Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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MEAN EMISSION TEMPERATURE OF EARTH AND THE GREENHOUSE EFFECT PART 3

Good morning class and welcome to our course on climate dynamics, climate variability and climate monitoring. In the previous class, we were discussing the simple greenhouse gas models and the global energy balance of the earth. We showed how the solar energy flux that is coming from the sun is being distributed into parts that are being reflected back into space, parts that are being absorbed by the atmosphere and the ground. We also saw how the atmosphere is radiating heat, thermal radiation which is also called long wave radiation both towards space and towards the surface. While, the surface is radiating, convecting as well as transporting heat to latent heat transfer from the surface to the atmosphere. We looked at the various fluxes associated with each of these energy transport processes that are occurring on a mean average basis over the entire globe and averaged over the entire year.

The one thing that we also spoke about is that there is an unbalanced flux of 0.6 watt per meter square that is the difference between the incoming flux and the outgoing flux and represents the heating caused by the current greenhouse gas emissions by human beings which is leading to the slow heating of the earth's surface. We looked individually at the energy balances at different layers, the energy balance at the top of the atmosphere,

$$\dot{e}_s - \dot{e}_\rho - \dot{e}_o^{Lw} = \dot{e}_{GW}$$

the energy balance at the surface of the earth,

$$\dot{e}_{sl}^{abs} + \dot{e}_{al}^{Lw} - \left(\dot{q}_{la} + \dot{L}_{la} + \dot{e}_{la}^{Lw} + \dot{e}_{lo}^{Lw}\right) = \dot{e}_{GW}$$

and the energy balance for the entire atmosphere as a whole,

$$\dot{e}_{sa}^{abs} + \dot{e}_{la}^{Lw} + \dot{q}_{la} + \dot{L}_{la} - (\dot{e}_{al}^{Lw} + \dot{e}_{ao}^{Lw}) = 0$$

In today's class, we will go beyond these mean energy balances and look at the variations with seasons and with latitude for these various energy terms that are important in these equations.

So, we will see that the energy fluxes vary a lot with the time of the seasons as well as for the latitudes. And this leads to overall climatic variability and eventually the flow of large scale wind and oceanic circulation systems. So, let us look initially on the term ės which is the total solar insulation that is incident on the top of the atmosphere in watt per meter square. We know that the average solar insulation is 340 watt per meter square per unit area of the surface. However, as we have already showed in different ways earlier, there is a considerable variation in the daily average solar insulation with the seasons and with latitude.

Of course, solar insulation changes with the time of day. So, if you see during the noon time when the sun is right near the top of the sky, you will have much higher solar insulation than in the mornings and in the evening when the sun is lower down in the sky and this is something that is true at every location on the earth. But also, as we discussed at high latitudes at any given time the sun is considerably lower in the sky than at low latitudes which causes attenuation effects as well as beam spreading effects which decreases the solar insulation that is actually reaching the surface of the earth. Hence, we see large differences in the incident solar radiation per square meter of Earth's spherical surface on the top of the atmosphere. These values are plotted below.

So, here what you see is at the bottom the latitude values. So, 0 to 90 is 90 degrees north, 0 to minus 90 this is 90 degree south. So, this is north pole and this is south pole. The black line is the annual mean solar insulation in watt per meter square at the top of the atmosphere that a certain location in the latitude is receiving. And you can see that the annual mean solar insulation is nearly 400 watt per meter square at the equator and it kind of decreases to around 180 watt per meter square near the north and the south pole.

And if the mid-latitudes like at 45 degree south or 45 degree north, it is around 300 to 320 watt per meter square. So, this effect is primarily due to the inclination of the sun with respect to the earth surface local normal which leads to the beam spreading effect. Hence, the effective solar insulation per unit meter of the area is much lower at the high latitudes compared to the low latitudes. One other thing is the mean plot is nearly symmetrical with respect to the equator primarily because the effect is due to the symmetrical curvature of the earth away from the equator. But beyond this mean variation you will also see considerable seasonal variation.

For Example, in June 20, which is near the summer solstice period, you will see that you get the largest value of incoming solar insulation is actually occurring in the north pole and the high latitudes, the values are actually quite large. You are getting insulations of the rate of 450 to 500 watt per meter square from the mid latitudes to the north pole and north pole is getting the highest solar insulation of above 520 watt per meter square, 520 to 550 watt per meter square. Why is this the case? Because even though the inclination of the sun is still low compared to at the lower latitudes, you are getting 24 hours of daylight during the summer solstice time above the 66 degree north latitude causing a huge increase in a large amount of solar flux incident in these locations throughout the day. So, this increase in the solar insulation during the summer months is primarily due to this effect that the summer hemisphere is inclining towards the sun. So, the sun is at a much higher angle in the sky and hence has less beam spreading effect and the number of daylight hours is also quite large.

In contrast, the winter hemisphere which is the southern hemisphere in June 20, the solar flux decreases very steeply from 400 watt per meter square at near the equator to nearly around 80 watt per meter square at 45 degree north latitude and it goes to 0 above 66 degree south latitude because that is the period of nearly 24 hours of night. So, this decrease is due to, firstly, the lower angle of inclination, the higher angle of inclination of the sun and secondly, the considerably shorter daytime periods as we go higher up in the latitudes in the winter hemisphere which is the southern hemisphere here. Similarly, during December 21 which is the winter solstice, the entire southern hemisphere receives very high solar insulation between 500 to 550 watt per meter square. The equator is still receiving around 400 watt per meter square of solar flux and the northern hemisphere is getting very little amount of solar incident solar flux. So, we see large variations, whereas in the equinox period in March 21 you see a perfectly parabolic profile of symmetrically around the equator with the maximum value in the equator around 420 or 450 watt per meter square and exactly zero in the North Pole and the South Pole region, where it is exactly in the illuminated age of illumination.

So, it is exactly evening or morning in the North Pole and the South Pole throughout the day. So, these points are noted here. And what we see here is two things, the mean daily average insulation is largest near the equator 400 watt per meter square and falls to 180 watt per meter square near the poles. And in the summer hemisphere usually gets a very large incident solar flux of 500 to 550 watt per meter square between 30 degree north and 90 degree north latitude in the summer or 30 degree south and 90 degree south latitude in the winter that is in the December period and this is actually larger than what the flux is at the equator. This has considerably effects on the climate as you would expect because that would mean that the summer hemisphere would heat up much more and the winter hemisphere will be significantly cooler.

So, you will see a very large temperature gradient during the summer and the winter seasons between the hemispheres. This figure gives you the iso-insolation contours. So, for example, in the June-July period which is the peak summer time in the northern hemisphere, the northern hemisphere gets insolations between 450 and 500 watt per meter square throughout, ok. Whereas, the southern hemisphere the insolation decreases very steeply to less than 150 watt per meter square in 45 degree south and 0 watt per meter square below 66 degree south latitude. Similarly, in the December-January period, the southern hemisphere gets 500 to 450 watt per meter square throughout and a very rapid decrease in insulation as we move higher in the latitude in the northern hemisphere in winter from 400 watt per meter square equator to nearly 150 or 100 watt per meter square at 6 degree north or 45 degree north latitude.

So, this kind of gives us the variation of the incoming solar radiation E dot s at the top of the atmosphere. What else is important if you look at the energy balance at the top of the atmosphere? The E dot rho which is the net sunlight getting reflected from the either the clouds and the atmosphere or from the surface of the earth and this albedo flux also changes with latitude and with season as we will see next. So, planetary albedo and its variation which is E dot rho, okay. The average albedo fraction alpha is 29 percent. So, around 29 percent of the incident solar radiation E dot s is reflected back into space by earth.

However, just like the total solar insulation incoming, the albedo fraction is also changes significantly with latitude and with seasons. So, let us look at the planetary structure of albedo, the albedo value alpha. So, here this is albedo alpha is plotted and you can see it starts from 0 to 0.88. So, there are regions of the world where the albedo is actually 0.

All the radiation is being absorbed and there are regions of the world where albedo fraction reaches around 90 percent. That is 90 percent of the radiation is being reflected back into space. So, let us first look at the mean region and see what are the trends and we see that very low albedo values less than 0.1 exists primarily in the subtropical oceans. So, subtropical Indian Ocean, subtropical Atlantic Ocean, subtropical Pacific Ocean these have very low albedo values of less than 0.1. And the reason that these have extremely low albedo values is because oceans are usually dark so it's dark blue so it does not reflect much light back it absorbs most of the radiation furthermore, in the subtropical region because of the climatic conditions it is usually quite dry. So, there are very little cloud or associated things like fog etcetera over the subtropical oceans between say 10 degrees north to 40 degrees north and 10 degrees south to say 25, 30 degrees south. So in this region you have very deep blue region showing regimes of extremely low albedo. Where do we see regimes of extremely high albedo? The Antarctic continent, the Greenland and the Arctic region. Why? Primarily because of two things.

Firstly, these regions are covered with ice which is a highly reflective and shiny material. Hence, you will have a lot of reflection from the surface of any sunlight that is hitting the surface at this point. As a result, you will have a large albedo of surface reflection from the sun. Furthermore, these regions are typically quite cloudy and you will get extremely cold low elevation clouds, which are usually white in color and hence will reflect sunlight a lot and hence it enhances the albedo effect on these high latitudes. Mid latitudes are also similar.

Significant fraction of the mid latitude winter time is covered in snow. As a result, because snow is highly reflective again, you will get higher reflection or a higher albedo from these regions. Furthermore, the temperate regions are also typically cloud covered with white snow covered cloud formation and this also increases the albedo. The other thing you will see is albedo generally increases with high latitude. This is because the sun comes lower and lower with respect to the ground normal as we go into higher and higher latitudes.

Because the sunlight's angle of incidence with respect to the ground normal is increasing with latitude, the ground is able to reflect more of the sunlight back and absorb less. If you may recall from basic optic courses in your school, normal light is far more easily absorbed than light that is incident at large angle. So, light which has large which is close to the horizontal it has a tendency to get reflected far more in the light that is coming normally to the surface. This effect also causes the gradual increase in albedo from the 30 degree north or 30 degree south latitude up towards the high latitudes. A second point is that albedo values are also typically large in tropical belt in land.

So, the Brazilian Amazon, so this is the tropics, the Brazilian Amazon, the African tropical region, these regions also have large albedo values because this tropical rainforest zone are covered with a lot of cloud and that cloud reflects the sunlight back into space. You will also see a significant variation in the albedo values between the winter season and the summer season. So, in the December, January, February which is winter in the northern hemisphere, you get very high albedo values throughout the northern hemisphere beyond the subtropics. This is because northern hemisphere is covered significantly with snow during the winter time and this snow reflects a lot of the sunlight back into space. The reverse case is true in the June, July, August period where you will see the albedo values are typically larger in the southern hemisphere than in the northern hemisphere.

So, you can see this effect here and this is because of high insulation a lot of the non-permanent snow in the northern hemisphere has melted during the summer giving rise to dark ground which has better absorption as well as because the smaller angle of the sun with respect to the sky means that the fraction of radiation that is being reflected will also decrease. Next we will look at the total outgoing long wave radiation to space. So, this term here the total outgoing long wave radiation that is going into space. Now this outgoing long wave radiation going into space is primarily emitted by the top of the atmosphere ok. In general, regions which have cold clouds and cold atmospheres will emit less outgoing long wave radiation compared to regions which are warm and have hotter clouds because a warmer atmosphere will radiate more long wave radiation than a colder atmosphere.

So, we would expect a priority that regions near the equator will have large values of outgoing normal radiation whereas regions close to the pole will have very small values since, it is complete night for 6 months of the year which makes the region extremely cold also. So, here are the charts for the annual variation of the outgoing thermal radiation into space. The values are given from 110 watt per meter square to 330 watt per meter square. So, a very large variation in the effective outgoing thermal radiation for this case. So, if you look at the places where you are getting large outgoing thermal radiation, so this is the large outgoing.

So, red is large and blue is small, you will once again see that the subtropical oceans between 10 degrees and 30 degrees north and 10 degrees and 30 degrees south have very large values of outgoing thermal radiation. This is because once again these regions do not have a lot of clouds, it is a dry region. Hence, the air above the surface is extremely hot and it emits radiation along with the atmosphere which is also heated up above these regions to space. And because the atmosphere is hot here and the ocean surface is also hot, you will get large values of outgoing thermal radiation in these regions of the world. So, this is true in the subtropical Pacific, subtropical Atlantic.

Regions in Saudi Arabia etcetera are also looking at this in very serious detail. In contrast, the clouds, there are significant amount of clouds in the temperate in the north latitudes and the emission from the top of the clouds is actually much lower than the emissions near the equator primarily because these clouds being formed in a cold climate have much lower temperature. So, cold poles with cold cloud tops have the lowest temperature and hence have the lowest outgoing thermal radiation 100 to 170 watt per meter square. Hot deserts with little cloud cover emit primarily from hot air near the surface and hence have a significantly higher thermal radiation flux. So, if you see the deserts like the ocean have a hot surface and hot air above it.

So, they emit a relatively higher temperature and hence have a higher outgoing thermal flux. So, the subtropical oceans and the subtropical deserts have the largest values of outward outgoing thermal radiation whereas the poles have the lowest values of outward going thermal radiation. We can also see the seasonal impact of this thermal radiation in cases. One other point is the equatorial region on land, Central Africa, Central Latin America and the Indonesian regions are covered with cloud most of the time because these are rain forest areas and these clouds are constantly emitting radiation back to space and because these clouds are colder than the hot surface of the deserts, these have relatively low outgoing thermal radiation. So, the presence of clouds also decreases the outgoing thermal flux over land areas in the tropics over the rainforest compared to the drier subtropics.

Now that we have looked at the three terms, the solar insulation, the outgoing thermal radiation. and the total reflectivity and how these varies with latitude and with the seasons, we can look at the net radiative flux imbalance at the top of the atmosphere. So what we do here is we plot the daily average absorbed solar radiation. So this is the absorbed solar shortwave radiation. Shortwave because the wavelengths are smaller for solar radiation compared to long wave which is the which is that emitted by earth.

So, here we have plotted the absorbed short wave solar radiation from minus 90 to plus 90 latitude and the irradiance is watt per meter square. And you can see that the net absorbed is very high in the subtropical region where it varies between 250 to 320 320 watt per meter square. So, the equatorial in the subtropical regions absorb a lot of the solar shortwave radiation ok, because firstly they have a lot of the radiation that is number one, secondly their alpha the albedo is much smaller compared to near the poles and the temperate regions. Now, the outgoing long wave radiation behaves slightly differently near the equator the outgoing long wave radiation is smaller than the short wave radiation being absorbed by the earth. This means excess heat is being is coming towards the equator in the subtropics which is not being completely dispersed by the outgoing long wave radiation.

And we see when you subtract the advanced absorbed short wave minus outgoing long wave we see the net radiation effect. And we see that the net radiation is positive between minus 30 to plus 30 degree latitude that is in the subtropical regions whereas the net radiation which is the difference between the absorbed short wave and the outgoing long wave is much smaller at the high latitudes and goes towards minus 100 watt per meter square near the south pole. Similarly, in the north pole also we see a monotonously decreased to negative below above 30 degree north and goes to over minus 120 watt per meter square of deficiency at in the north pole. Here the picture of the annual and the seasonal contours of the net imbalance values are given. So, you can see as we note that in the tropical region and the subtropical region there is a net positive value of effective accumulation of energy flux in watt per meter square.

This is true particularly in the equatorial regions, equatorial seas and the subtropical seas and the land surfaces. However, this is not true in the desert regions where the values are 0 or slightly negative because even though the solar insulation is large, the outgoing long wave radiation is even larger in many cases because of the clear skies and the emission from the hot atmosphere and the land. So, the non-desert areas act as a source of excess energy on earth because it is absorbing a lot more radiation than it is emitting. It is exactly different at the as we move to higher latitudes, there we see that we have a negative flux balance that is outgoing exceeds the incoming radiation and the incoming radiation falls off quickly primarily because of the increasing angle of inclination when you are averaging over the entire year. If you see the effect on December, January, February which is the winter month, there you can see that the entire winter hemisphere which is northern hemisphere has negative flux.

They have negative flux because while thermal radiation is efficient at removing flux from the atmosphere and the surface. The incoming solar insulation is extremely small in the winter months whereas albedo is quite high. So, the heat lost to space cannot be compensated by the sun but has to be transported from elsewhere and it is usually transported from the summer hemisphere. In the summer hemisphere due to very high insulations you will get mostly red regions where you will get more amount of solar energy than you can dissipate into space. This is why the entire summer hemisphere is red and you can get large scale winds from the summer hemisphere to the winter hemisphere trying to ameliorate this difference in temperature.

Again the same thing but reverse in June, July, August. So I will stop here. I will conclude this section and we will move on to the next in the next class. Thank you for listening and see you in the next class.