Answer Key for Planetary Energy Balance Assessment Questions

1. When a planet is in a state of thermal equilibrium, which of the following statements about energy flow is most accurate?

a) More energy **flows to** the planet than away from it.
b) The flow of energy to the planet is about the same as the flow of energy away from the planet. (correct)
c) More energy **flows away from** the planet than to it.
d) More information is needed to answer this question.

2. If a planet receives more energy than it emits, what would you expect to happen to the average temperature of that planet?

a) The planet would become warmer. (correct)
b) The temperature of the planet would stay about the same.
c) The planet would become cooler.
d) More information is needed to answer this question.

3. If a planet gives off more energy than it receives, what would you expect to happen to the average temperature of that planet?

a) The planet would become warmer.
b) The temperature of the planet would stay about the same.
c) The planet would become cooler. (correct)
d) More information is needed to answer this question.

4. There are three ways heat moves around: by conduction, by convection, and by radiation. Which of these is the main way that heat arrives at Earth and leaves Earth?

a) Conduction
b) Convection
c) Radiation (correct)
d) None of the above

5. Suppose you had two black, iron spheres. Sphere A has a temperature of 100° C (212° F). Sphere B has a temperature of 0° C (32° F). What can you say about the infrared heat energy being emitted by these two spheres?

a) **Both spheres are radiating infrared heat energy. Sphere A is emitting more energy than sphere B. (correct)**
b) Both spheres are radiating infrared heat energy. Sphere B is emitting more energy than sphere A.
c) Both spheres are radiating about the same amount of infrared heat energy.
d) Neither sphere is radiating infrared heat energy.
e) Only sphere A is radiating infrared heat energy.
f) Only sphere B is radiating infrared heat energy.

6. Suppose you had two black, iron spheres and an instrument that could measure the amount of electromagnetic radiation being emitted by each sphere. Your measurements show that sphere A is emitting less electromagnetic radiation than sphere B. What, if anything, can you conclude about the temperatures of the two spheres?

a) These measurements would not tell me anything about the temperatures of the spheres.
b) The spheres have the same temperature.
c) Sphere A is warmer than sphere B.
d) **Sphere B is warmer than sphere A. (correct)**

7. What would Earth be like if there were no greenhouse gases at all in its atmosphere? Based on your knowledge of how sunlight heats our planet, which of the following descriptions of Earth's climate seems most accurate?

a) Earth's climate would be much warmer. Most of the land would be covered with scorching deserts or steamy jungles. Seas would be warm and iceberg-free, and there would be no polar ice caps or glaciers on high mountains.
b) Earth's climate would be pretty much like it is in modern times.
c) Earth's climate would be similar to the way it was before about 1750, when humans started burning lots of fossil fuels and warming the climate. The climate would be a little bit cooler than Earth's climate is in modern times.
d) **Earth's climate would be much colder. Most of the land would be covered in snow and ice, including ice caps and glaciers. Most of the world's oceans would be covered with sea ice and icebergs. (correct)**
e) More information is needed to answer this question.

8. If Earth's albedo changed from its current value of about 31% to 70%, what would you expect to happen to Earth's average global temperature?

a) **Temperature would decrease - Earth would cool. (correct)**
b) Temperature would stay pretty much the same.
c) Temperature would increase - Earth would warm.
d) More information is needed to answer this question.

9. If Earth's albedo changed from its current value of about 31% to 10%, what would you expect to happen to Earth's average global temperature?

a) Temperature would decrease - Earth would cool.
b) Temperature would stay pretty much the same.
c) Temperature would increase - Earth would warm. (correct)
d) More information is needed to answer this question.

10. Suppose the surface of Earth suddenly became much lighter in color. For example, imagine all of the land being covered with white sand. What would you expect to happen to Earth's average global temperature?

a) Temperature would decrease - Earth would cool. (correct)
b) Temperature would stay pretty much the same.
c) Temperature would increase - Earth would warm.
d) More information is needed to answer this question.

11. Suppose the surface of Earth suddenly became much darker in color. For example, imagine all of the land being covered with black rock from volcanoes. What would you expect to happen to Earth's average global temperature?

a) Temperature would decrease - Earth would cool.
b) Temperature would stay pretty much the same.
c) Temperature would increase - Earth would warm. (correct)
d) More information is needed to answer this question.

Calculations

1. Suppose you had two black, iron spheres. Sphere A has a temperature of 20° C. Sphere B has a temperature of 40° C. Calculate the relative amount of electromagnetic radiation being emitted by sphere B compared to sphere A.

First **convert temperature values** from degrees Celsius to kelvins:

$$T_{A,Kelvin} = T_{A,Celsius} + 273.15 = 293.15\ kelvins$$

$$T_{B,Kelvin} = T_{B,Celsius} + 273.15 = 313.15\ kelvins$$

Assuming the two spheres are the same size, calculate the energy emission rate (j^*, in units of energy per unit area per unit time) using the Stefan-Boltzmann Law:

$$j^* = \sigma T^4$$

T = temperature in kelvins

σ = Stefan-Boltzmann constant = 5.670373 x 10^{-8} watts/m^2 K^4

$$j^*{}_A = \sigma {T_A}^4 = 5.67 \times 10^{-8} \times 293.15^4 = 418.8\ \frac{watts}{m^2}$$

$$j^*{}_B = \sigma {T_B}^4 = 5.67 \times 10^{-8} \times 313.15^4 = 545.3\ \frac{watts}{m^2}$$

$$\frac{j^*{}_B}{j^*{}_A} = \frac{545.3}{418.8} = 1.302$$

Sphere B is emitting about 1.3 times as much energy as (or 30 % more than) sphere A.

Alternately, one could calculate the ratios of the temperatures (in kelvins!), then raise that ratio to the 4th power, to obtain the same result:

$$\left\{\frac{T_B}{T_A}\right\}^4 = \left\{\frac{313.15}{293.15}\right\}^4 = \{1.0682\}^4 = 1.302$$

Note: if students don't convert the temperatures from the Celsius scale to the Kelvin scale, they might mistakenly conclude that sphere B is emitting 16 times as much energy as sphere A; based on the false assumption that sphere B is twice as hot (40°/20°) as sphere A.

2. Suppose you had two black, iron spheres. Sphere A is emitting about 5 times more electromagnetic radiation than sphere B. Calculate the relative temperatures of the two spheres.

$$\frac{{j^*}_A}{{j^*}_B} = \left\{\frac{\sigma T_A}{\sigma T_B}\right\}^4 = \left\{\frac{T_A}{T_B}\right\}^4$$

$$\frac{T_A}{T_B} = \sqrt[4]{\frac{{j^*}_A}{{j^*}_B}} = \sqrt[4]{\frac{5}{1}} = \sqrt[4]{5} = 1.495$$

Sphere A is about 50% (1.5 times) warmer than sphere B.

Note, we cannot determine the **absolute** temperatures of the two spheres. Sphere A might have a temperature of 75 kelvins (-198° C or -325° F) compared to sphere B's temperature of 50 kelvins (-223° C or -370° F) … or sphere A might be at 300 kelvins (27° C or 80° F) while sphere B is at 200 kelvins (-73° C or -100° F)… or any number of other possibilities for which the temperature of sphere A is 50% higher (on the Kelvin scale!) than the temperature of sphere B.

In each of the questions below, use the law of energy conservation and the Stefan-Boltzmann Law to calculate the average global temperature for Earth. Assume that there is no warming due to the greenhouse effect.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}}$$

T = temperature in kelvins

K_S = solar constant = 1,361 watts/m²

σ = Stefan-Boltzmann constant = 5.670373 x 10^{-8} watts/m^2 K^4

Where m = meters and K = kelvins

3. Calculate the expected average global temperature for Earth, given that our planet's average albedo is about 31%.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (1 - \mathbf{0.31})}{4 \times 5.67 \times 10^{-8}}} = 253.7\ kelvins$$

$$T_{Celsius} = T_{Kelvin} - 273.15 = -19.5°\ C$$

$$T_{Fahrenheit} = \frac{9}{5} \times T_{Celsius} + 32 = -3.1°\ F$$

4. What would Earth's average albedo have to be to produce an average global temperature above the freezing point of water?

We'll use the same equation as our starting point:

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}}$$

Using some algebra to rearrange, we'll solve for albedo using temperature as an input:

$$albedo = 1 - \frac{4\sigma T^4}{K_S}$$

The freezing point of water is 32° F or 0° C, which is 273.15 kelvins. Plugging in values:

$$albedo = 1 - \frac{4 \times 5.67 \times 10^{-8} \times 273.15^4}{1361} = 0.072$$

Earth's overall, average albedo would need to be about 7% or less for the average global temperature to be at or above the freezing point of water.

5. If Earth was completely black, what would its average surface temperature be?

Assume "completely black" means albedo is equal to zero.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (1 - \mathbf{0})}{4 \times 5.67 \times 10^{-8}}} = 278.3\ kelvins$$

$$T_{Celsius} = 5.2°\ C \qquad T_{Fahrenheit} = 41.3°\ F$$

6. If Earth was completely white, what would its average surface temperature be?

Assume "completely white" means albedo is equal to 100%.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (\mathbf{1 - 1})}{4 \times 5.67 \times 10^{-8}}} = 0\ kelvins$$

$$T_{Celsius} = -273.15°\ C \qquad T_{Fahrenheit} = -459.7°\ F$$

In this extreme, hypothetical case, the temperature would plummet to absolute zero. If the albedo actually was 100%, all incoming energy from sunlight would be reflected away… so there would be no energy to heat the planet at all.

7. The planet Venus is completely covered with clouds. Its overall albedo is around 90%. If Earth was like Venus in terms of cloud cover and albedo, what would the average surface temperature on Earth be? (assuming the clouds did NOT produce warming via the greenhouse effect)

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (1 - \mathbf{0.9})}{4 \times 5.67 \times 10^{-8}}} = 156.5\ kelvins$$

$$T_{Celsius} = -116.6°\ C \qquad T_{Fahrenheit} = -177.9°\ F$$

8. According to the Snowball Earth hypothesis, there may have been times in Earth's distant past when Earth was mostly or completely covered with snow and ice. If Earth was completely covered in snow and ice today, what would you expect the average temperature on our planet to be? Assume an average overall albedo of about 60%.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (1 - \mathbf{0.6})}{4 \times 5.67 \times 10^{-8}}} = 221.3\ kelvins$$

$$T_{Celsius} = -51.8°\ C \qquad T_{Fahrenheit} = -61.3°\ F$$

9. Scientists sometimes use the concept of a "Water World", a planet completely covered by oceans, when testing aspects of climate models. Calculate the expected average global temperature if Earth was a Water World, assuming an albedo of 5%. Based on your calculated temperature, do you think a 5% albedo for a Water World in Earth's orbit is plausible?

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{1361 \times (1 - \mathbf{0.05})}{4 \times 5.67 \times 10^{-8}}} = 274.8\ kelvins$$

$$T_{Celsius} = 1.6°\ C \qquad T_{Fahrenheit} = 34.9°\ F$$

A Water World with an albedo of 5% produces a planet with an average global temperature just slightly above the freezing point of water. We would expect that temperatures near the equator would be a bit higher than freezing, but that temperatures at high latitudes near the poles would be below freezing.

Sea ice would probably form at high latitudes. Sea ice has a high albedo. It seems unlikely that this Water World version of Earth could have such a low, overall average albedo (5%) if parts of the global ocean were covered by sea ice with an albedo of 50% or higher.

10. Early in Earth's history, scientists think the Sun wasn't as bright as it is now. Assuming the young Sun was about 70% as bright as it is now, calculate the expected average global temperature for Earth (assume global albedo matched the current value of 31%).

In this case we need to adjust the value of K_S to match the reduced brightness of the "Faint Young Sun".

K_S = solar constant = **0.70** x 1,361 watts/m² = 952.7 watts/m²

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{\mathbf{952.7} \times (1 - \mathbf{0.31})}{4 \times 5.67 \times 10^{-8}}} = 232\ kelvins$$

$$T_{Celsius} = -41°\ C \qquad T_{Fahrenheit} = -42°\ F$$

11. Early in Earth's history, scientists think the Sun wasn't as bright as it is now. Assuming the young Sun was about 70% as bright as it is now, calculate the highest expected average global temperature for Earth. Choose a value for albedo that gives the highest temperature under these conditions.

Earth would absorb the most energy from incoming sunlight if it was completely black, so we set the albedo value to zero.

$$T = \sqrt[4]{\frac{K_S \times (1 - albedo)}{4\sigma}} = \sqrt[4]{\frac{\mathbf{952.7} \times (1 - \mathbf{0})}{4 \times 5.67 \times 10^{-8}}} = 254.6\ kelvins$$

$$T_{Celsius} = -41°\ C \qquad T_{Fahrenheit} = -42°\ F$$