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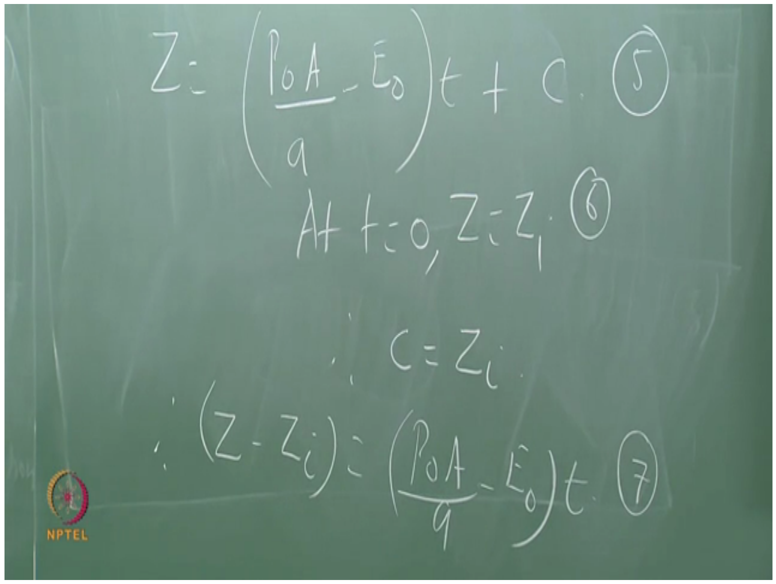


Some equation number is there for this. Did we start with some number? Why do not you assign some number? The same 3 know, okay. Is it a first order or a second order equation? First order, Is it a boundary value problem or initial value problem, initial value boundary value problem? It is in IVP. It is an initial value problem. That means you have to specify the initial value at time T = 0. You also call it as IC, initial condition, okay, pretty simple.

But it is pretty deep if you think about it. It is a linear response the height of the lake linearly increases with this linear response is because of our largely because the a P and the E they are not functions of either the time or Z if I make if I make P and if I still have P and E as constant but I change a as a function of Z then things will behave differently then you may get a Z cube Z 2, Z squared Z cube and so on.

Right side, you will still get the integration with respect to time will get only T Z may then go as T to the power of half or T to the power of 1 3rd and so on which means even if even if you had range like mad the lake will be able to hold on. This is not a very good design. This is a very good design for places where the rain is low. You have a lake a neighboring, you have got a big metropolis, and big city then, the linear response is not very good. Clear so, that is a design consideration of hydrologist.

How to design and this, alright, well then you will never check dam and then release it into the ocean, there are many other options available all right, fine. Now switch off here. We will switch your hydrology and get on to the carbon cycle. Any doubt so far? We can consider more in hydrology but I think this you just got a glimpse of this thing. Why is hydrology important because there is an atmosphere of ocean coupling, coupling rate, the hydrological cycle you have got there is also the water on the land apart from water and water vapor in the atmosphere, okay.

Now, if you recall, we are still looking at the Earth System, components: oceans, cryosphere, terrestrial biosphere, earth's crust and mantle over, hydrological cycle over; then, we will have to look at the carbon cycle and the oxygen in the Earth's system. If you are now being today's class and possibly tomorrow's class, we look at the carbon. We look at the carbon cycle, the next two days in the next class we look at the oxygen in the Earth's system.

Then, chapter 2 also will be complete. We have will have a fairly good in then we will have her you will have done we would have gone through, we will have gone through a fairly good introduction to the various components of the Earth System. And then, we have all set to take on deeper things in Atmospheric science like atmospheric thermodynamics, atmospheric radiation, atmospheric dynamics and then, the dessert will be the climate science and climate changes, okay. Carbon cycle:

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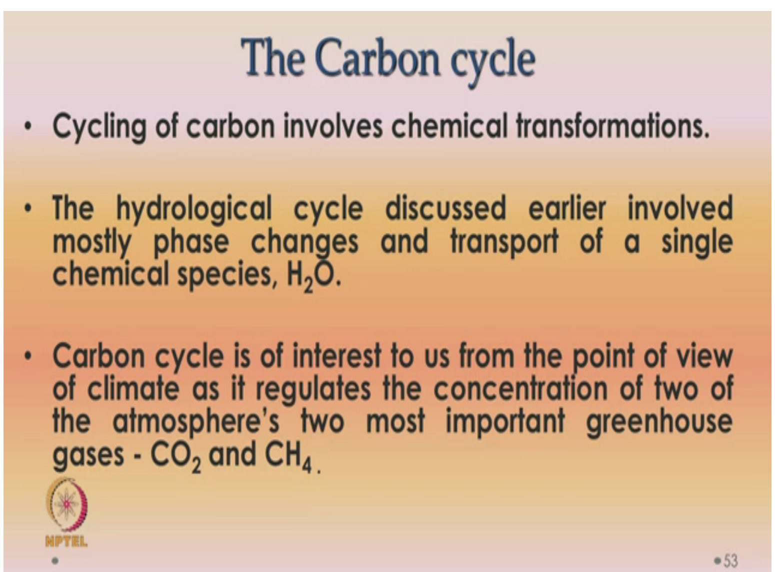

The cycling of carbon involves chemical transformation. The cycling of water involves no chemical transformation. The cycling of water involved only phase change ice to water, water to water vapor, water vapor to water, water to ice and so, it is only physical change. So, the hydrological cycle discussed earlier involved mostly phase changes and it is a transport of only one single species which is H2O. The carbon cycle is little more involved carbon, carbon monoxide, carbon dioxide and then, methane, very good.

Then this is all as far as the atmospheric. Go a little down, Glucose in photosynthesis, then it is Crust mantle, oil then further, calcium carbonate, calcium silicate, limestone. So, calcium carbonates that caco3 some C is there, okay. Then calcium silicate why is coming is calcium silicate and calcium carbonate some interactions are taking place which we look at in a subsequent class. So, there are lots of chemical reactions which are involved in the study of carbon cycle.

So, we have to be so some little bit of chemistry will be there, some basic chemistry, okay. We will look at some basic chemistry. Carbon cycle is of interest to us from the point of view of climate, as it regulates a concentration of two of the atmospheres. Already the answer was here, okay. So, concentration or two of the atmospheres, two most important greenhouse gases namely carbon dioxide and methane, okay.

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**Major carbon reservoirs of the Earth system**

| Reservoir | Capacity in kg/m$^2$ of Earth's area | Residence time |
|---|---|---|
| Atmospheric $CO_2$ | 1.6 | 10 years |
| Atmospheric $CH_4$ | 0.02 | 9 years |
| Green part of Biosphere | 0.2 | Days to seasons |
| Tree trunks and roots | 1.2 | Up to centuries |
| Soils and sediments | 3 | Decades to millennia |
| Fossil fuels | 10 | - |
| Organic carbon in sedimentary rocks | 20,000 | 2 x $10^8$ years |
| Ocean dissolved $CO_2$ | 1.5 | 12 years |

Please take down this figure, this table. The major carbon reservoirs of the earth: So, it is a three column table. Table, column one indicates the name of the reservoir; number two, gives the capacity in kg per meter square of Earth sea area. Why you are allowed to take down is, we will have to solve problems in the subsequent classes I will always refer to the table. So, you have to copy the table for ha getting the values. And the third one is the residence time.

I will keep talking slowly as you take down. The first entry is atmospheric carbon dioxide. The capacity is about 1.6 kilogram per meter square, okay. It is measured and it is okay. We will work out a problem soon on this. The residence time is 10 years, if you burn carbon and put in the atmosphere, it will have a residence time of 10 years, before it gets subsequently changed absorbed or this thing somewhere. So, 10 years.

Atmospheric methane, very low concentration but it stays in the atmosphere for 9 years. The green part of the biosphere, photosynthesis, decay, respiration, decay and all these, days to seasons. Tree trunks and roots: This below the soil 1.2 kilogram per meter square that can stay upto centuries. Soils and sediments: 3 kilogram per meter square, decades to 1000's of years. Fossil fuels, there is no residence time know, okay so, 10 kilogram per meter square.

Organic carbon in sedimentary rocks: that is a lot. So, from that if you are able to get some fuel that is also 20,000 kilogram per meter square billions of years, no, millions of years. Obviously, they are short of billion. Ocean dissolved carbon dioxide 1.5 kilogram per meter square and 12 years. Shall I move on or? Vishwajeet, what happened, very sleepy, done, yes the table continues:

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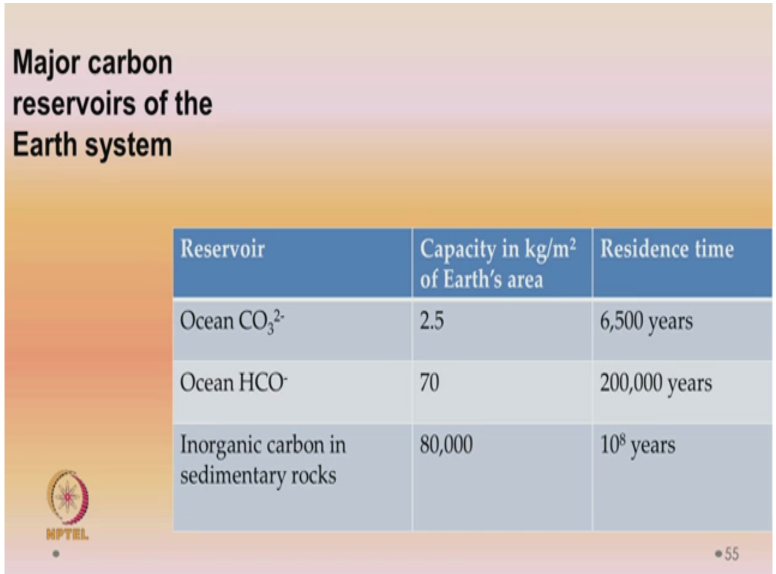

Major carbon reservoirs of the Earth system

| Reservoir | Capacity in $kg/m^2$ of Earth's area | Residence time |
|---|---|---|
| Ocean $CO_3^{2-}$ | 2.5 | 6,500 years |
| Ocean $HCO^-$ | 70 | 200,000 years |
| Inorganic carbon in sedimentary rocks | 80,000 | $10^8$ years |



Oceanic bike, oceanic carbonate or ocean carbonate is 2.3 kilogram per meter square, 6,500 years. You have not copied, yes okay hang up, okay sorry done? The quiz will be open notes, okay. So, sometimes I allude to the table. So, you do not come to class you are in trouble. So, what is the value of concentration of carbon dioxide in atmosphere I will not believe it is there in the table? At least copy from your friends if you miss the class. Shall we move on?

Done, you are still writing, yeah good. Done, go ahead. We will stay for 10 years in the circle or an atmosphere ah sorry Hayley no this basically you can have some models you have some measurements. So that this comes under atmospheric chemistry so, they have a way of tracking or you can track a molecule and so you can do some residence time, residence time studies and all that.

But these are a well documented, done okay. The ocean carbonate is 2.5 kilogram per meter square and it is about 6500 years. The oceanic bicarbonate is about 70 kilogram per meter square and 200000 years. Then inorganic carbon in sedimentary rocks, 80,000 kilogram per meter square, okay. Now let us make use of this table to solve the problem. People who have completed just wait for the others.

That is just three entries. Oceanic carbonate, Oceanic bicarbonate and inorganic carbon in sedimentary rocks. Sometimes it may be Marius sometimes it may just estimate but it is a good estimate exactly we cannot be nobody lives for more than 70 years here. So, one person cannot measure, so it is all somewhere you ask the question know to measure the estimate, we cannot do some experiment in the lab and measure it. If it is a few days we can, few months we can, do it all right, fine.

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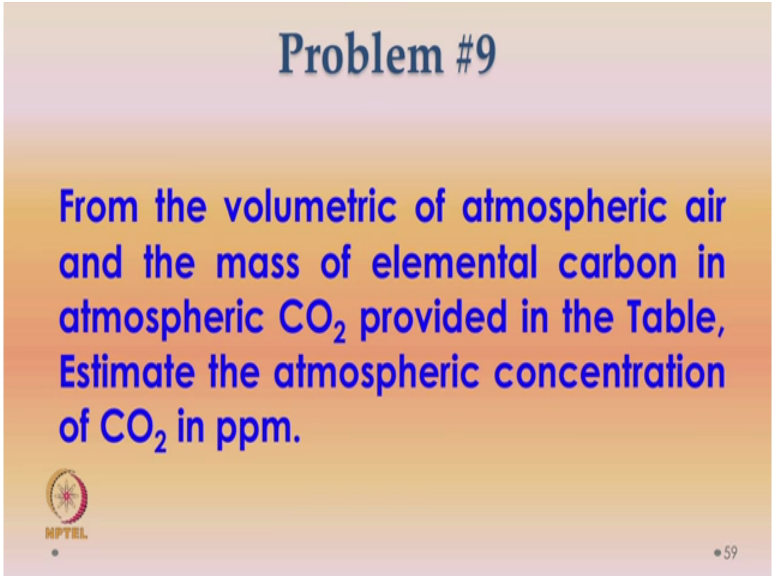


Yes. So, I am skipping all this in the interest of maintaining in enthusiasm in the class so that both the theory part we will do it tomorrow, so problem number 9, okay. We have to go back to the slides but it is too much of theory, right. Let us get on to the problem. Problem number 9: from the volumetric what is it? From the volumetric analysis of atmospheric air which was given in an earlier class.

From the volumetric analysis of atmospheric air and the mass of elemental carbon in the atmospheric CO2, provided in the new table, estimate the atmospheric concentration of estimate the atmospheric concentration of CO2 in parts per million, okay. So, how do you proceed? Mass of the carbon dioxide is = mass of the air into 12 grams divided by wall divided by molecular weight of air okay.

And then the mass of the air is itself given by 1.004 into 10 to the power of kilogram per meter cube. Then, you will find the mass of the carbon dioxide then 1.6 kilogram per meter cube is there. From this, you will concentrate you will change it to the volumetric to this thing you will get a value between 360 and 380 ppm. Do that, ok I will wait.

Understand the question? So, the first part is from the volumetric analysis of atmospheric air based on that we already calculated the molecular weight of air. So, you can use that value straightaway 28.93 or something right or you can use 20. We did it in one of the earlier classes so you can use 28.93 or 28.97 93. Please go ahead and use 28.93. Shall I start solving or and wait, start solving, okay. Please do not look at the board. After 5 minutes you can look at the board.

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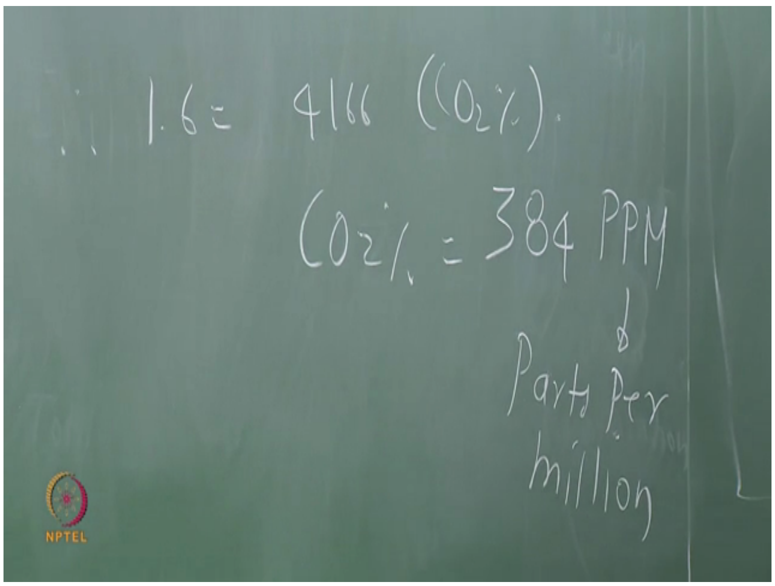


A typical quiz question for example for6 marks or 7 or 8 marks out of 40, right should take about 8 to10 minutes, okay. Problem number 9 so what did I give you? So, mass of CO2 is = the mass of air into the CO2 in percentage into molecular weight of carbon divided by molecular weight of air, okay. So, mass of air is; so 1.004 into 10 to the power of 4 into 12 divided by 28.93, what is that value? 1.004 Into 10 to the power of 4. This mass density we worked out in the first class, correct based on that we found some 2.5 into 10 to the power of 18 or 11 something, right some big number, okay.

So, what is this? What is that? No carbon. It is given in carbon, so you take 12. It is not carbonate; it is given as carbon okay. So, this is 4166. So, there are several things we have assumed a prior. In this 1.00 for ten to the power of our kilogram per meter cube is already worked out 28.93 is all from an earlier table and we worked out. So, based on this, I am getting an equation but the mass of $CO_2$ is 4166 into $CO_2$ percentage.

But $CO_2$ percentage is dimensionless. 12 divided by molecular weight is dimensionless. So, M of a is kilogram per meter cube sorry kilogram per meter square. So, the left hand side, we stay with kilogram per meter squared throughout. And the kilogram per meters cube, kilogram per meter square is the entry in the new table also, correct.

Now, $CO_2$ percentage is 384 percentage parts per million into 380 very good. Now, now you know why it is 384 ppm, okay. But it is very small. It appears to be just 300 parts per million but it can give a lot of trouble well it has the capacity to differentially absorb radiation in different parts of the electromagnetic spectrum which we will see in the later class. That is why the GHG it is a greenhouse gas, okay.

So, it is fairly well dispersed. We already saw the Mauna Loa experiments, so, if you measure atmospheric carbon dioxide over Chennai and over Hawaii it will be more, more or less uniform. Middle East its well dispersed and carbon dioxide is basically chemically inert. Therefore, its concentration remains uniform throughout the Earth's atmosphere and this residence is about 10 years. So, the jet goes; jet fuel exhausts carbon dioxide at 39,000 feet.

If the Jets leave that for years, for years that is what I said know. For years they will stay there. Now, they are carbon capture technology, sequestration all that these are all the subjects of current investigation okay. So, we meet at 2’o clock tomorrow. We will complete this. We will solve some more problems involving the carbon cycle. And then, we look at carbon in the biosphere, carbon in the ocean and so on, okay.