Climate Change Science
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Lecture – 5
Planetary Albedo

In the last lecture, we spent quite some time distinguishing between how the atmosphere absorbs solar radiation and how it absorbs the radiation emitted by the Earth, as well as how it emits radiation. To clarify again, below, we have an expression for the absorptivity of the atmosphere to **solar radiation**. You can take spectral emissivity, but you have to weight it against the intensity of radiation coming from the Sun, i.e., the emissive power of the black body at the Sun's temperature, assuming that the Sun is a black body, which is not a bad approximation. The very first expression is integrated between 0.4 and 4 microns because that is the region where the Sun emits radiation.

Atmospheric Absorption of solar radiation

$$\alpha_a = \frac{\int \varepsilon_\lambda(atm) e_{\lambda b}(T_{sun})\, \mathrm{d}\lambda}{\sigma T_{sun}^4}$$

The above integration is done from 0.4 to 4 microns

Atmospheric emission

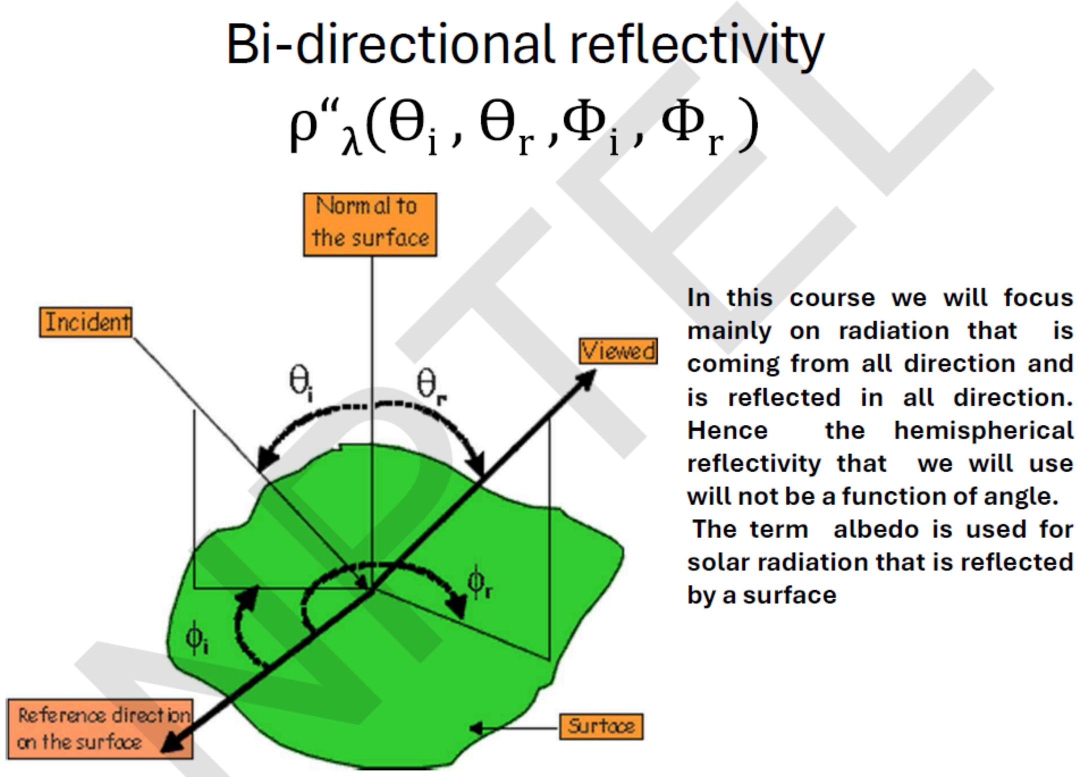
$$\varepsilon_a = \frac{\int \varepsilon_\lambda(atm) e_{\lambda b}(T_a)\, \mathrm{d}\lambda}{\sigma T_a^4}$$

The above integration is done from 4 to 100 microns

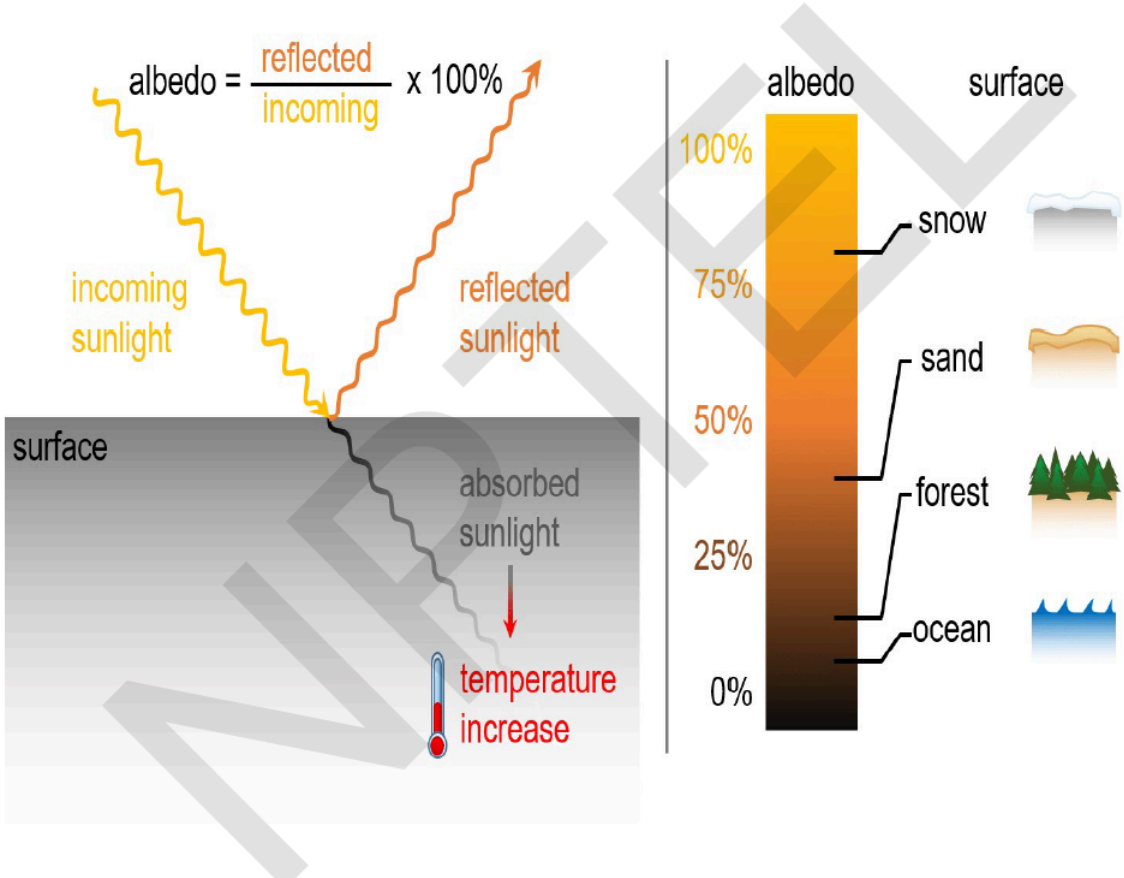
T_{sun} is Sun's blackbody temperature
T_a is the mean atmospheric temperature

When you want to calculate the total emissivity of the **atmosphere,** you take the same spectral emissivity, but you weight it with the blackbody emissive power at the temperature of the atmosphere. Since the atmospheric temperature is very different from that of the Sun, the wavelength range it will cover is 4 microns to 100 microns. So, although ε_λ is the same in both the above equations, the absorptivity and the emissivity calculated in the two equations will be very different. Typically, α_a will be around 0.2 or 20 percent; ε_a will be around 0.95 or 95 percent. This is what makes the Earth's atmosphere unique, because it is pretty transparent to the Sun's radiation, but pretty opaque to the Earth's radiation. This also makes Earth much warmer than it would have been otherwise.

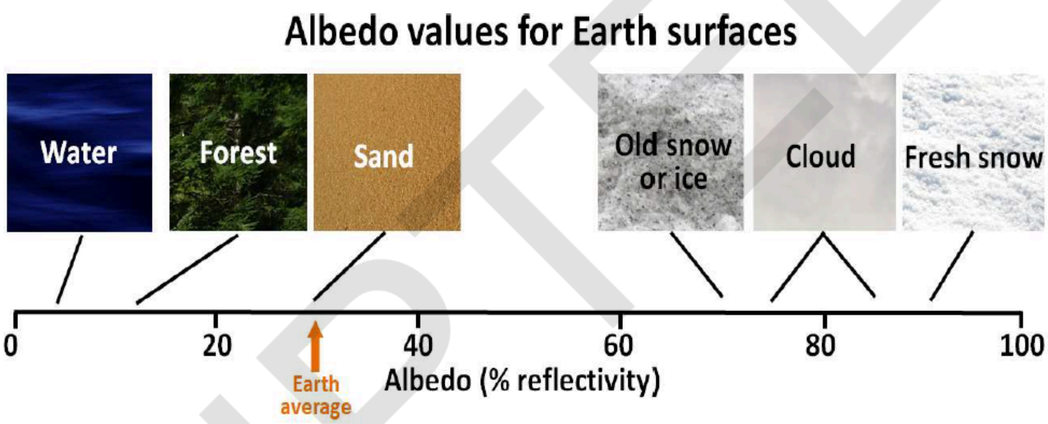
Let us continue further with a simple model. First let us talk about 'reflectivity'. So, every surface has emissivity and absorptivity at the spectral level, and we are going to assume them to be the same at the spectral level. It also has reflectivity because any surface can either absorb radiation, emit radiation, or reflect radiation. Reflectivity is much more complex than absorptivity or emissivity because it depends both on the direction of the incoming radiation and the direction of the reflected radiation.



There are two angles here: θ_i and φ_i, showing the incoming radiation angle, and θ_r and φ_r, showing where the radiation is reflected. Now, as far as we are concerned, we are only interested in how much radiation is reflected in all directions. So, we are going to integrate over all angles θ_r and φ_r, and we are going to neglect the dependence on the reflectivity of incoming radiation, which is there, but is not that important. Here we get a quantity that is called hemispherical reflectivity, which is considered independent of angle. So, that makes life easier; otherwise, this subject gets very complicated. Because we are concerned only about energy balance at the surface, we do not care where the energy is reflected; as long as it is reflected. So, keep this in mind, this is a complex quantity that has to be measured in the laboratory or by satellites, and then you integrate to take care of all the directions in which the radiation is reflected. So, the term albedo in this course will be used to refer to solar radiation that is reflected by a surface in all directions. We will integrate over all θ_r and φ_r and get a total number that shows how much energy is lost by reflection.

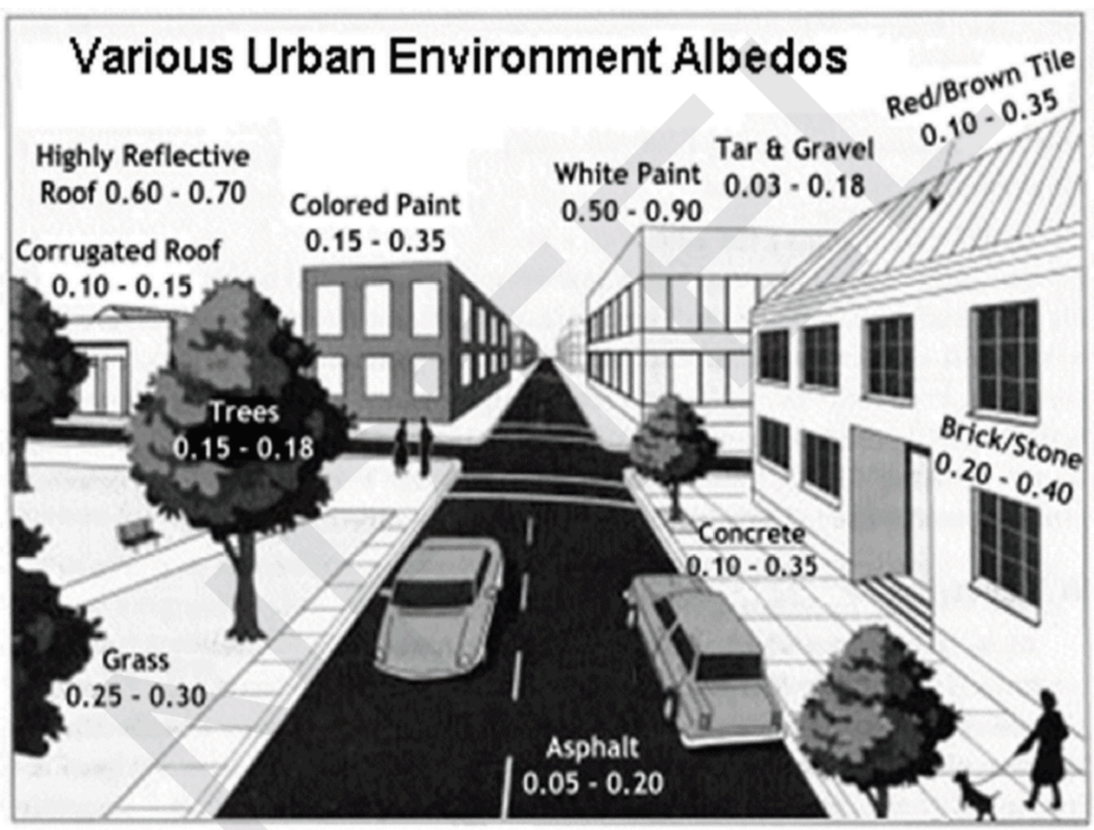


Now, just to give you an idea, radiation coming in from the Sun can either be absorbed by an opaque surface or get reflected back. The typical value of albedo is the total radiation reflected by a surface at all angles, and in this case, in the solar region. For snow, the reflectivity is 75, 80, or 90 percent, depending on whether it is fresh snow or old snow. When you look at sand, it is more like 30%. If you look at a forest that is dark, it is more like 15 percent. The ocean, which is much darker than the forest, is more like 10 percent. So, you can see that the albedo of various surfaces that we encounter in climate science is very different. But when we look at the overall energy budget of the entire Earth, of course, we have to take care of all the surfaces: snow-covered, ice-covered, vegetation, bare land, agricultural land, and ocean; all of them we have to take care of and give a total value.



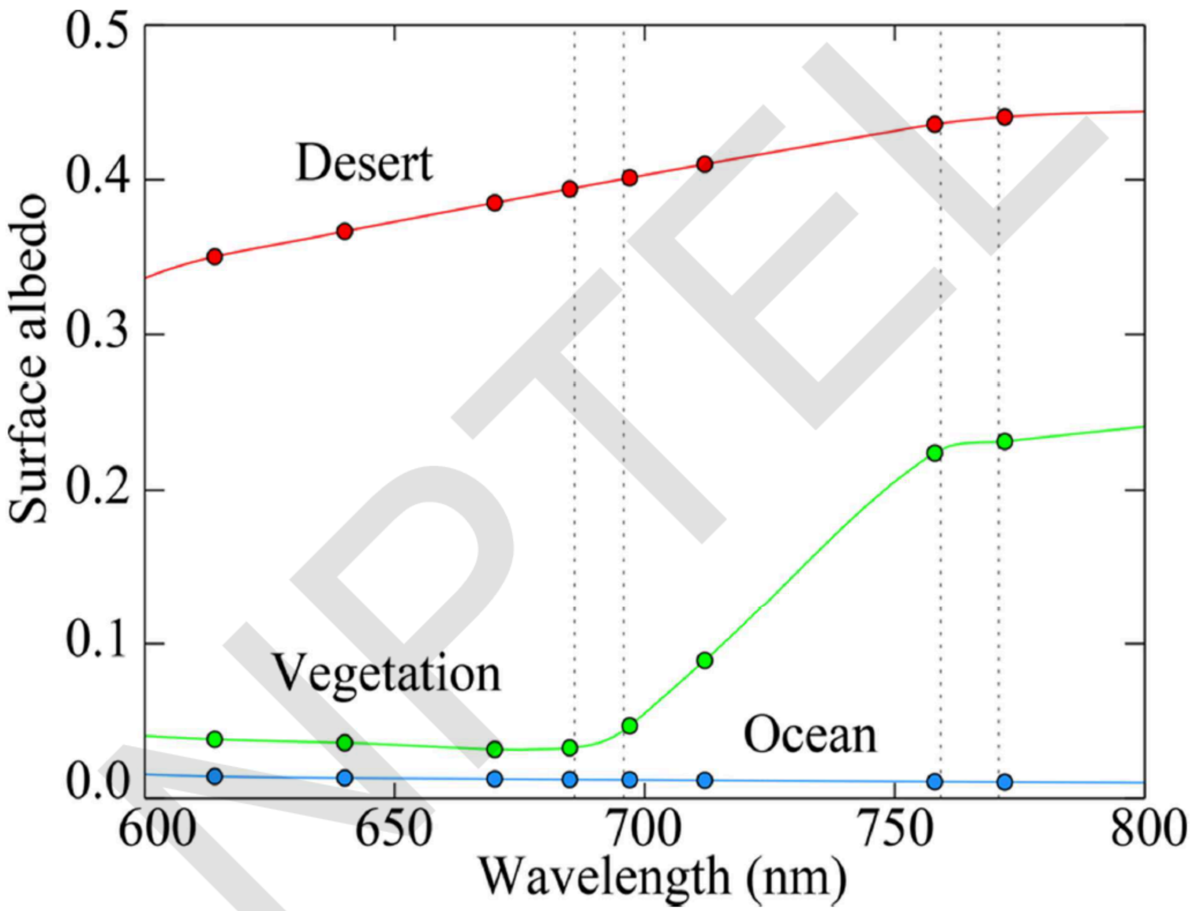
Now, here is another way to look at the same value. See how the albedo varies from that of water, which is very low at 10 percent, then forest, sand, then old snow or ice, then cloud, which is very important for Earth's mean temperature, and fresh snow, which has very high reflectivity. All of this is in the solar radiation region.

Now, let us look at albedo values for various urban surfaces so that you get an idea.

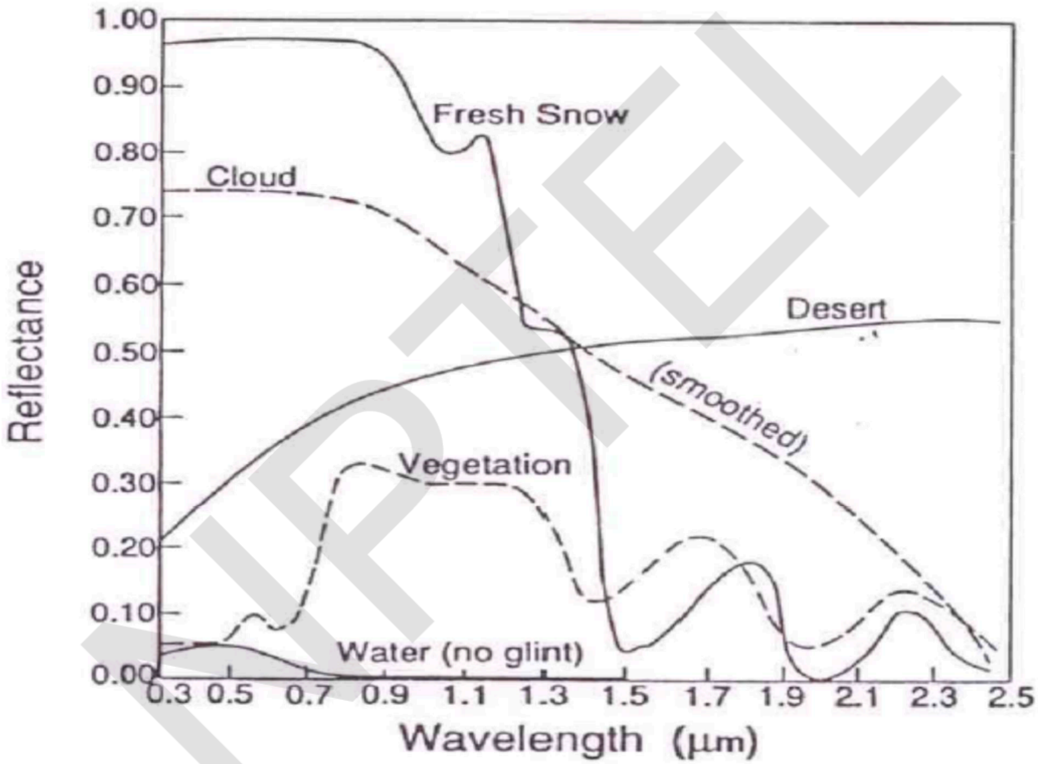


Trees have an albedo of around 0.15-0.18. In urban areas, a lot of roads are tarred, that is, they contain asphalt, and thus have a very low reflectivity. That is why they absorb a lot of solar radiation, making urban areas very hot. Now, the roof of a building has a low albedo, if it is made of red or brown tiles, or if it is covered with tar or gravel. But if we use white paint, it (albedo) will go up. So, today when people are concerned with the urban heat island effect, they recommend that all roofs be painted white to reduce the absorption of solar radiation. This is now a movement that is receiving a lot of coverage.

Next, let us look at how these albedos vary with wavelength. We have to worry about that.

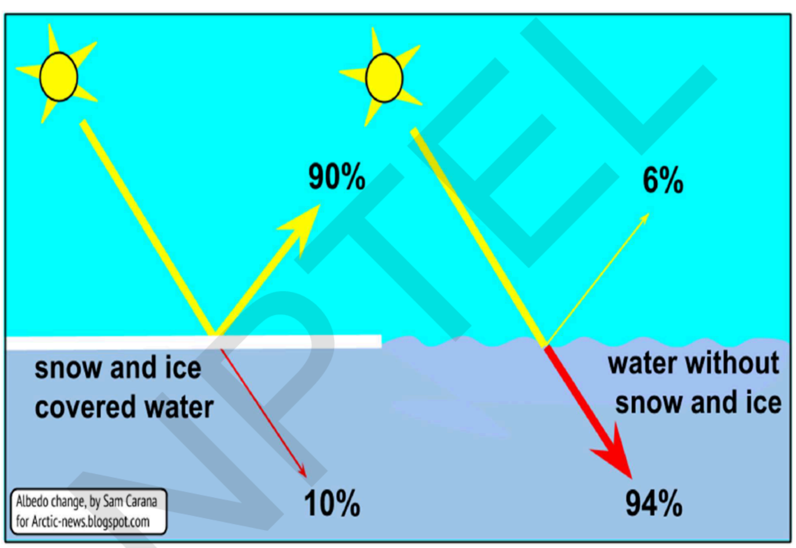


Desert albedos are quite high in the visible range, and as we move to near infrared, they start increasing. Vegetation, on the other hand, is very complex. Vegetation has a fairly low reflectivity or albedo in the region below 0.7 microns, slightly increases in the visible, and is quite high in the region beyond 0.7 microns. Ocean, on the other hand, has very low reflectivity.

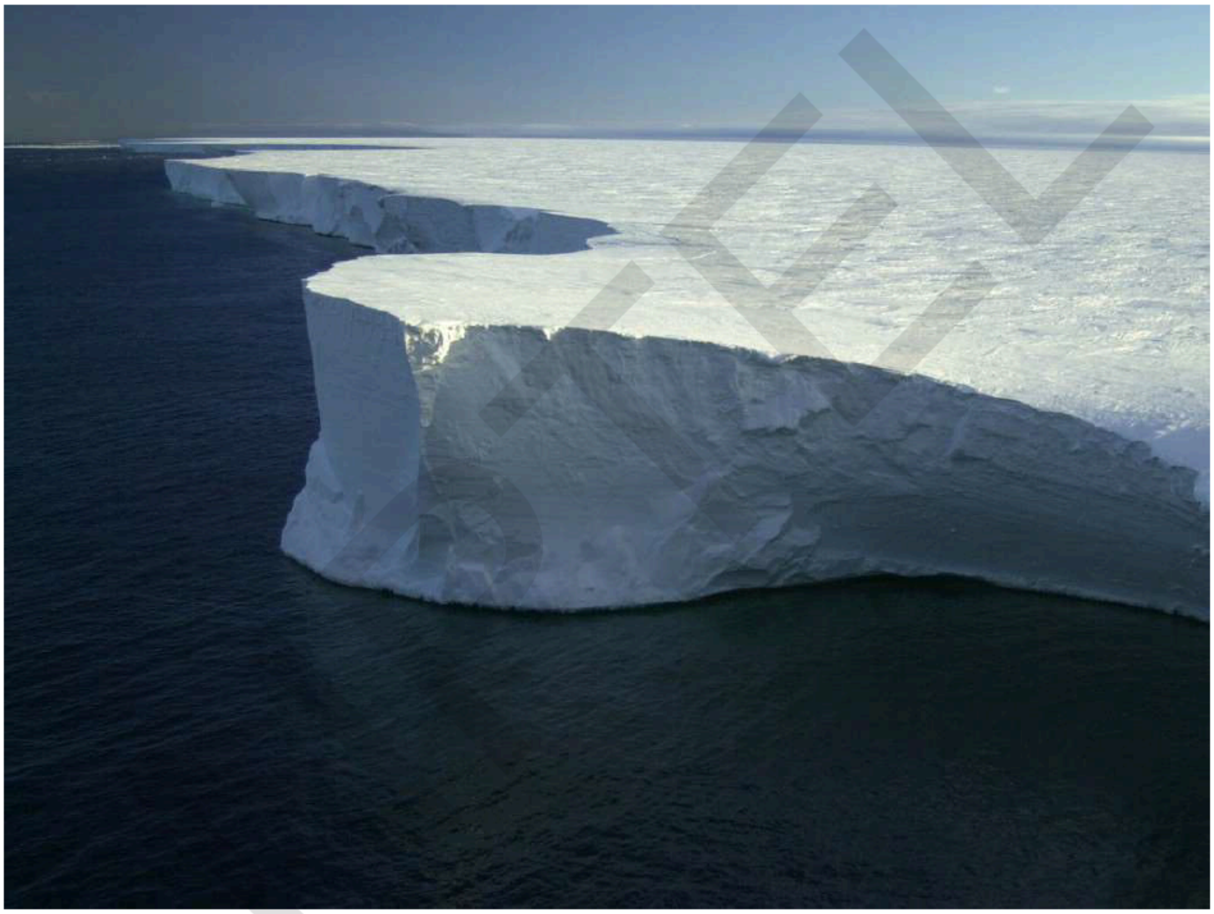


Here is another source showing how fresh snow, which has a high albedo in the region below 1.5 microns, has an extremely low albedo beyond 1.5 in the near infrared, which is opposite to the desert; desert albedo increases with wavelength. Vegetation has a complex variation depending on the type of leaves and the type of vegetation. Clouds come in a variety of forms. We will discuss that later in the course, but typically, they have a high reflectivity in the visible and low reflectivity in the infrared.

It is important to highlight the difference between ice and snow, which have a huge impact on Earth's climate.



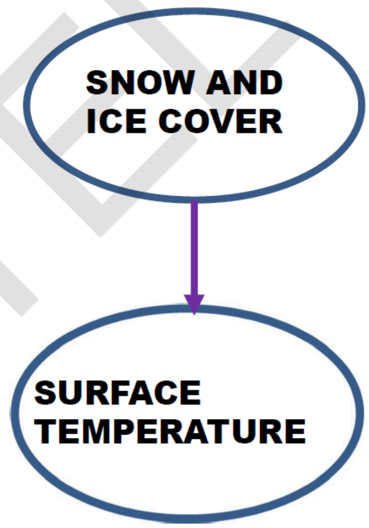
Snow and ice on water—that is, sea ice—reflect 90 percent of the incoming radiation, while water without snow and ice covers only 6 percent. So, when you convert an area with snow and ice to open ocean, you are changing the reflectivity by 84 percent. You must remember that as sea ice melts—and it is melting rapidly, as you saw in the first lecture—that area starts absorbing about 10 times more solar radiation. This has a huge impact on Earth's climate, which we will discuss further in this course. Now, for you to remember this well, I have a very nice picture of a major ice sheet and open ocean.



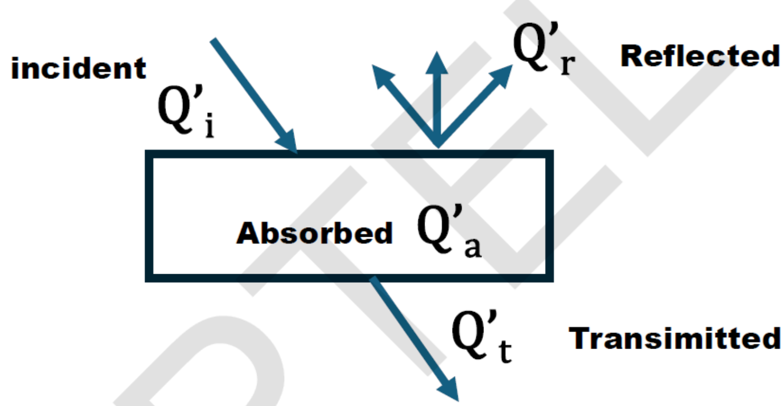
See the difference in reflectivity between an iceberg and the ocean. An iceberg reflects most of the radiation, while the ocean hardly reflects any. So, when ice is melting in the northern and southern polar regions, large areas of the Earth that were reflecting a lot of radiation are now absorbing much more radiation. This has a huge impact: as more and more ice melts in the polar regions, more radiation is absorbed, and Earth's warming is accelerated. This is a great cause for concern regarding the impact of climate change.

Now, just to remind you: snow on ice cover, by altering Earth's albedo, has an impact on surface temperature. When snow on ice melts, albedo decreases dramatically, and the amount of solar radiation absorbed increases dramatically. Thus, it has a huge impact on Earth's temperature.

Snow and ice covered area control the earth’s surface temperature by altering the amount of solar radiation reflected to space



Now, we will come to one more aspect that we have to study before we start doing the Earth’s energy budget, namely that we have so far considered an opaque surface—a surface which either reflects or absorbs radiation. In contrast, Earth's atmosphere is not an opaque surface. Earth's atmosphere is a transparent medium, like glass. The Sun's incoming radiation is either absorbed, transmitted, or reflected. Thus, we have to know the relation between reflected, transmitted, and absorbed radiation. Note that when we say “reflected” in this course, we mean all rays reflected back in any direction. We will examine the incoming radiation, how much is reflected in all directions, how much is transmitted, and how much is absorbed.



Relation between reflected , transmitted and absorbed radiation

Note that the reflected radiation includes all rays reflected back in any direction

From energy balance, we know that the incoming radiation must be either reflected, absorbed, or transmitted; the sum of these three must equal the incoming radiation. That equation is written here. At a given angle, the incoming radiation equals the radiation absorbed plus the radiation reflected plus the radiation transmitted. This is true at any wavelength. Dividing by the incoming radiation, we obtain three quantities: the directional spectral absorptivity, the directional spectral reflectivity, and the directional spectral transmittivity. They are defined by these ratios, and their sum is equal to 1 by energy balance.

Earth's atmosphere can reflect , absorb or transmit the incident solar or thermal radiation. The total incoming radiation at a given angle and wavelength is either absorbed, transmitted or reflected. Therefore

$$Q_i' = Q_a' + Q_r' + Q_t'$$

dividing by Q'_i , we get

$$1 = \alpha_\lambda' + \rho_\lambda' + \tau_\lambda'$$

where

$$\alpha_\lambda' = \frac{Q_a'}{Q_i'}, \rho_\lambda' = \frac{Q_r'}{Q_i'}, \tau_\lambda' = \frac{Q_t'}{Q_i'}$$

The above equations define the directional spectral absorptivity, reflectivity and transmissivity respectively. Note that if the atmosphere is opaque, then transmissivity is zero and hence

$$\alpha_\lambda' + \rho_\lambda' = 1$$

If we use Kirchoff's law,

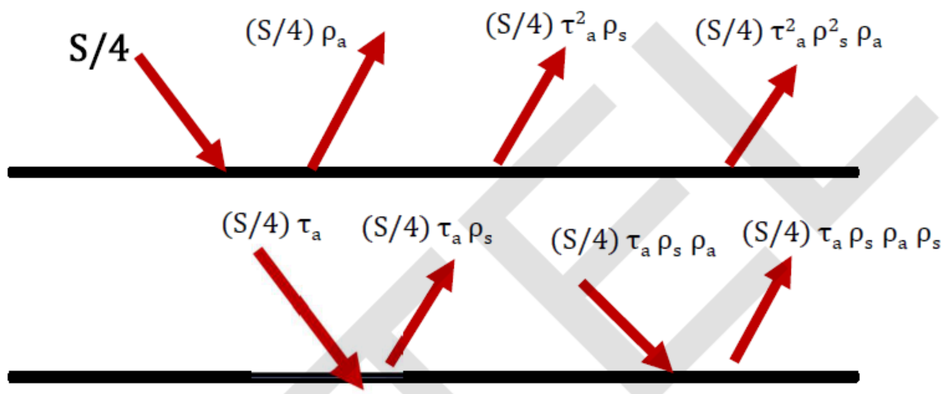
$$\alpha_\lambda' = \varepsilon_\lambda'$$

$$\varepsilon_\lambda' + \rho_\lambda' = 1$$

Note that we can estimate emissivity from the measurement of reflectivity

So, note that if the atmosphere is opaque then the transmission term goes to 0, and you have a simple equation relating absorptivity and reflectivity. If you use Kirchhoff's law—which states that the directional spectral absorptivity is equal to the directional spectral emissivity—then you have a simple relation between emissivity and reflectivity. This is very important because, in the laboratory, we typically obtain emissivity from reflectivity, as it is easier to measure. In the lab, you can subject any surface to incoming radiation, measure the reflected radiation, and, based on that, calculate emissivity and absorptivity. This is standard practice.

Thus, this equation is very important. When dealing with the reflectivity of the Earth–atmosphere system, we must take into account reflection by the surface, reflection by atmospheric molecules, reflection by particles in the atmosphere (called aerosols), and reflection by clouds. All of these are combined, and this is measured by satellites. When a satellite is hovering over the Earth, it measures the reflectivity from all surfaces: clouds, the atmosphere, aerosols, and the surface. This quantity is called the planetary albedo—the albedo of the entire planet, composed of many surfaces, clouds, and the atmosphere. That is a complicated function of all these individual components.



Reflected solar radiation (after multiple reflections)

$$= (S/4)\,\rho_a + (S/4)\,\tau^2_a\,\rho_s + (S/4)\,\tau^2_a\,\rho^2_s\,\rho_a + \ldots\ldots\ldots\text{infinite series}$$

$$= (S/4)[\,\rho_a + \{\rho_s\tau_a^2\}/\{1-\rho_s\ \rho_a\}\,]$$

After dividing by incoming radiation we get the planetary albedo as

$$\rho = \rho_a + \{\rho_s\tau_a^2\}/\{1-\rho_s\ \rho_a\}$$

Where ρ_a is atmospheric reflectivity

ρ_s is the reflectivity of the earth's surface

τ_a is atmospheric transmissivity

I have shown a diagram above illustrating how the incoming radiation (S/4, as we know) is partly transmitted to the surface. If it is not transmitted, it is reflected on the first pass. Once it reaches the Earth's surface, it is reflected by the surface. This reflected radiation is transmitted through the atmosphere and can go to space. If it is not transmitted, it can be reflected again by the atmosphere; this reflected radiation can again be transmitted and then exit the atmosphere.

Again, to repeat, it is very complicated: the incoming radiation may be transmitted, reflected and then transmitted again through the atmosphere, or reflected by both the atmosphere and the surface and then transmitted once more. Now, this is not just the first reflection; the process continues many times and goes on as an infinite series. There is a first reflection, a second reflection, a third reflection, and so on. You can represent this process as an infinite series. After the first reflection, when it is reflected and transferred to space, there is a second reflection; then a third, fourth, fifth, and so on. You can sum this infinite series; if you recall your high school math, this series sums to

$1/(1 - \rho_s \quad \rho_a)$, which represents the contribution from both the surface and atmospheric reflections. If these two are 0, then this term drops out, and you have only the first two terms. Thus, this represents the contribution of multiple reflections. Please go through this carefully and understand this method of adding contributions from multiple reflections, which we must do because there are many surfaces and a photon coming in can be reflected in the first, second, or third pass due to interactions with the Earth's surface, clouds, and the atmosphere.

Planetary albedo at the top of the atmosphere (measured by satellites)

$$\rho = \rho_a + \{\rho_s \tau_a^2\}/\{1-\rho_s \quad \rho_a\}$$

Where

ρ is the planetary albedo

ρ_a is reflection by clouds and atmosphere

ρ_s is the reflection from the earth surface

τ_a is the transmission through the atmosphere

A_a is the absorption of solar radiation by the atmosphere

Solar absorptivity

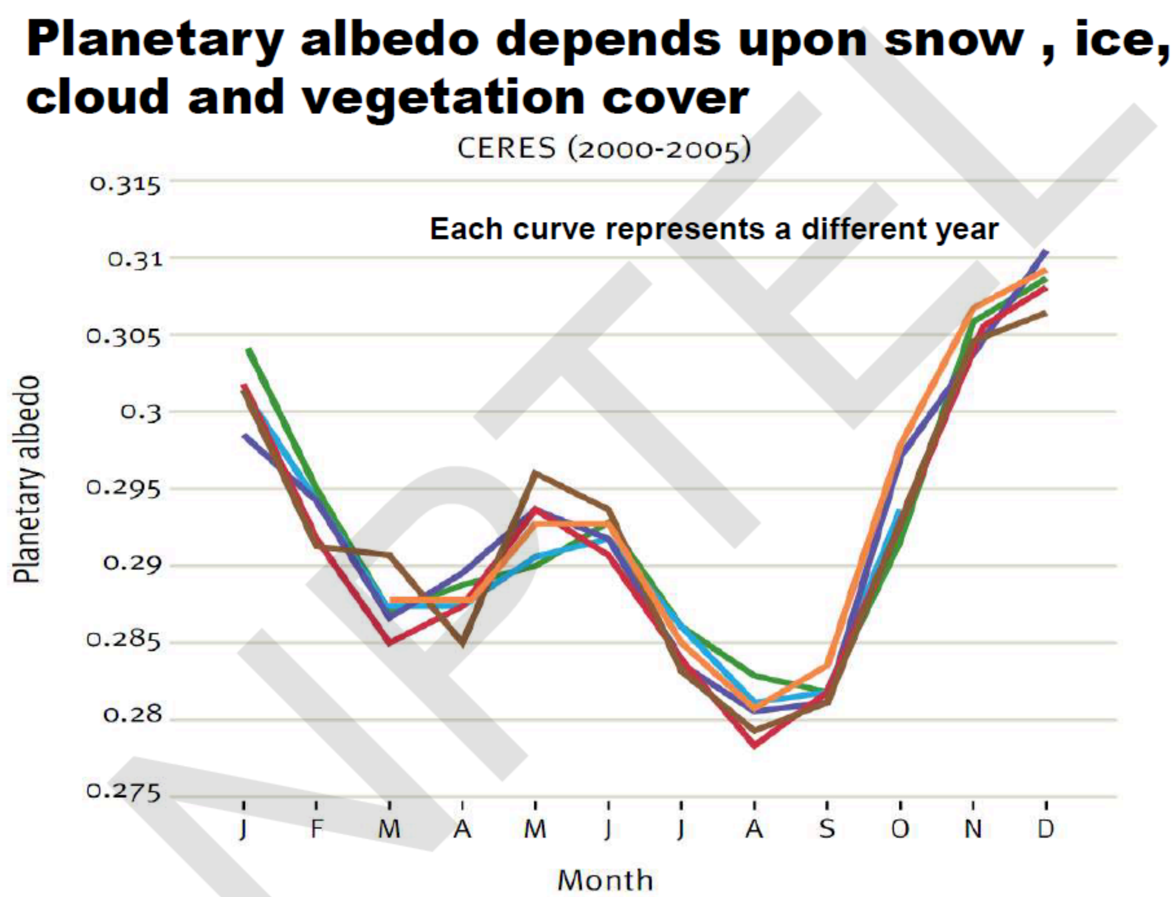
Directly and after multiple reflections

$$A = A_a + \{\rho_s \tau_a A_a\}/\{1- \rho_s \rho_a\}$$

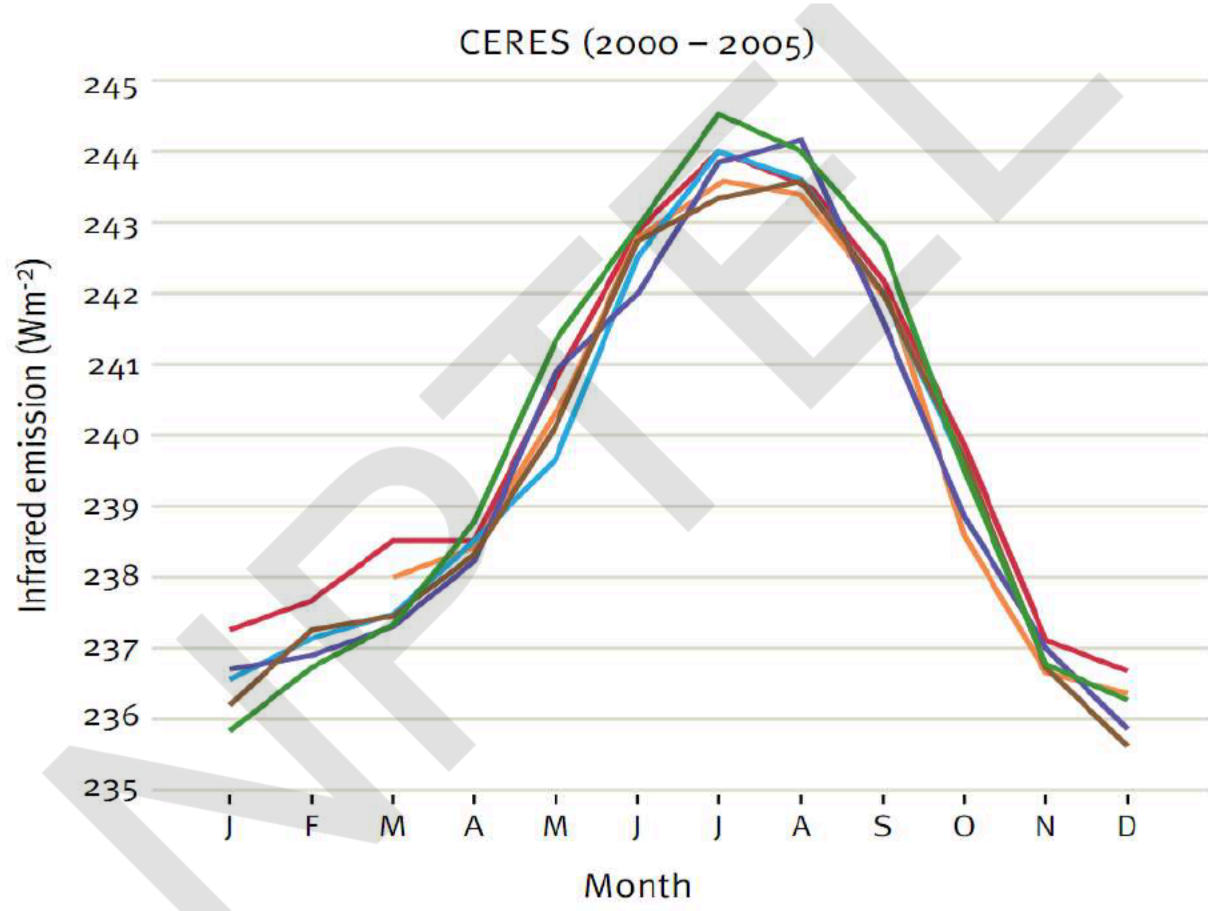
Thus, the final expression for the planetary albedo (ρ) depends on the atmospheric reflectivity, the surface reflectivity, the atmospheric transmittance, and the impact of multiple reflections. Please go through this carefully and ensure that you understand how we arrive at the planetary albedo from surface reflection, atmospheric reflection, and atmospheric transmittance. If you understand this, you can also perform a similar calculation for the absorptivity of solar radiation. It can be absorbed on the first pass, or after reflection by the surface and multiple reflections—using the same logic, but now for absorption. Thus, you can construct this series similarly to what you have done here. This will be given as an assignment for you to do, so that you understand what was done here and how it can be repeated.

Thus, both the total atmospheric absorption of solar radiation and the total atmospheric reflection of incoming radiation consist of terms that involve the atmosphere, surface reflection, and atmospheric reflection. Therefore, when we do the overall Earth energy balance, we will consider only ρ (albedo) and a (absorptivity); we will not discuss the individual terms. I want to remind you that if you go back and look at various textbooks on climate science and radiation, they may treat it differently. Be careful and determine whether they are referring to ρ, ρ_a, or ρ_s. Each textbook treats the subject slightly differently, and we will only treat the planetary contributions, a and ρ. We will not look at individual values; we will assume that you will obtain those individual values and calculate these quantities.

This quantity, ρ, is measured by satellites. I will use it directly without worrying about how it was derived, but if you are running a climate model, you must provide these values. Keep in mind that the surface contribution must be added to obtain the planetary contribution. The same applies for absorption. Although it is a complicated method, we will keep it simple and assume these two quantities are known. “ρ” is known from satellite measurements and “a” is known from model calculations.



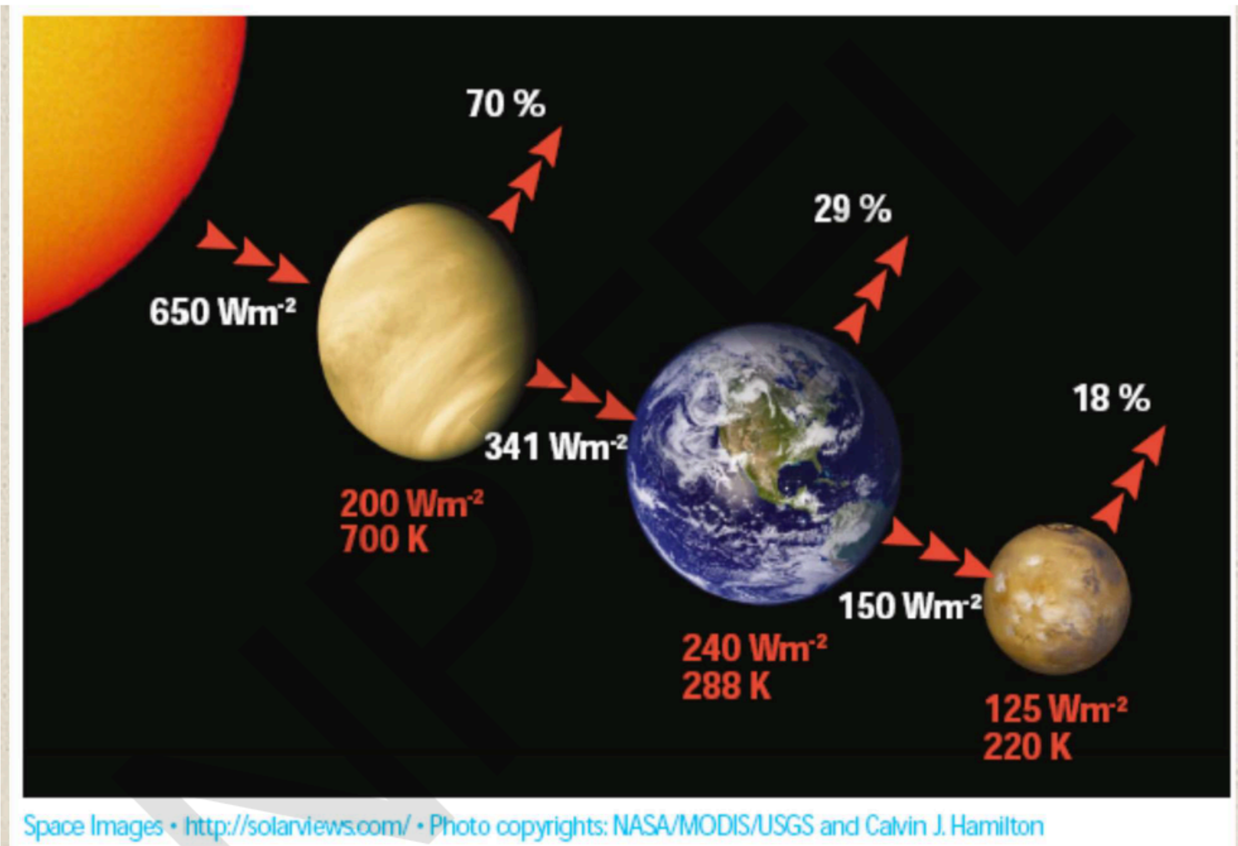
Now, let me give you a few examples of how satellites measure these values. We now have excellent satellite data from NASA, called the CERES satellite, which measures both the Earth's albedo and its absorption. The planetary albedo is measured over 5 years in this graph. You can see that there are variations from year to year and month to month. You can see that the lowest albedo occurs in August, as most of the snow in the Northern Hemisphere has melted due to summer heating. As the Northern Hemisphere transitions to winter, the snow cover increases, and the highest albedo occurs in December. There are some minor variations due to changes in clouds, which are more complex. Remember that we will only consider the planetary albedo, which, when averaged over all months, is roughly around 0.3. We will look at the yearly mean, so we will not consider the details of each month, although it is computed from monthly data.



Now, let us examine the outgoing infrared radiation from Earth, which is again measured by satellites. You can see that it is lowest in January and December because that is winter in the Northern Hemisphere. As winter ends and summer arrives, the temperature of the land and ocean increases. Consequently, the infrared emission to space reaches a maximum of 244 watts per meter square in July and a minimum of around 236 in winter, with an annual mean of approximately 240 watts per meter square. These numbers are very important for understanding the Earth's radiation budget.

Note that there are variations from year to year because clouds vary each year due to the various complex interactions between the ocean and the atmosphere, making each year somewhat different from the previous one. That is why some people are confused when one year is somewhat colder than the previous year, asking why there is no global warming. Global warming is a term used for long-term temperature change, not year-to-year variations. Year-to-year climate variations occur due to the natural energy exchange between the ocean and the atmosphere. However, if you average over many years, you will obtain a fairly constant value. Only one year may be somewhat extreme while others are very similar; if you average all of them, the value remains fairly constant. Year-to-year changes are due to natural climate variability and are not part of the discussion on climate change.

Now, before you go further into Earth's climate, I want you to appreciate the differences between Earth and its near neighbors, Venus and Mars. Venus is, of course, very close to the Sun. Thus, the value of S/4—which indicates the incoming solar radiation per unit area—is larger for Venus than for Earth; almost twice as large because it is closer to the Sun. Moreover, Venus has complete cloud cover, so it reflects much more of the Sun's radiation than Earth does; Earth's albedo is around 30 percent. Thus, although Venus receives more solar radiation, it reflects most of it and absorbs only about 200 watts per meter square, while Earth, although farther away, reflects less radiation and thus absorbs about 240 watts per meter square.



Venus as a more Earth-like planet

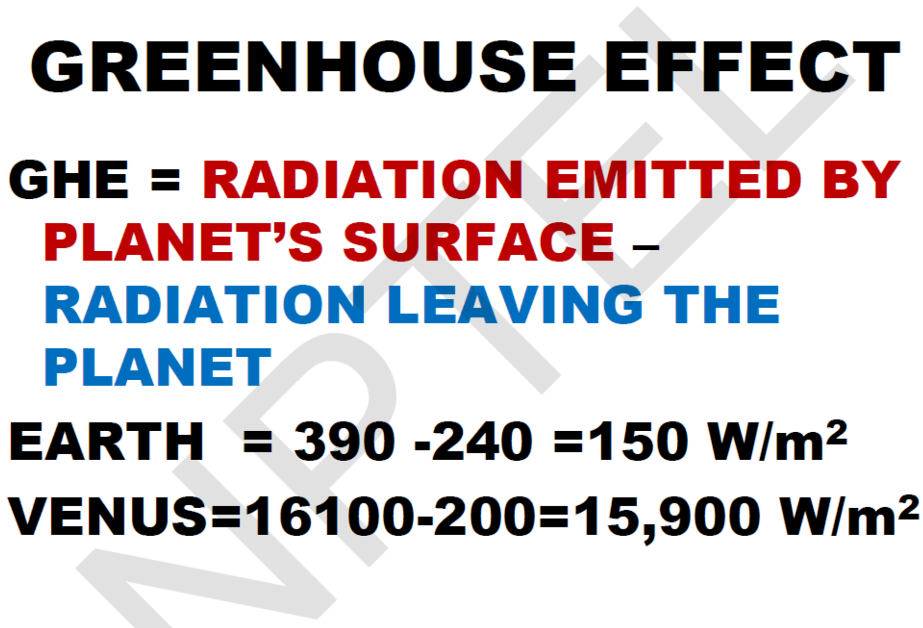
Look at Mars. Mars is farther away, so it only receives about 150 watts per meter square. It reflects less than Earth because it has hardly any atmosphere, and with a surface albedo of around 18 percent, Mars absorbs only about 125 watts per meter square from the Sun. Thus, note that the radiation absorbed by Mars from the Sun is about half of that absorbed by Earth. That is why the average temperature of Mars is around 220 Kelvin. Mars has hardly any atmosphere—it's very thin—while Earth has an average temperature of about 280 Kelvin, and Venus's temperature is much higher. A paradox is that Venus has a much higher temperature than

Earth, even though Venus absorbs less solar radiation; this is due to the greenhouse effect. Venus has a much thicker atmosphere than Earth and contains much more CO_2. Although Venus is very similar to Earth in size, mass, and density, its much thicker atmosphere and higher CO_2 concentration result in a very strong greenhouse effect. We must understand Venus because both Venus and Earth started with similar conditions when the planets were first formed, but Venus diverged in one direction and Earth in another. As far as we know, Venus has no life, while Earth teems with life. We must understand this because over the last 100 years, Earth has been warming rapidly—about 1 degree per 100 years. We do not want Earth to become like Venus. This issue will be discussed later in this course, but keep in mind that Venus is warmer than Earth, even though it absorbs less solar radiation, due to the strong greenhouse effect, which we will discuss shortly.

Composition of the Present Atmosphere

	Venus	Earth	Mars
Surface Pressure	100,000 mb	1,000 mb	6 mb
CO_2	>98%	0.04%	96%
N_2	1%	78%	2.5%
Ar	1%	1%	1.5%
O_2	0.0%	21%	2.5%
H_2O	0.0%	0.1%	0–0.1%

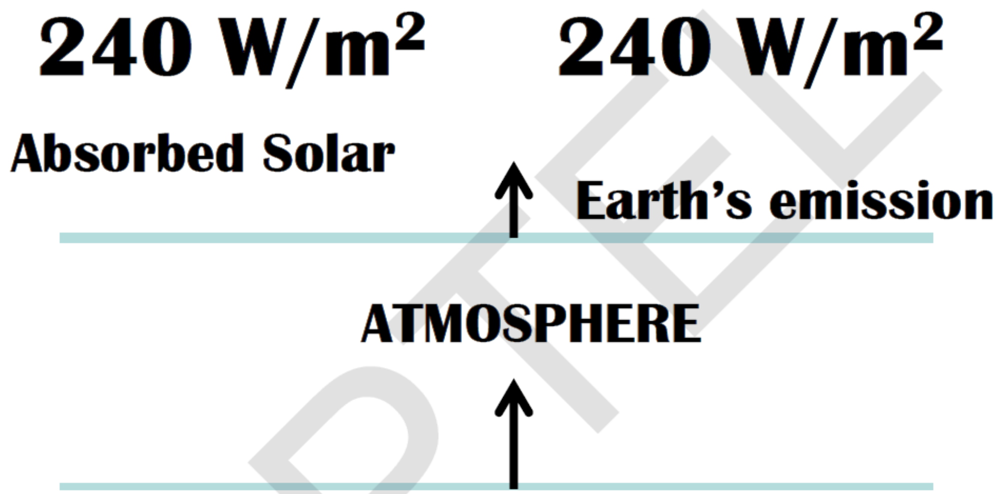
To summarize the differences between Venus and Mars: Venus has a very high surface pressure—about 100 times that of Earth—while Mars has almost no atmosphere, with a surface pressure of about 6 mbar, which is roughly 200 times less than Earth's. But consider the composition: Venus's atmosphere is mostly carbon dioxide; Earth's is only about 0.04 percent CO_2, while Mars's atmosphere is about 96 percent CO_2. Although Mars's atmosphere contains a high percentage of carbon dioxide, the greenhouse effect on Mars is weak because the overall amount of atmosphere is very low. Venus, on the other hand, has a very strong greenhouse effect because it has about 100 times more atmosphere. Earth is unique because its atmosphere is composed of approximately 78 percent nitrogen and 21 percent oxygen, neither of which absorbs the Sun's radiation or the Earth's infrared radiation. Thus, they do not directly participate in the Earth's radiation budget.



Now, let us define the greenhouse effect, which is very important. It is defined as the difference between the radiation emitted by a planet's surface (as measured at the surface) and the radiation that escapes to space (as measured by a satellite). This difference constitutes the greenhouse effect. If there is no atmosphere, the greenhouse effect is 0.

Measurements indicate that Earth's surface emits around 390 watts per meter square, while what reaches space is about 240 watts per meter square, making the greenhouse effect approximately 150 watts per meter square. These quantities are accurately known because we measure the absorbed solar radiation and the emission to space via satellites. We also measure surface temperature and surface emissivity. We know that the emission is around 300 watts per square meter. Thus, the greenhouse effect amounts to 150 watts per meter square. Now, because Earth contains CO_2, water vapor, methane, and ozone—minor gases—these absorb the Earth's emitted radiation and thus control Earth's temperature. That is the greenhouse effect on Earth.

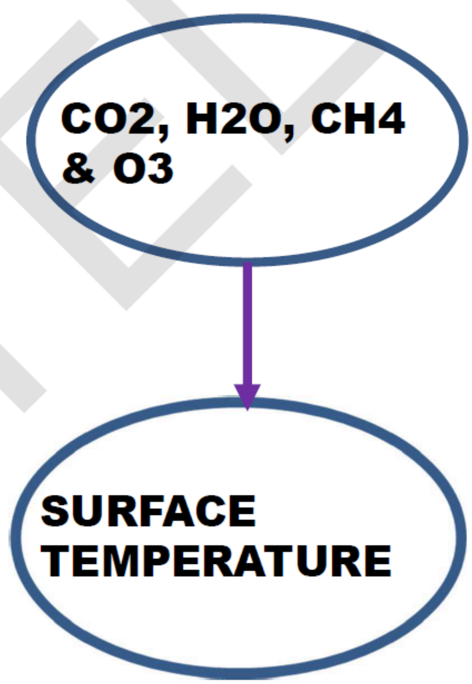
On Mars, it is 0 because there is hardly any atmosphere. For Venus, based on its surface temperature measured by special sensors, it emits approximately 16,100 watts per meter square while what goes to space is just 200 watts per meter square, as measured by satellite. Thus, the difference is 15,900 watts per meter square—almost 100 times. I want you to clearly realize that the Venus greenhouse effect is 100 times larger than Earth's. But remember, once upon a time, Venus was like Earth and had values somewhat like these; however, carbon dioxide built up on Venus. We will discuss how it happened. It soon reached a value 100 times larger than Earth's, and that is why Venus became much hotter than Earth. Consequently, it is not habitable by any living being because it is very hot.



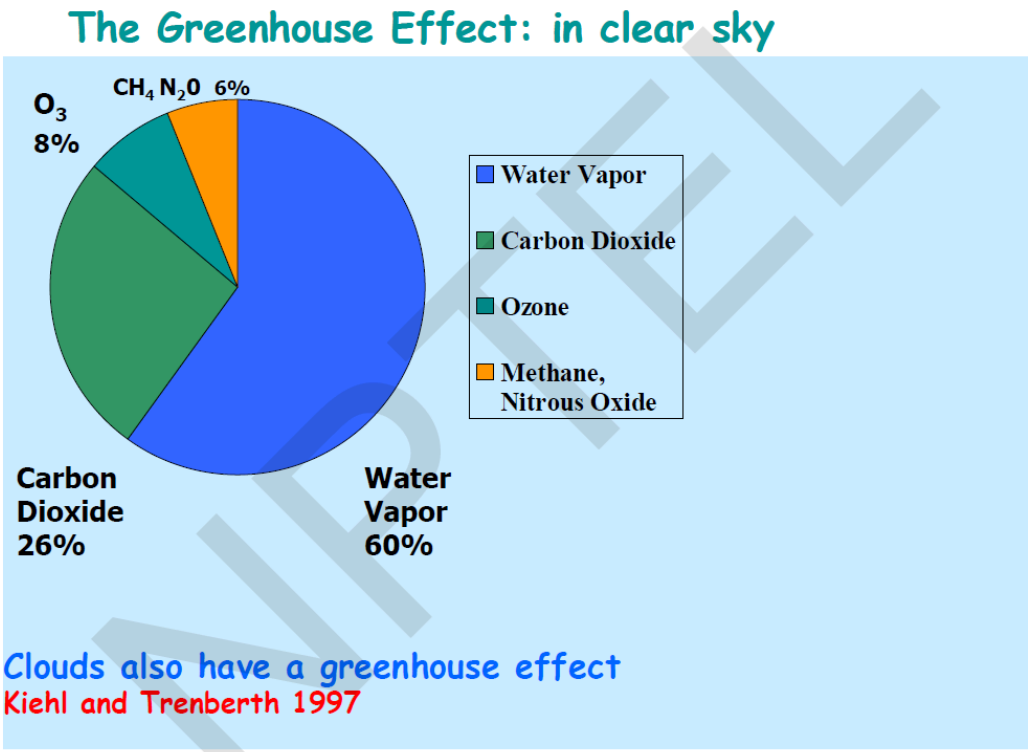
$\sigma\ T^4 = 390\ W/m^2$ for T_s =288K

Greenhouse effect=390 -240=150

Four minor gases (CO_2, H_2O, CH_4 & O_3) control the earth's surface temperature by reducing the amount of radiation that can emitted to space



Earth's temperature is controlled by four minor gases. Many people find it difficult to believe that water vapor makes up only a few percent of the atmosphere, CO_2 about 0.04 percent, methane only parts per billion, and ozone parts per million—small quantities that, however, have a huge impact on surface temperature because the three major gases—nitrogen, oxygen, and argon—are totally transparent to the Sun's radiation and the Earth's infrared radiation. This is a fact to remember clearly.



Under clear-sky conditions on Earth, the greenhouse effect can be resolved into contributions as follows: water vapor accounts for 60 percent, carbon dioxide for 26 percent, ozone for 8 percent, and methane and nitrous oxide together for 6 percent. Thus, water vapor is very important. However, in global negotiations we do not discuss controlling water vapor because we cannot control it—the amount of water vapor in the atmosphere is determined by thermodynamics. We can control CO_2 if we choose to, but we cannot control water vapor. Therefore, even though water vapor is a dominant greenhouse gas, it is beyond our direct control. This is something many people do not understand, and they ask why we try to control CO_2 and not water vapor—especially since CO_2 does not condense in the Earth's atmosphere. CO_2 accumulates, whereas the amount of water vapor is controlled by temperature.

We will conclude this lecture on this topic and continue the discussion on the Earth's radiation budget in the next lecture.