Slide 1 – Title Slide

Hello and welcome to Week 1, Part 3 of EGM703: Thermal Properties of Objects. In this lesson, we'll learn more about how objects interact with electromagnetic radiation and energy in the form of heat.

Slide 2 – Surface energy balance

We'll start off by reviewing how energy interacts with the Earth's surface. From the first law of thermodynamics, we know that energy is neither created nor destroyed – it is conserved. Another way to say this is that all of the energy, or radiation, that falls on a surface is either reflected, absorbed, transmitted, and so on. For the Earth's surface, a simplified version of that balance looks something like this, so long as we are neglecting factors like precipitation. The first part of this equation, is the incoming shortwave radiation. By shortwave, we typically mean radiation with a wavelength under about 3000 nm or so – that is, shorter than the thermal infrared. By incoming, we mean that this is radiation that is incident on, or directed towards, the surface. For the Earth, the main source of this radiation is of course the Sun. Some part of that incoming shortwave radiation is reflected by the surface, which gives us the shortwave outgoing radiation. Next, we also have the longwave incoming radiation – this is thermal radiation that is for the most part emitted by the atmosphere, and especially by clouds. We also have the longwave outgoing radiation, which is the thermal radiation emitted by the Earth's surface. Next up, we have something called the "sensible" heat flux – this is the loss of energy by the surface via heat transfer to the atmosphere – when this is positive, it means that heat is being directed away from the surface, to the atmosphere. We also have the latent heat flux, which is the energy that is lost (or gained) by the surface due to changes in phase, such as evaporation, sublimation, melt, or freezing. And finally, we have the ground heat flux, which is the energy that is conducted away from the surface through the ground.

Slide 3 – Surface energy balance (cont.)

We can simplify this expression a bit further. For example, we can define the net radiation as the difference between the incoming and outgoing radiation. For the longwave radiation, that expression looks like this, and for the shortwave radiation it looks like this. But, remember that the Earth's surface does not typically emit at shorter wavelengths – that means that we can simplify this expression further using the shortwave albedo, which is the fraction of the incoming shortwave radiation that is reflected by the surface. Then, the net radiation, the sum of the net shortwave and net longwave radiation, is given by this expression here, in terms of the incoming shortwave radiation and the net longwave radiation. Putting this together with the equation from the previous slide, we have that the net radiation is equal to the sum of the sensible heat flux, the latent heat flux, and the ground heat flux, respectively.

Slide 4 – Radiation and Earth's surface

What this tells us is that the net radiation: warms up (if the net radiation is positive), or cools (if the net radiation is negative) the ground layer, in the form of the ground heat flux. It also warms up or cools the air in the form of the sensible heat flux, and it can cause phase changes in the form of the latent heat flux (i.e., through melting snow and ice, evaporating water, or condensing water vapor). How much it does this depends on the atmospheric conditions for the sensible heat flux, as well as the surface properties such as the albedo, the absorptance of the surface material, the emissivity of the surface material, or the temperature of the surface; as well as different material properties. The figure here on the right, from the fourth annual report of the Intergovernmental Panel on Climate Change, shows average the Earth's energy balance – the different numbers here are given in Watts per square meter, and it gives you a rough idea of how much each of these different processes contributes to the overall surface energy balance, or budget.

Slide 5 – Material properties

Hopefully you will recall that heat is a form of energy, measured in joules. Heat is transferred via a number of different processes. Advection is the transport of heat due to motion of some fluid or substance – in the figure here, it would be represented by us physically moving the pan of water away from the fire. We also have convection, where heat is transferred in a fluid as a result of flow within the fluid – illustrated here as the heated water rising to the surface, cooling and sinking, then rising to the top again. Radiation, of course, is the transfer of energy via the release of electromagnetic waves or particles, illustrated here by the energy released, or radiated, by the wood fire. Finally, we also have conduction, or diffuse heat transfer – here, the heat is transferred within an object or a material, or between objects that are in contact – for example, the hand holding the hot pan here. The properties of the material, or the surface, that we are looking at, determine how each of these different processes occur. For example, we don't normally get convection in solids, but it's a very common process in gases and liquids.

Slide 6 – Material properties: heat capacity (C)

The first material property that we'll cover is heat capacity, normally denoted as C. This is defined as the ratio of the change in heat energy to the change in temperature of the material. In other words, it tells us how much energy we have to transfer to a material in order to raise its temperature. We define specific heat capacity per unit mass, as more massive objects will typically require more energy to raise their temperature. The units of specific heat capacity are Joules per kilogram per kelvin – again, the change in energy, divided by the mass, divided by the change in temperature. The specific heat capacity of a given material will depend on the molecular structure of that material – as a general rule, liquids have a higher heat capacity than gases, for example. Higher specific heat capacity means that we need more energy to heat, or increase the temperature of, a material. Some examples here: pure water has a specific heat capacity of 4184 J kg^{-1} K^{-1}, or one calorie per gram per degree Celsius. Air, on the other hand, has a specific heat capacity around 4 times lower than that, at only 1003.5 J kg^{-1} K^{-1} – that is, it takes about 4 times as much energy to heat water as it does to heat a comparable amount of air. Copper has an even lower specific heat capacity, at only 385 J kg^{-1} K^{-1}, meaning that it both heats up and cools down quickly.

Slide 7 – Material properties: conductivity (k)

The next material property that we will cover is the thermal conductivity, usually denoted with a k. This measures the rate at which a material conducts – the conductor shown here, Gustavo Dudamel, has a very high conductivity – that is, he is conducting very quickly. Another way to think about this is the energy per unit time, per unit distance, per unit of temperature – in other words, the units of conductivity are Watts (Joules times seconds) per meter per Kelvin. Some common examples of thermal conductivity are shown here. From this, we can see that air is a very poor thermal conductor – it conducts very, very slowly. Water is a much more efficient conductor, though not nearly so good as concrete or copper – again, one of the reasons why copper is a popular element for making pots and pans for cooking.

Slide 8 – Thermal Inertia (P)

Next up, we will discuss thermal inertia, normally denoted P. Like the name might suggest, thermal inertia is the tendency of a material to resist changes in temperature – it's a way of describing how quickly or slowly different materials react to changes in energy. Thermal inertia is calculated as the square root of the thermal conductivity times the heat capacity times the density of the material. It has units of Joules per square meter per Kelvin per seconds to the one-half power. Another way to think about this is that thermal inertia tells us how well a surface, or material, retains heat during the day, and how well it radiates heat away at night; or, what the rate of heat transfer is at the contact between two materials (for example, the Earth's surface and the atmosphere). Unfortunately, calculating thermal inertia directly is difficult – we need to know the thermal conductivity, the heat capacity, and the density of the material. For remote sensing studies, this is even more difficult, which is why we have something called the apparent thermal inertia – this is measured as one minus the albedo divided by the difference in temperature measured during the day and during the night. These are all things that we can estimate using remote sensing, and the apparent thermal inertia provides similar information about a surface or material as does the thermal inertia.

Slide 9 – Diurnal cycles

Hopefully it is clear to you that Q_{net}, because it is so heavily tied to solar radiation, follows a diurnal, or day/night, cycle. From the graph here, we can see that at night, both the incoming and outgoing shortwave radiation is zero. However, we can also see that the incoming and outgoing longwave radiation also follows a diurnal cycle, albeit slightly shifted. This is because surface temperature also follows a diurnal cycle – as the surface is heated up during the day by the sun, it warms up, then cools down throughout the day and into the night. Different materials, given their different thermal properties, will show a different diurnal cycle. Because water typically requires more energy to increase its temperature, it heats up more slowly, does not get as warm during the day, and cools down less at night, compared to something like dry soil. Because of these differences, we typically want to plan thermal remote sensing acquisitions between midnight and dawn, when surface temperatures are relatively stable, or during the middle of the day, when we see the greatest temperature contrast between different materials. We want to avoid acquisitions during the time of day when we see these two lines crossing over each other, as it becomes much more difficult to distinguish between different materials.

Slide 10 – Summary

Remember – the Sun supplies a lot of energy to the Earth's surface.

As we increase the energy, or the net energy, to a surface, we also increase its temperature. Exactly how much will depend on the different properties that we've discussed in this lesson.

Because the Sun has a diurnal, or day/night, cycle, there are better times of day for thermal remote sensing than others. We typically want to select times of day when we will see temperature contrast between different materials – otherwise, we have a hard time differentiating between them.

Slide 11 – Additional resources

Once again, you can read further about most of the concepts we have covered in this lesson in the textbooks, chapter 4.9 and 4.10 of Lillesand, Kiefer & Chipman, and chapter 2 and 9.6 of Campbell & Wynne. I've also included a link to this 1996 paper by Cracknell and Xue, which reviews how to estimate thermal inertia from remote sensing observations. That's all for this lesson – I hope you found it interesting, and you have any questions, please don't hesitate to e-mail me or post in the discussion forum on blackboard. Bye!