METEOROLOGY TODAY, 2nd Canadian Edition

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ENRICHED INSTRUCTOR'S MANUAL

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Chapter 2
Energy

Contents

General Introduction

This chapter begins with a discussion of the flows of energy among Earth systems. Heat, the flow of energy between objects having different temperatures, occurs in the atmosphere by the processes of conduction, convection, and radiation. Air is a relatively poor conductor of heat but can transport heat efficiently over large distances by the process of convection. The latent heat energy associated with phase changes of water is shown to be a very important energy transport mechanism in the atmosphere. An explanation of why rising air cools and sinking air warms is given.

The rules that govern the emission of electromagnetic radiation are reviewed next. The greenhouse effect and the exchange of energy between Earth's surface, the atmosphere, and space are examined in detail. As the role of greenhouse gases in climate change is undergoing vigorous investigation, the latest research results are presented. Students will realize that because the amounts of energy absorbed and emitted by Earth are in balance, Earth's average radiative equilibrium temperature varies little from year to year. Selective absorbers in the atmosphere, such as water vapour and carbon dioxide, absorb some of Earth's longwave radiation and reradiate a portion of it back to the surface. Due to this effect, Earth's average surface temperature is much higher than would otherwise be the case. Results from recent research on the effects of increasing concentrations of carbon dioxide and other greenhouse gases on global climate and the effects of clouds on Earth's energy balance are reviewed.

Chapter Outline

- Energy and Heat
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- Radiation
  - Radiation and Temperature
  - Radiation of the Sun and Earth
- Incoming Solar Energy
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- Radiation, Absorption, Emission, and Equilibrium
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- Energy Balances
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Focus Sections

- Characteristics of the Sun
- The Fate of a Sunbeam
- Wave Energy, Sunburns, and Ultraviolet Rays
- Blue Skies, Red Suns, and White Clouds
- Daily Radiation and Energy Budgets at Earth's Surface

Key Concepts

- Energy is the ability to do work on some form of matter. It takes many forms; it cannot be created or destroyed, but it can change forms.

- The temperature of a substance is a measure of the average speed or kinetic energy of its atoms and molecules.

- Latent heat is the energy absorbed or released during phase changes.

- Evaporation absorbs energy and is a cooling process, whereas condensation releases energy and is a warming process.

- All objects with a temperature above absolute zero emit radiation. The higher an object's temperature, the more total radiation emitted each second by the object and the shorter the wavelengths of emitted radiation.

- Radiation drives the energy budget, which in turn determines how the air and ground warm and cool, as well as how the humidity of the air changes.

- Earth's surface behaves as a blackbody for longwave radiation, making it a much better absorber and emitter of longwave radiation than the atmosphere.

- Water vapour and carbon dioxide are important greenhouse gases that selectively absorb and emit radiation, thus keeping Earth's average surface temperature warmer than it would be otherwise.

- As greenhouse gases increase in concentration, the average surface air temperature is projected to rise substantially by the end of this century.

Earth Systems

[[Insert Earth Systems Image from Chapter 2 (pg. 32)]]

Energy enters the *atmosphere* from the sun as radiation and warms Earth's surface. Heat on the ground drives processes in the *lithosphere*, particularly surface weathering and erosion. These shape our landscapes and create soil, thus allowing further interactions with the *biosphere*. Energy on the surface melts the *cryosphere's* snow and ice into water, which changes how Earth reflects sunlight and determines how the ground absorbs heat. Heating the cryosphere also supplies water for the lithosphere and *hydrosphere* by delivering freshwater runoff to land and surface waters. Additionally, heating Earth's surface heats the lower atmosphere and evaporates water. The water vapour eventually condenses into clouds and falls to the surface again as precipitation, playing an essential role in the hydrosphere. When water changes state between gas, liquid, and solid, very large amounts of energy are exchanged in the processes involved. Sunshine is essential for photosynthesis as plants use solar energy to convert carbon dioxide and water into matter for all the food webs in the biosphere, including the *anthrosphere*. It is the presence of sufficient energy predominantly in the form of heat, as measured by temperature, that makes all Earth's systems function.

Student Motivation

- Students are introduced to the greenhouse effect in this chapter. It should be stressed that an understanding of the greenhouse effect is fundamental to understanding the issue of global climate change. Many students are aware of the major implications forecasted to be caused by climate change but may lack knowledge of the scientific principles responsible for it.
- Students will likely find the discussion of sunburns and UVB radiation in this chapter to be interesting and relevant.
- The section on energy in this chapter leads in to the study of temperature in the following chapter.
- The study of heat transfer and the warming of the surface and atmosphere provide a basis for understanding the formation of clouds and precipitation, which will be studied in later chapters.

Barriers to Learning

- Students may not immediately understand the differences between shortwave and longwave (infrared) radiation. It should be made clear that the energy Earth absorbs from the sun consists primarily of shortwave radiation. Energy emitted by Earth is almost entirely in the form of longwave radiation.
- Many students do not realize that a coloured object appears that way because it reflects or scatters light of that colour. For example, there may be a misconception that a green object reflects all colours except for green.
- Latent heat can be a difficult concept for students to grasp. This can be remedied by explaining how the phase change of water either results in the production or loss of latent heat to the atmosphere. Perhaps make reference to the latent heat produced by condensation that fuels storms. Explain to students that we feel cold when exiting the shower because water is evaporating from our bodies. This analogy will aid them in understanding that evaporation results in the environment losing heat (in this case, the environment is our skin) and that evaporation is a cooling process.
- Ensure that students realize it is not the greenhouse effect itself that is a concern but the enhancement of it due to increasing levels of greenhouse gases. Some students mistakenly think of the greenhouse effect in a negative manner; however, without the greenhouse effect, Earth's average surface temperature would be 33°C colder than it is currently.

Engagement Strategies

Engaging Students from the Start

1. Heat a thin iron bar in a flame (from a Bunsen burner or a propane torch). Begin by holding the bar fairly close to the end. Students will see that heat is quickly conducted through the metal when you are forced to move your grip down the bar. Repeat the demonstration with a piece of glass tubing or a glass rod. Glass is a poor conductor and you will be able to comfortably hold the glass just 5 to 10 cm from the tip. Ask the students if they believe energy is being transported away from the hot glass and if so, how? Without heat loss by conduction, the glass will get hotter than the iron bar and the tip should begin to glow red – a good demonstration of energy transport by radiation. Faint convection currents in the air can be made visible if the hot piece of glass is held between an overhead projector and the projection screen. Ask the students what they would do to quickly cool a hot object. Many will suggest blowing on it, an example of forced convection. Someone might suggest plunging the hot object into water. This makes for a satisfying end to the demonstration. Evaporating water can be seen and heard when the hot iron rod is put into the water (the glass will shatter if placed in the water). The speed with which the rod is cooled is proof of the large amount of latent heat energy associated with phase changes.

2. Ask the students whether they believe water could be brought to a boil most rapidly in a covered or an uncovered pot. The question can be answered experimentally by filling two beakers with equal amounts of water and placing them on a single hotplate (to ensure that energy is supplied to both at equal rates). It is a good idea to place boiling stones in the beakers to ensure gentle boiling. Cover one beaker with a piece of foil. The covered pot will boil first. Explanation: A portion of the energy added to the uncovered pot is used to evaporate water, not to increase the water's temperature.

3. Use a lamp with a 150 Watt reflector bulb to help explain the concept of radiation intensity. Blindfold a student and hold the lamp at various distances from the student's back. Ask the student to judge the distance of the bulb. Use the same lamp to illustrate the concepts of reflection, albedo, and absorption by measuring the amount of reflected light from various coloured surfaces with a sensitive light meter. The reflectivity of natural surfaces outdoors could be measured or form the basis for a student or group project.

4. A 200 Watt clear light bulb connected to a dimmer switch can be used to illustrate how the temperature of an object affects the amount and type of radiation that the object will emit. Explain that passage of electricity through the resistive filament heats the filament. The filament's temperature will increase until it is able to emit energy at the same rate as it gains energy from the electric current. With the dimmer switch set low, the bulb can be made to glow a dull red. At low temperatures, the bulb emits low-intensity, longwave radiation. As the setting on the dimmer switch is increased, the colour of the filament will turn orange, yellow, and then white as increasing amounts of shortwave radiation are emitted. The intensity of the radiation will increase dramatically.

Other Engagement Strategies

1. This demonstration explains the concept of equilibrium. Place a glass of water on a table top and ask the students whether they think the temperature of the water in the glass is warmer, cooler, or the same as the surroundings. Many will say it is the same. Ask the students whether they think there is any energy flowing into or out of the glass. With some encouragement, they will recognize that the water is slowly evaporating and that this represents energy flow out of the glass. Energy flowing out of the glass will cause the water's temperature to decrease. Will the water just continue to get colder and colder until it freezes? No, as soon as the water's temperature drops below the temperature of the surroundings, heat will begin to flow into the water. The rate at which heat flows

into the glass will depend on the temperature difference between the glass and the surroundings. The water temperature will decrease until energy flowing into the glass balances the loss due to evaporation.

2. This demonstration explains the scattering and reflection of light by objects. Emphasize to students that objects do not emit visible light (ask the students whether they would see the object if all the lights in the room were turned off). Similarly, it is important that students understand that a red or green filter transmits red or green light. Put a red and a green (or blue) filter on an overhead projector and draw a hypothetical filter transmission curve. Put the two filters together and show that no light is transmitted. Ask students what happens to the light that is not transmitted by the filter. This helps clarify the misconception that objects of a certain colour (i.e. green) reflect all other colours but green.

Assessment Tools

Student Projects

1. Solar irradiance (energy per unit time per unit area) at the ground can be measured relatively easily. Begin with a rectangular piece of aluminum 5 to 10 cm on a side and 1 or 2 cm thick. Drill a hole in one side so that a thermometer can be inserted into the middle of the block. Paint one of the two surfaces with flat black paint. Position the block in a piece of Styrofoam insulation so that the painted surface faces outward and is flush with the Styrofoam surface. Insert the thermometer into the side of the block. Orient the block so that the black surface is perpendicular to incident radiation from the sun. Note the time and measure the block temperature every 30 seconds for 10 to 15 minutes. When plotted on a graph, the temperature, T, should increase linearly with time, t. The slope of this portion of the graph can be used to infer the solar irradiance, S, using the following equation:

2. Compare the solar energy balance for two different locations. What are the noon albedos for each location? Why are they different? Which component of the albedo (Earth's surface, clouds, or atmosphere) dominates in each case? Explain why.

Answers to Questions for Review

1. Temperature is a measure of the average speed of atoms and molecules.

2. Heat is energy in the process of being transferred from one object to another because of the temperature difference between them.

3. (a) Conduction: The transfer of heat from molecule to molecule within a substance.
(b) Convection: The transfer of heat by the mass movement in liquids and gases.
(c) Radiation: Heat transfer from one object to another without the necessity of the space between the objects being heated.

4. When water vapour condenses into clouds, latent heat is released into the atmosphere. This provides a tremendous amount of heat in storms, such as thunderstorms and hurricanes.

5. Advection is horizontal; convection is vertical.

6. A small increase in temperature results in a large increase in the amount of radiation emitted because doubling the absolute temperature of an object increases the maximum energy output by a factor of 16.

7. Because Earth is cooler than the sun, it emits much less radiation than the sun.

8. Because Earth is cooler, its radiation is at longer wavelengths than that of the sun.

9. Ultraviolet.

10. The amount of radiation entering the surface of the body equals the amount exiting the surface of the body.

11. This is because it is also continually receiving energy from the sun and the atmosphere.

12. This is because they absorb radiation at certain wavelengths and not others.

13. The atmosphere allows visible radiation to pass through, but inhibits, to some degree, the passage of longwave radiation leaving Earth's surface.

14. Carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons.

15. This is because of the enhancement of Earth's greenhouse effect.

16. Reflection and scattering of solar radiation by the atmosphere, clouds, and Earth's surface.

17. The atmosphere near Earth's surface is warmed and cooled by conduction and convection from below.

18. The absorption of shortwave radiation along with the processes of conduction and convection cause the air to warm during the day. Longwave radiation loss from Earth, conduction, and convection cause the air to cool at night.

19. This is because they absorb and radiate with nearly 100 percent efficiency for their respective temperatures.

Answers to Questions for Thought

1. The bridges will become icy first because they lose heat energy over their entire surface; they cool on top, on the sides, and on the underside. The roads, on the other hand, lose heat energy quickly, but only at their upper surface. Also, when roads begin to cool, heat may flow up from warmer ground below.

2. The branches cool rapidly by emitting infrared energy. The bare ground cools also, but it gains heat from the warmer soil below. Thus, the temperature of the bare ground may not drop below freezing and the freshly fallen snow will melt.

3. These objects must be good emitters of radiation. Good emitters of radiation will cool to temperatures less than that of the surrounding air. Energy lost by radiation is not quickly replaced by conduction. Air is a selective emitter of radiation and does not cool as rapidly as the ground.

4. The ice can form when the air is dry and a strong wind blows over the water, causing rapid evaporation and cooling to the freezing point.

5. This would occur in winter. Even though the oceans are cooler in winter than in summer, there is a greater temperature contrast between the oceans and the atmosphere in winter.

6. It is transferred in the form of electromagnetic radiation only.

7. Ultraviolet radiation carries more energy per photon than visible radiation does.

8. At a given distance from the large fire, the energy received per unit area and per unit time is greater than the energy received at the same distance from the small fire.

9. Without water vapour to absorb Earth's emitted longwave radiation, it will lose more heat.

10. A ploughed field would show the greatest increase in temperature. The field is dark and has a low albedo; it is a poor reflector and a good absorber of sunlight. The snow surface has a high albedo and is a good reflector and poor absorber of sunlight.

11. The low cloud absorbs energy emitted by Earth's surface and reradiates longwave radiation back to the surface. A portion of the energy lost by Earth is returned.

12. Removing the water vapour would have the greatest effect. This is because water vapour is a good absorber of longwave radiation and atmospheric concentrations of water are much higher than concentrations of carbon dioxide.

13. An increase in cloud cover would increase the Earth-atmosphere albedo and, thus, less sunlight would reach Earth's surface. Depending on the height and thickness of the cloud cover, the clouds might absorb more longwave radiation from Earth and thus tend to strengthen the atmospheric greenhouse effect.

14. This could happen in the thermosphere, where the air is less dense. Here the molecules move at average speeds proportional to a temperature of 1000^{o}C. However, few molecules would strike the thermometer and transfer heat to it. Consequently, the thermometer would lose energy much faster than it would gain energy. The thermometer would cool until it eventually registered a temperature near -273^{o}C.

Answers to Problems and Exercises

1. 0.5 kg * 2500 kJ/kg = 1250 kJ

   1250 kJ / (100 kg * 1.005 kJ/kg K) = 12.4 K warmer

2. Planet A, with the largest surface area, would be emitting the most radiation. The wavelength of maximum emission for both planets would be λ_{max} = 2897 μm K / 1500 K = 1.9 μm.

3. (a) The wavelength of maximum emission for Planet B would be λ_{max} = 2897 μm K / 3000 K = 1 μm.

   (b) Near-infrared

   (c) Once its temperature is doubled, Planet B would emit 8 times more energy per unit time than Planet A. Once its temperature is doubled, Planet B would emit 16 times more energy per unit area of surface than Planet A (Stefan–Boltzmann law). However, Planet B has only half the total surface area that Planet A does.

4. Radiant energy $E = \sigma T^4$. Converting T from Celsius to Kelvin gives T = [30 + 273.15] = 303.15 K. Using T = 303.15 K and $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4, we find E = 479 W/m^2.

Reflections on Teaching

- What topics or concepts engaged the students most?
- What topics or concepts confused the students? Why did this occur?
- Do the assessment results suggest that students understand major concepts and how the topics relate to one another? Or do the results suggest that students are studying by just memorizing key terms?
- What do I need to change to improve student success?
- How can I receive ongoing feedback from students about my teaching?

Additional Resources

Active Figures

Active Figure 2.12: The Absorption of Radiation by Gases in the Atmosphere

Active Figure 2.13: The Greenhouse Effect

These figures are found at http://www.nelson.com/student

Websites

Incoming Solar Energy Interactive Applet
http://profhorn.aos.wisc.edu/wxwise/radiation/sunplot6.html

Net Radiation Distribution Maps by Month http://itg1.meteor.wisc.edu/wxwise/museum/a2/a2net.html

Outgoing Longwave Radiation Maps and Dataset
http://neo.sci.gsfc.nasa.gov/view.php?datasetId=CERES_LWFLUX_M

Shortwave, Longwave, and Net Radiation Animation
http://geography.uoregon.edu/envchange/clim_animations/gifs/three_rads_web.gif

Video Clips

A Year in the Life of Earth's CO_2
http://video.nationalgeographic.com/video/news/141119-global-co2-nasa-vin?source=searchvideo