Climate: Earth’s Dynamic Equilibrium

PA STEM
review session

CCIU

April 30, 2016

High-school standard HS-ESS2-4 focuses on the role energy flows play in Earth’s climate

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HS-ESS2-4 Use a model to describe how variations in the flow of energy into and out of Earth’s systems result in changes in climate.

[Clarification Statement: Examples of the causes of climate change differ by timescale, over 1-10 years: large volcanic eruption, ocean circulation; 10-100s of years: changes in human activity, ocean circulation, solar output; 10-100s of thousands of years: changes to Earth's orbit and the orientation of its axis; and 10-100s of millions of years: long-term changes in atmospheric composition.]

[Assessment Boundary: Assessment of the results of changes in climate is limited to changes in surface temperatures, precipitation patterns, glacial ice volumes, sea levels, and biosphere distribution.]

Earth’s climate is determined solely by how much light energy it receives from the Sun and how that energy is distributed on Earth

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3.9×10^{26} W

6.33×10^{7} W/m^2

Irradiance at Earth (S_E):	1368 W/m^2	
Average Irradiance (S_{toa}):	342 W/m^2	(S_E/4)
Irradiance absorbed:	240 W/m^2	(70%)

Temperature of a perfectly absorbing object (black body) is given by the Stefan-Boltzmann law

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For an irradiance (S):

$$S = \sigma T^4$$

σ = 5.67 x 10^{-8} W/m^2 (Stefan's constant)

T is measured in kelvins (absolute temp scale)

Example: What is the surface temperature of the Sun?

$T^4 = S/\sigma$

T =

Earth's climate is an equilibrium system in which energy in equals energy out

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(Solar energy absorbed by Earth) = (Thermal energy emitted by Earth)

$(0.70)S_{TOA} = S_E$

$$S_E = \sigma(T_E)^4$$

If the Earth absorbs more or less energy than it is emitting (S_E), the Stefan-Boltzmann law ensures that Earth can change its temperature (T_E) until absorption and emission are equal.

Stefan-Boltzmann law predicts Earth's temperature based on the average absorbed irradiance

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Q: What is the expected temperature of Earth with 70% absorption?

$(T_{expected})^4 = (0.70)S_{toa}/\sigma =$

$T_{expected} =$

Compare with actual temperatures:

$T_{surface}$ = 288 K

$T_{troposphere}$ = 222 K

The blackbody model is reasonably good at predicting Earth's equilibrium temperature

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Question: Why is the Earth's surface temperature significantly above the temperature predicted by the blackbody (Stefan-Boltzmann) law?

Sunlight is absorbed in the atmosphere by a variety of gases, especially ozone, carbon dioxide, and water vapor

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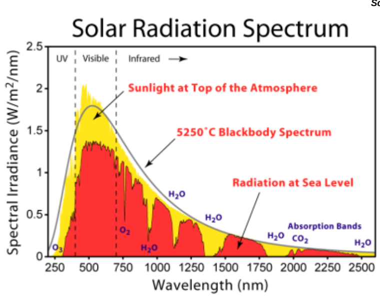

Much of the Sun's radiation is absorbed as visible light, but radiated by Earth as infrared light

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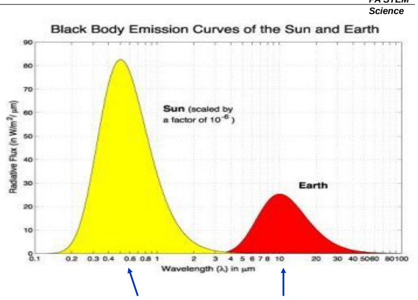

Different wavelengths of light reach different levels in the atmosphere, causing variations in temperature

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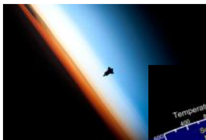

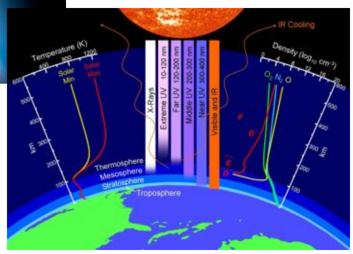

Temperature is also significantly affected by Earth's *albedo*, which is how much light is reflected

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Snow and clouds reflect 40 – 80% of visible light

Oceans reflect less than 10% of visible light

Earth reflects about 30% of the sunlight back into space and emits the remaining energy as infrared light to stay in equilibrium

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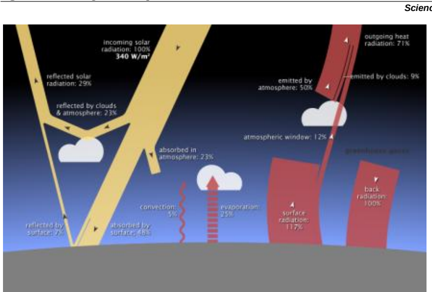

Changes in Earth's climate system can occur when external "forcings" cause an imbalance in the absorption and emission of energy

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Question: What are the main forcings that can cause Earth's climate system to change?

Climate change occurs as part of Earth's attempt to restore equilibrium

Solar irradiance shows little variation even over millenia, which implies little impact on climate change over those time scales

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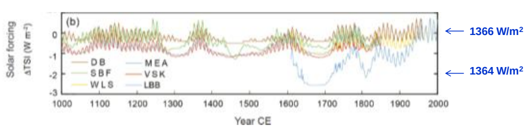

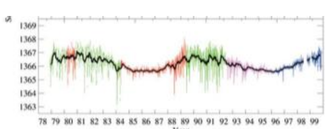

Changes in Earth's orbit around the Sun, called Milankovitch cycles, can affect how much energy Earth receives

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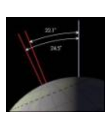
Milankovitch Cycles are caused by variations in

- **shape of Earth's orbit (eccentricity)**

- **Earth's tilt angle (obliquity)**



- **wobbling of Earth's axis (precession)**

Milankovitch cycles, which occur over 10- and 100-thousands of years, caused past ice ages

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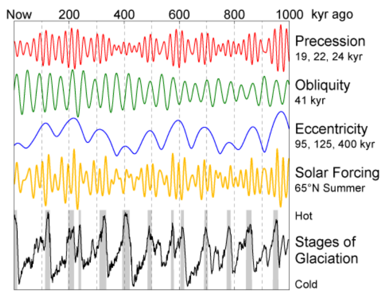

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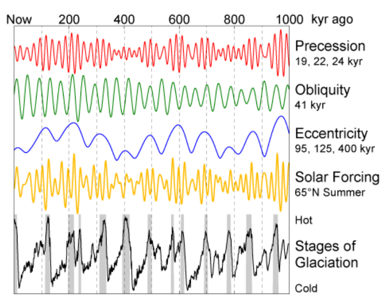

Changes in Earth's albedo (reflectivity) have a wide range of possible causes and operate over many time scales

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Question: What are some possible causes that contribute to Earth's changing albedo?

Cause **Time Scale**

Changes in energy emission are mainly affected by changes in the concentrations of "greenhouse gases" in the atmosphere

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Gas	Pre-1750 tropospheric concentration[1]	Recent tropospheric concentration[2,3]	GWP[4] (100-yr time horizon)	Atmospheric lifetime[5] (years)	Increased radiative forcing [6] (W/m^2)
Concentrations in parts per million (ppm)					
Carbon dioxide (CO_2)	~280[7]	399.5[2,8]	1	~ 100-300[5]	**1.94**
Concentrations in parts per billion (ppb)					
Methane (CH_4)	722[9]	1834[2]	28	12.4[5]	**0.50**
Nitrous oxide (N_2O)	270[10]	328[3]	265	121[5]	**0.20**
Tropospheric ozone (O_3)	237[1]	337[2]	n.a.[3]	hours-days	**0.40**

In comparison to longer-lived greenhouse gases, water vapor plays a dominant role in controlling emission of thermal (infrared) radiation

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