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

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NET RADIATIVE FLUX IMBALANCE ANNUAL AVERAGED AND SEASONAL

Good morning class and welcome to our continuing discussions on climate dynamics, climate variability and climate monitoring. In the previous, class we were discussing the variations in the different energy flux rates at the top of the atmosphere. Which while we discussed the mean values also vary in terms of the latitude and the seasons. What we saw in the previous case are the variations in the albedo, the incoming solar insulation and the outgoing thermal radiation. First, when we looked at the solar insulation at the top of the atmosphere and how it changes with seasons and with latitudes, what we saw was a flux like this. This is the flux of the incoming solar energy at the top of the atmosphere per unit area of the earth's surface.

And we saw that while the annual mean was symmetrically situated about the equator with the equator getting the maximum annually averaged solar insulation flux of 400 watt per meter square and the poles receiving the lowest values at around 180 watt per meter square. However, especially at the high latitudes there is significant seasonal variations where in the summer hemisphere the high latitudes get more than 500 watt per meter square of solar insulation. Whereas, the winter hemisphere can get less than 50 to 0 watt per meter square of solar insulation at those same latitudes. This creates a large variation of in the incoming energy flux between the seasons so that high latitudes have very sharp seasonal variations from winter to summer.

These solar insulation values were also plotted in a contour map where we could see that during the summer months the northern hemisphere gets very high insulation and very low insulation in the winter months whereas the situation is reversed for the southern hemisphere. We also saw that contour maps of the planetary albedo values both the annual means and the seasonal means. We saw that in annual average the albedo which is the amount the percentage of reflected insulation that is escaping the atmosphere is extremely low in the subtropical oceans because the oceans are a dark surface and the subtropical oceans are mostly cloud free. Whereas, the albedo values are extremely high in the high latitudes due to the presence of clouds. Where, the cloud tops reflect a lot of the solar radiation as well as due to the presence of ice in the north and the south poles since ice is a highly reflective surface.

This situation is accentuated especially in the winter hemisphere because winter months are typically cloudy, foggy and the ground is covered with snow all of which reflect sunlight extensively and increase the albedo to close to 0.7 or 0.8. So that during the winter months not only is the winter hemisphere getting low amounts of solar insulation. It is also reflecting most of it back to space creating extremely cold conditions.

Next we look at the outgoing thermal or long wave radiation to space and how it varies with respect to seasons and with latitude. Remember the outgoing thermal radiation is the thermal radiation that is being emitted back to space primarily by the atmosphere but also a small fraction by the ground. So, the magnitude of this thermal radiation depends strongly on the temperature at which the atmosphere is emitting this radiation. So, regions where the thermal radiation is being emitted by hot atmosphere closer to the ground, you are getting much larger outgoing thermal radiation. Whereas in regions where the emission is happening at much higher altitudes due to the presence of clouds and where the atmosphere is naturally colder, you will get much lower thermal radiation outflow.

This fact can be seen in the annual and the seasonal maps as well. So, in the annual map we see that the outgoing thermal radiation is especially high in the subtropical regions and especially over the deserts which are primarily cloud free and hence the emission is happening at much lower altitudes where the atmosphere is significantly hotter. Whereas in the high latitudes the outgoing thermal radiation is lower because the atmosphere is typically much colder and because the emission is happening over the altitude of the clouds making the altitude also much higher. Hence, in the high latitudes emission is happening from much colder regions of the atmosphere causing much lower outgoing thermal radiation. We also see that the tropical region over the land especially in the rainforest regions like in Brazil, Central Africa and Indonesian peninsula, you are having lower outgoing thermal radiation again due to the presence of high altitude clouds.

Hence, atmosphere radiates heat over these high altitude cloud tops where it's much colder naturally and hence the outgoing thermal radiation values are lower. These three fluxes together determine the net radiative flux imbalance at the top of the atmosphere. Let us understand this idea.

$$\Delta\dot{e} = \dot{e}_s(1-\alpha) - \dot{e}_o^{Lw}$$

At any given area the net radiative flux imbalance delta E dot is effective solar insulation per unit area of the earth surface at the top of the atmosphere minus the fraction that is being reflected back to space through albedo effects minus the outgoing thermal or long wave radiation. When you take the global mean of this value then this delta E is nothing but the unbalanced global warming flux which is causing the overall heating of the earth.

However, at specific locations this delta E value can be much larger because in many regions the incoming insulation can exceed the outgoing thermal radiation and albedo values, whereas it may be the reverse in other regions. So, when you do a geographic analysis, then this unbalanced radiative flux can have large positive and large negative values depending on the seasons and on the location. Whereas, the averaged value is a small amount of around 0.6 watt per meter square which is the average flux imbalance caused due to anthropogenic global warming. So, if we look at the net radiative flux imbalance at the top of the atmosphere and we first look at the plot.

Where the mean values of this delta E dot over a over an entire latitude circle is taken. So, what we do is at a given latitude say 30 degrees north and 30 degrees south, we take the mean value of the incoming insulation, the mean value of the outgoing albedo and the mean value of the outgoing thermal radiation and that difference gives the mean or latitude mean, it is also called the zonal mean. So, if you integrate over the entire latitude circle, it is called the zonal mean. So, it is the zonal mean radiative flux imbalance at a given latitude value. This zonal mean of flux imbalance is given by this black line.

Whereas, the outgoing long wave is given by the red line and the absorbed short wave that is the incoming solar radiation minus the albedo effect that is the absorbed solar radiation is given by the blue line. Then we see that between 30 degrees south and 30 degrees north latitude the radiative flux imbalance is positive that is in these latitudes you are getting more incoming flux than outgoing flux causing an effective heating of the earth's surface in these regions. Whereas between 30 degrees and 90 degree latitude both in the northern and the southern hemisphere the radiative flux imbalance becomes negative over time. So, the zero value is around 30 to 33 degrees north and south latitudes, whereas, the maximum negative values are coming near the poles between 80 degrees to 90 degrees north and south latitudes. And the maximum positive value occurs at the equator of around 50 watt per meter square.

Whereas, the maximum negative value occurs around the north and the south poles of around minus 100 watt per meter square. It is important to note, that while the balance looks somewhat skewed towards the negative side, this is not really true. If you think of the spherical surface and you look at the total area covered by the lower latitudes versus covered by the higher latitudes, you will see that the lower latitudes have a much larger zonal mean area because the radial distance is much larger. So, the 2 pi r value the circumference is much larger at the lower latitudes compared to the higher latitudes where the latitudinal circumference is much smaller. Hence, even though the latitude mean values look smaller on the positive side than on the negative side because the radius is decreasing as the latitude is increasing.

If you take the area based average, these two will more or less cancel out and you will get the unbalanced global warming flux only. So, the net imbalance is positive between 40 degrees south and 40 degrees north. So, it is around 30 to 40 degrees and the maximum positive imbalance is around 75 watt per meter square near the equator. In contrast, the balance becomes negative between 40 degrees and 90 degrees north and south and become as low as minus 120 watt per meter square near the southern pole. Now what is the reason that you have a positive imbalance? That is you have a net incoming flux at the lower latitudes and net outgoing flux at the higher latitudes.

This is because the absorbed shortwave radiation is much higher at the lower latitudes going up to 325 watt per meter square near the equator compared to the absorbed shortwave radiation near the poles which can go as low as 100 to 50 watt per meter square between the 80 degrees and 90 degrees north and south latitudes. So, there is more than 6 times decrease in the absorbed shortwave radiation between the equatorial regions and the polar regions. In contrast, the outgoing longwave radiation which is higher especially in the subtropical regions up to around 250 to 270 watt per meter square. However, the falloff of the outgoing longwave radiation is not as much and it just falls to around 150 watt per meter square near the north and the south poles. Hence, you are getting a negative imbalance starting from around 40 degrees north and south latitudes, whereas we have a positive imbalance in the low latitudes.

So, what are the main points here? The net imbalance is extremely negative at the poles, particularly in winter when there is little or no incoming solar insulation. The winter hemisphere has another important aspect and there we will look at the seasonal aspects. So, this is the annual value. So, positive values at the low latitudes, negative value at the high latitudes. But we can also see large seasonal variations.

So, in the winter of the northern hemisphere the negative imbalance near the poles can be as high as minus 180 watt per meter square because the high latitudes above 66 degrees north is not receiving any sunlight and no insulation at all but it is steadily losing thermal radiation to the outer space. So, the negative imbalance becomes extremely large and is generally large over the entire winter hemisphere, both in the northern hemisphere and in the southern hemisphere. Whereas the summer hemisphere, the imbalance has significant positive values of over 120 watt per meter square in certain regions, especially in the subtropical ocean regions where you are getting a reasonably long daylight hours and extremely low albedo values. So, you have in general in the summer hemisphere large positive imbalances exist in the subtropical oceanic regions whereas in the winter hemisphere large negative imbalances exist in the polar regions. So, the winter hemisphere is negative balance in general due to shorter daylight hours and larger solar angles.

So, the larger solar angles here also increases the albedo amount because of the beam spreading effect and high albedo effect. While the summer hemisphere has positive balance in general for the opposite reason except over land at the poles, Antarctica and Greenland which because of the high ice cover still has negative imbalances. So, despite 24-hour daylight in the summer, the poles continue to have negative radiation balance due to high albedos over snow and due to low solar angles. So, high albedo is partially because of the reflectivity of the source of snow as well as the low solar angles. So, the sun is lower on the horizon in the poles even during the summer causing large reflectivity, large attenuation effects, and larger beam spreading effects, all three aspects come into the picture here.

Net imbalance is strongly positive 120 to 150 watt per meter square over tropical and subtropical oceans due to high insulation and low albedo values. Desert regions also have net negative energy flux balance. So, this is also an important aspect when you look at the mean cases, the desert regions paradoxically have negative flux balances, zero to negative flux balances. The Saharan desert, the Arabian peninsular regions, the Rajasthan regions here, the deserts in the southern Africa and the reason here is despite the high insulation, desert surfaces have high albedo because it's mostly covered with extremely shiny sand and have high outgoing thermal radiation due to low cloud cover and high emission temperature of hot near surface air. So, it has reasonably high albedos and very high outgoing thermal radiation because of the hot surface air and the cloudless nature of the deserts.

So, these two together increase the outgoing radiation and the albedo effects become higher than the incoming insulation making the net flux actually negative in the deserts. It is also why desert regions even though become they become very hot during the daytime become extremely cold at night because of the extremely efficient loss of energy through thermal radiation at night. So, what is the impact of this latitudinal variations as well as the seasonal variations of net energy flux imbalance. What this means is on the annual scale, subtropical regions get more heat than it can lose and its air and its oceans get heated up progressively over time whereas the high latitude regions lose heat more than they gain it and so the ocean currents and the air become progressively colder there over time. Therefore, what happens is longitudinal or meridional transport of heat begins to happen from the lower latitudes to the higher latitudes through winds and the ocean currents.

So, the primary convection cells and the ocean currents and the wind circulation patterns are governed by this transport of heat from the low latitudes to the high latitudes. And this transport of heat is what makes it possible for a specific region to have a stable temperature over time. If heat was not getting transported from the low latitudes to the high latitudes, then the imbalances will continue to exist and the equator will continue to become hotter and hotter and the poles will continue to become colder and colder which is an unsustainable situation. So, the entire wind and the ocean current patterns help to transport heat and distribute heat throughout the world. So, what we see is that the main climatic cell and the wind circulation patterns and the climatic structures are governed by this energy imbalance between the low and the high latitudes and we will see in later classes how the wind circulation patterns effectively transport this heat from the equator and the subtropics to the temperate and the polar regions.

This net flux of heat from the low latitudes to the high latitudes can also be plotted. So, there is a poleward flux of energy through oceanic and the wind currents. Large-scale wind and ocean circulation patterns in the world is the direct outcome of the poleward transport of energy from the tropical and the subtropical latitudes. The extent of the poleward energy can be evaluated for each latitude circle. So, again we take a zonal mean and see how much energy flux is crossing that specific latitude in the meridional that is in the north-south direction.

This we can plot here and this has been plotted and we can see, firstly, it is symmetric around the equator ok. So, the effective transport at the equator is 0, it is symmetric around the equator and it increases strongly. So, these are values in petawatts. It is a very high, large unit in terms of watts. You can see the values of petawatt, what a petawatt is in the internet.

So, these are extremely large energy flux values and they kind of increase rapidly from 0 degrees latitude equator to around 30 degrees in the poles. So, the mean energy flux from low latitudes to high latitudes kind of maximizes between say 30 to 50 degrees. So, this is 50 degrees. So, the maximum northward flux is happening at the subtropical and temperate transition zone, 30 to 50 degrees north and south latitudes. You can see here and here, and then it begins to fall off, and at the poles, it again goes to 0.

Remember, the southern hemisphere, it is negative because we have taken the south to north transport of heat as the positive direction. Hence, the north to south transport of heat in the southern hemisphere, because southern hemisphere, the heat transport is on this side, northern hemisphere, heat transport is on this side. So, this side is taken as negative and this side is taken as positive. Otherwise, it is basically symmetrical about the equator. The relative contribution of heat transport by the atmospheric wind currents and the oceanic water currents are also shown here and we see that in for most cases the atmospheric wind currents transport the largest amount of heat, especially in the temperate and the high latitudes.

But near the subtropics oceanic currents also transport a significant amount of the heat before the wind transport really picks up at around 50 degrees north and 50 degrees south latitudes. So, oceanic wind currents, oceanic water currents also transport significant amount of heat especially in the subtropical and equatorial regions whereas in the temperate regions it is primarily dominated by wind transport. So, we will discuss this oceanic fluxes and wind fluxes later in our course. But what we see here is that if the fluid envelope of the earth did not transport this heat polewards, the tropics would be much warmer and the poles would be much colder. So, the air and the ocean of earth play a very important role in keeping the climate of the earth much more equitable than what would have been the case if they were absent.

Specially, if you again compare it with moon which does not have any air or water, you will see large gradients of temperature between the low latitudes and the polar regions. And this is because they do not have that fluid transport effect that is regularly transporting heat from the equator towards the poles in earth.

So, we will stop here today. In the next class, we will do a few examples with this, with the kind of things that we learned this week. Thank you for listening and see you in the next class.