Balancing the Energy *Budget*

Just like a family budget for finances, the energy budget of the Earth should be balanced. In equation form:

Energy In = **Energy Out**

This balance can be considered at several levels in the Earth system:

At the top of the atmosphere, the energy coming in from the Sun is balanced by sunlight reflected back to space and the net infrared emission from the Earth. The equation is:

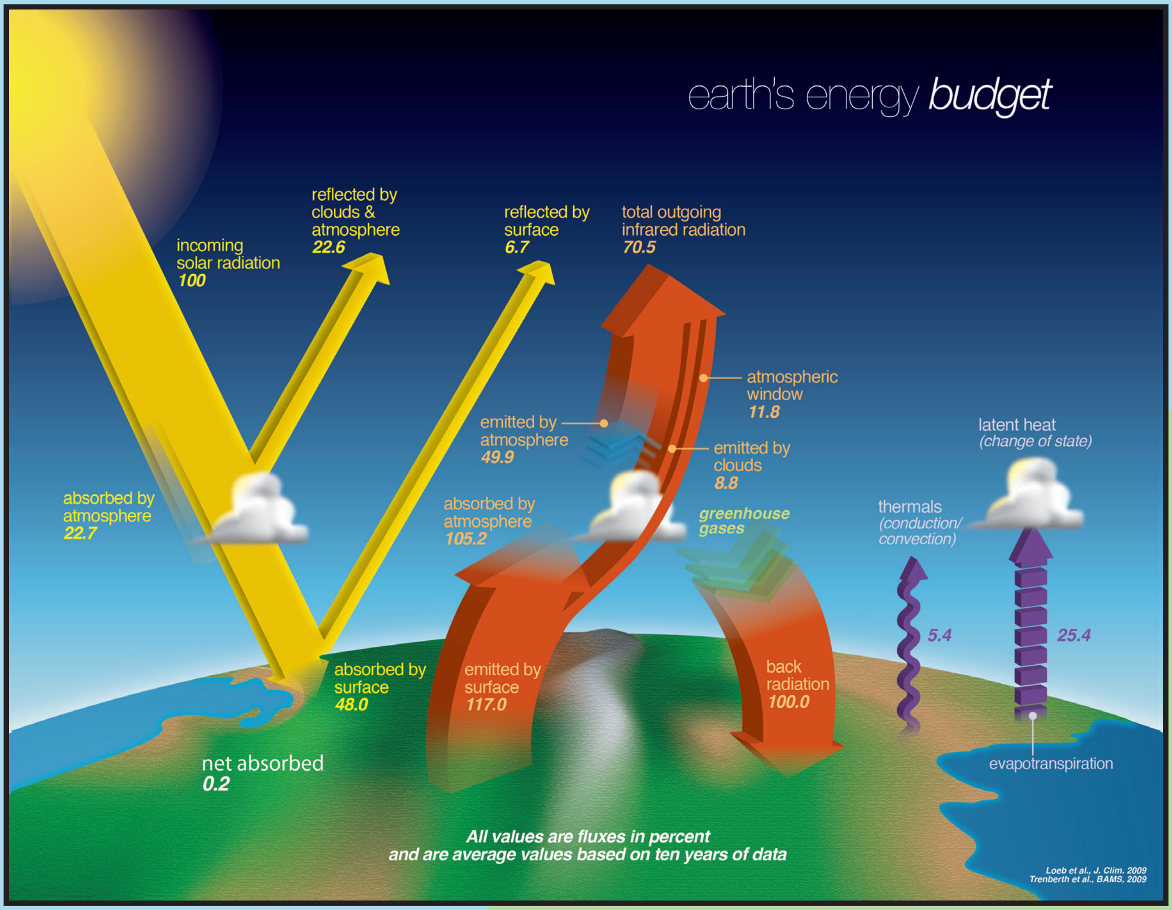
Sunlight In = Sunlight reflected from clouds/atmosphere + Sunlight reflected from surface + IR emission

At the Earth's surface, absorbed sunlight is balanced by the net IR emission and the conduction/convection and evapotranspiration. The equation is:

Sunlight absorbed + IR back radiation (greenhouse effect) = IR emission + Thermals + Evapotranspiration

The most complicated balance is in the atmosphere, where absorbed sunlight and energy absorbed from the surface are balanced by the net infrared emission. The equation is:

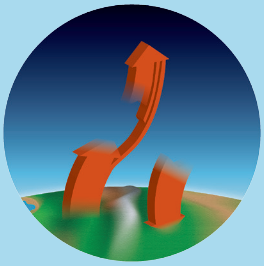
Sunlight absorbed + IR from surface + Thermals + Evapotrans = IR emitted to space + IR emitted to ground



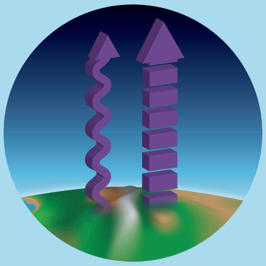
These balance equations are for an equilibrium state of the Earth. Equilibrium would be expected for a planet that has spent a long time in a stable solar system, but sometimes changes occur that take the system out of balance. For example, the ice ages occurred because of long-term changes in Earth's orbit around the Sun, which resulted in a change to the "Sunlight In" term. Over time, reflected sunlight and IR emission changed to balance the first equation. The result was a colder surface and major glacial advances.

The Story of Energy in the Earth *System*

- The Sun is the source of energy for the Earth system. This energy reaches the Earth primarily in the form of visible light, although it also includes some infrared energy (heat), ultraviolet energy, and other wavelengths of the electromagnetic spectrum. Taking into account night and day and the seasons, on average about 340 Watts of energy enter every square meter of the Earth system. This is slightly less than the energy that six 60 Watt light bulbs would produce, again, for every square meter of the Earth.
- As it reaches the Earth system, some of the sunlight is reflected back to space by clouds and the atmosphere (particularly dust particles or aerosols in the atmosphere). A little more sunlight is reflected to space from the Earth surface, particularly from bright regions such as snow- and ice-covered areas. In total, about 30% of sunlight is reflected directly back to space. This percentage is called the albedo.
- About 70% of the sunlight is absorbed by the Earth system (atmosphere and surface) and heats it up.



- The elements of the Earth system (surface, atmosphere, clouds) emit infrared radiation according to their temperature, following the Planck function (https://phet.colorado.edu/en/simulation/blackbody-spectrum). Cold objects emit less energy; warm objects emit more. This infrared radiation is emitted in all directions.
- One net effect of all the infrared emission is that an amount of heat energy equivalent to ~70% of the incoming sunlight leaves the Earth system and goes back into space. This is because the Earth system constantly tends toward equilibrium between the energy that reaches the Earth from the Sun and the energy that is emitted to space. Scientists refer to this process as Earth's "radiation budget.", and it happens because the system tends toward equilibrium.
- Another net effect of the infrared emission is that about 340 Watts of infrared energy is directed back to the surface from the atmosphere. This is called the greenhouse effect, and is due mainly to water vapor in the atmosphere. Carbon dioxide, methane and other infrared-absorbing gases enhance this effect. Without an atmosphere, the Earth would have an average temperature of -18 °C, too cold for life as we know it.



- At the surface, two additional heat transfer mechanisms operate to balance the system, in addition to the radiation transfer: 1) convection and conduction in the form of thermals (which create weather), and 2) a change of state of water through evapotranspiration (which also feeds weather).

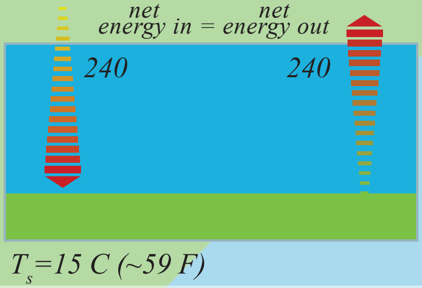
Bottom Line:

According to the best available data from the CERES satellite instrument, along with information from other data sources, the radiation budget at the top-of-atmosphere was not balanced during the 15 years from 2000-2015. Approximately 0.7 Watts of energy were added to the Earth system, on average, for each square meter of the Earth's surface. A continued imbalance of the radiation budget would mean a change in Earth's climate.

CO_2 *Forcing and Response*

Over long time scales, the Earth is in equilibrium with its space environment.

1: Starting Point



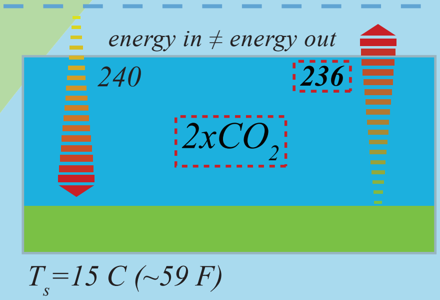
Earth at equilibrium with net energy input from the Sun.

(340 W/m^2 * (1 - albedo)) = 240 W/m^2

Average surface temperature 15 C (~59 F)

Earth's temperature has averaged 15 C (~59 F), with a balance of 240W/m^2 of energy being absorbed from the Sun; and 240 W/m^2 being emitted to space as heat energy.

2: The Experiment

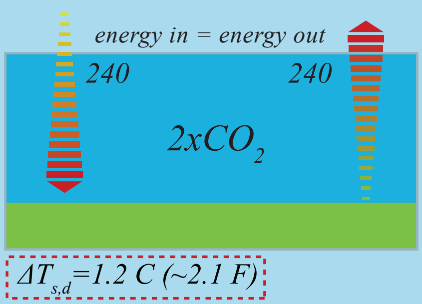


Instantaneously double CO_2 in concentration in atmosphere

Average energy emitted by Earth drops 4 W/m^2 (236 vs 240) because of additional energy absorption by CO_2

Using well understood physics, we can explore what happens if the concentration of carbon dioxide (CO_2) in the atmosphere doubles. Since CO_2 retains heat, the immediate effect is a small reduction in the amount of heat emitted to space – an imbalance.

3: Response

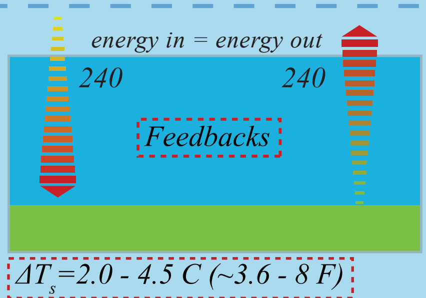


All other things being equal, simple physics theory says:
Average surface temperature rises 1.2 C (~2.1F)

Energy back in balance

To return to equilibrium, Earth's average surface temperature would increase by 1.2 C to 16.2 C (61.2 F) in order to emit more heat and return to balance with the Sun.

4: Feedbacks



In the Earth system, other processes kick in (water vapor feedback, cloud feedback, ice-albedo feedback, etc).

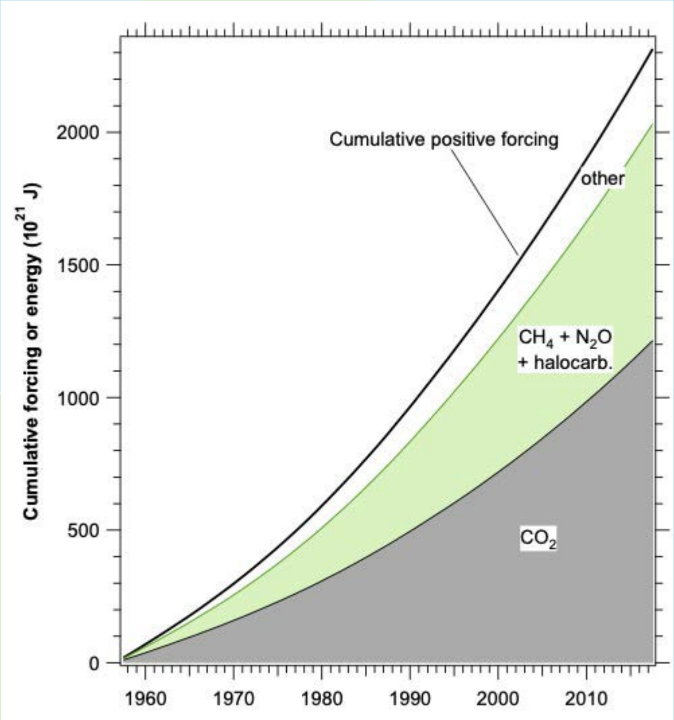
Net effect: Average surface temperature estimated to rise 2 - 4.5 C (~3.6 - 8 F)

However, the Earth is not quite that simple: rising temperatures have other effects, like increasing water vapor (a greenhouse gas) in the atmosphere, melting ice sheets (which reflect sunlight) and changing cloudiness. While not entirely understood, these feedbacks amplify the temperature rise to return to equilibrium. Scientists estimate the Earth's average temperature would actually rise between 2 and 4.5 C (3.5 and 8 F) before equilibrium was restored.

**Indicates a change has occurred*

Update: Energy Budget Changes Since *1950*

10 years after the Murphy et al., 2009 publication, researchers updated the analysis. They had to expand the vertical scale by 40%, but otherwise the graphs are qualitatively similar.



Items that have caused changes in the energy budget since 1950. Called forcing agents, these absorb additional energy in the atmosphere (enhanced greenhouse effect). The greenhouse gasses shown in the figure:

carbon dioxide – CO_2

methane – CH_4

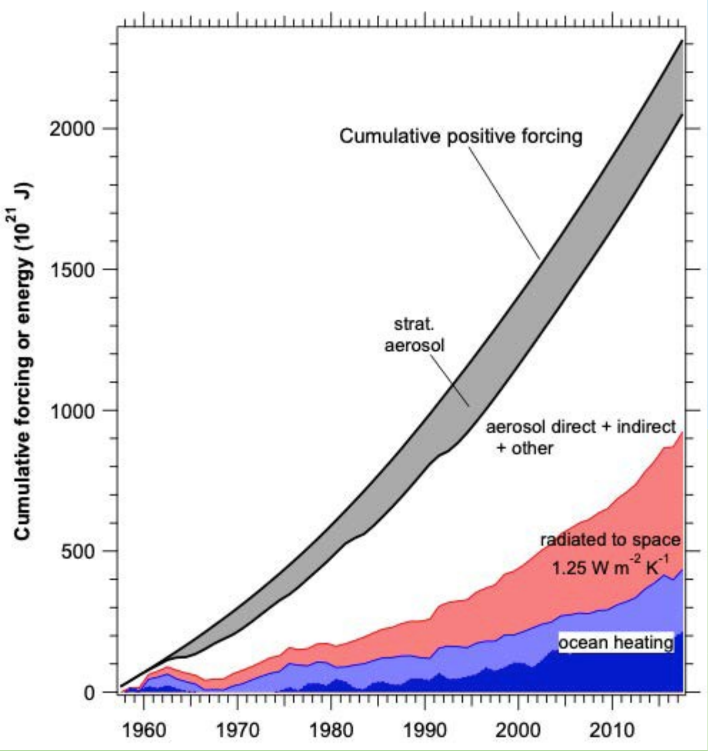
halocarbons,

nitrous oxide - N_2O

stratospheric + tropospheric ozone - O_3

have increased in the atmosphere mostly due to human activities. A natural change from variations in the Sun's output is no longer significant along the bottom of the graph. This figure shows the cumulative effect of small changes. The additional heat trapped each year continues to add up to a warmer Earth.

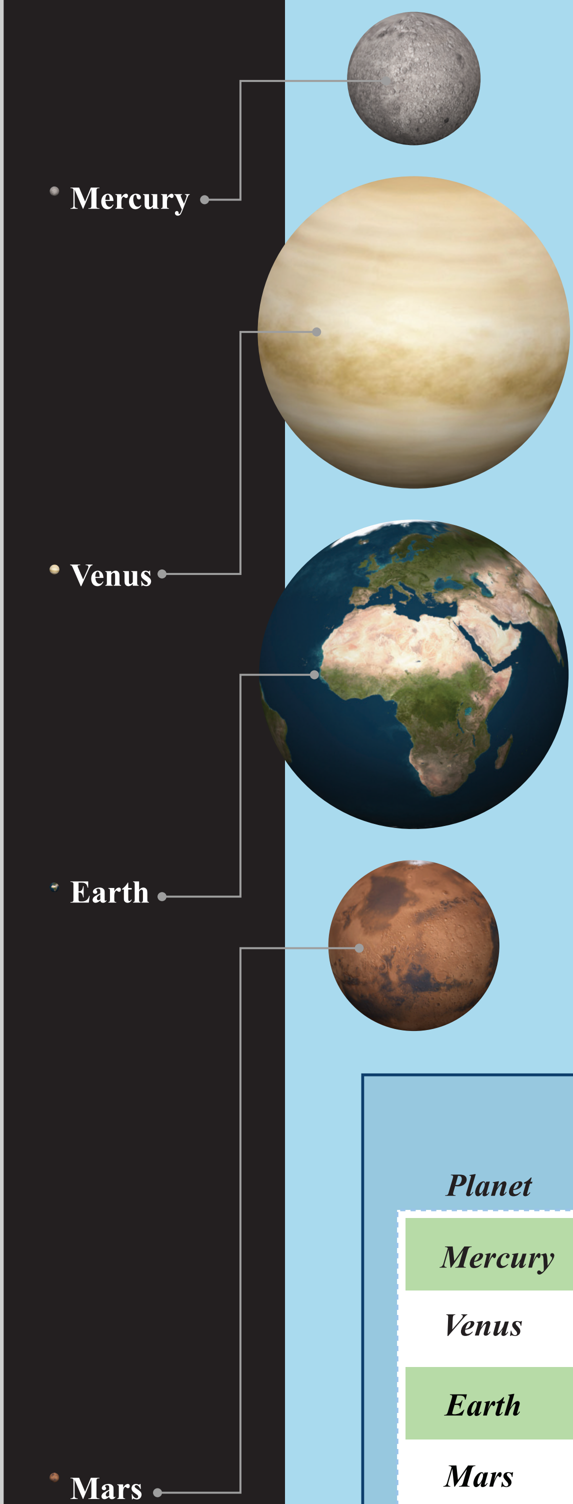
Knowing how much additional heat was absorbed (because we know how much of these gasses were emitted) the question becomes: where did the energy go? This figure partitions the added energy shown above based on observed changes in the Earth system. So far, a small amount of the energy has gone into warming the ocean, including the deep ocean – the part of the Earth that stores the most energy. Some has escaped Earth in the form of increased IR emission because of warmer temperatures. Some was reflected to space by aerosols (mostly volcanic in origin) in the stratosphere. The remainder (white band) is inferred to have been reflected due to aerosols (mostly pollution) in the troposphere, and other effects such as a changing reflection of the land surface due to deforestation, for example.



Figures from Murphy et al., 2019 personal communication

Our Natural Place *In the Big Picture*

The average temperature at the surface of a planet is controlled by several factors: distance from the Sun, gases in the atmosphere, and clouds.



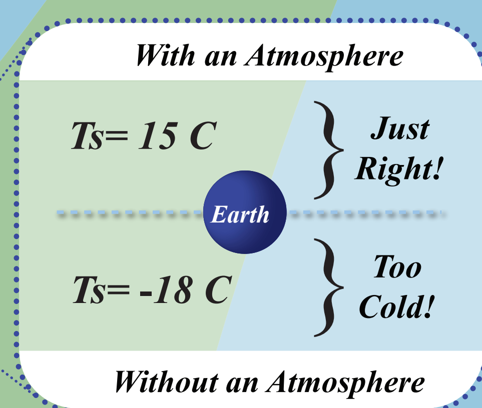
Mercury is closest to the Sun, and has no atmosphere or clouds. The surface of Mercury is very hot --- averaging 167 C (333 F) (oven temperature) but reaching temperatures of 427 C (800 F) during the day!

Venus, while farther from the Sun, is drastically hotter than Mercury because of its dense carbon dioxide atmosphere and overcast clouds, which retain heat.

What about **Earth**? Based only on its distance from the Sun, the Earth's average temperature would be -18 C (0 F) --- too cold for life as we know it. Even though clouds cool the surface, gases in Earth's atmosphere, through a process called the greenhouse effect, retain heat to increase the average surface temperature to 15 C (59 F) ---a comfortable temperature for life.

Mars, much farther from the Sun, has a very thin atmosphere and is quite cold.

Planet	*Distance from the Sun (Millions of km)*	*Average Surface Temp. (C)*
Mercury	*58*	*167*
Venus	*108*	*464*
Earth	*149*	
Mars	*228*	*-65*



*To scale by distance

*To scale by size

Energy Budget *Detectives*

Sorting all this out requires information on a lot of different things, and lots of different skills to bring it all together. Here are a few of the key players in creating this diagram.

Takmeng Wong
Research Physical Scientist

As a research physical scientist, Dr. Wong analyzes CERES satellite data to track and understand climate change. He works with teams of other researchers and computer programmers to seek answers to his scientific problems and achieve the research goals of his project. Takmeng explains that it isn't enough to just do your own research; reading people's scientific papers and news helps him to keep up with the latest scientific breakthroughs in his field. When Takmeng decided he wanted to become a scientist, he took a special academic path that lead him to his job at NASA today. He went to college and studied meteorology, and continued on to get his Ph.D in atmospheric sciences.

"We inspect nature to see how it is working, and find patterns that will help all of society."

Tim Marvel
Senior Graphic Designer

As part of the outreach team, Tim provides various graphic design and animation support for scientists at NASA. Each day is usually spent working on animations for space based missions, or on illustrations used in communicating science concepts. Tim has always been interested in film and animation, so he decided to get his Bachelor of Arts in Film Directing and 3D Animation, enabling him to work for several years in new media design before supporting NASA's missions.

Tim's job is valuable to the CERES team because he helps convey the CERES mission and the scientific data collected from it in a visual way that effectively communicates this information. Tim works closely with his coworkers, which consist of science writers and a Web programmer so that together, they can provide the necessary pieces that go into communicating science to the public.

Stacey Lee
Senior Project Planner

As a senior project planner, Stacey creates the CERES budget, tracks spending, and keeps an eye on what CERES was planning on spending versus what was actually spent. When scientists come up with new research ideas, Stacey creates "what-if" scenarios to see if CERES can afford those proposed ideas. Providing the financial constraints of a project allows the participants to make the most of their possibilities. Stacey has worked in finance for over 20 years, and it all began after she graduated from college with a degree in accounting. Stacey got a head start with a summer internship, and has worked for government contractors ever since.

"I work with a fantastic group of individuals who have one singular goal in mind– to make the world a better place," says Stacey. "The CERES group produces data that serves a worldwide scientific community. We all work hand-in-hand to produce the most accurate and useful data possible."

Vertley Hopson
Senior Computer Scientist

As a computer scientist, Vertley spends her time consulting with CERES supervisors, systems analysts and programmers to gather information about how and where they use the instrument's data. Once she understands their needs, she develops and runs codes for software to make sure the data product is high quality and meets everyone's needs. Vertley's job is especially important to CERES team members because this is the final step that ensures that people will be able see and use the valuable data.

Vertley has a bachelor of science in business and started work at NASA as an administrative assistant. As her knowledge, skills and abilities grew, she was able to become a computer scientist. Every day, Vertley uses her problem solving skills to make sure software is running smoothly and that scientists and the public have the data they need.

WORD *Match*

a. Thermals
b. Conduction
c. Convection
d. Evapotranspiration
e. Climate Forcing
f. Negative Forcing
g. Positive Forcing
h. Greenhouse Effect
i. Radiation Budget
j. Langley
k. Light
l. Mesosphere
m. Radiation
n. Reflection
o. Refraction
p. Exosphere
q. Stratosphere
r. Troposphere
s. Ultraviolet Radiation
t. Infrared
u. Cloud
v. CERES
w. Flux
x. Watt
y. Joule
z. Ozone

1._____ Shortwave electromagnetic waves having wavelengths between 0.1 and 0.4 micrometers; from the sun, it is significantly absorbed by the ozone layer in the stratosphere. It is harmful to plants and animals, including humans.
2._____ The redirection of light after entering a medium; in the atmosphere, solar rays are redirected by interactions with air, cloud and aerosol particles.
3._____ The Clouds and the Earth's Radiant Energy System is one of the scientific instruments developed for NASA's Earth Observing System (EOS) satellites.
4._____ The second layer of the atmosphere, which contains most of the ozone in Earth's atmosphere.
5._____ The lowest layer of the atmosphere extending from the surface to an altitude between 8 kilometers (at the poles) and 14 kilometers (in the tropics); most weather occurs in this layer.
6._____ Columns of rising air caused by uneven warming of the land's surface.
7._____ A standard unit of power.
8._____ The transfer of energy through a medium from molecule to molecule due to a gradient in temperature (or electric potential).
9._____ More outgoing energy or less incoming energy: results in cooling.
10._____ The rate of transfer of a fluid, particles or energy across a unit area. In the atmosphere, this can be air, a particular pollutant or aerosol, or light or heat energy (which has units of Watts per square meter).
11._____ Any change to the Earth's climate system that affects how much energy enters or leaves the system alters Earth's radiative equilibrium and can cause temperatures to rise or fall. http://earthobservatory.nasa.gov/Features/EnergyBalance/page7.php
12._____ The outermost layer of the Earth's atmosphere.
13._____ A molecule consisting of 3 oxygen atoms found primarily in the stratosphere. When it is created in the troposphere, it can be a harmful pollutant.

a. Thermals
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14._____ The combined energy transfer from evaporation of water from the surface and transpiration of water by plants growing on that surface.
15._____ Collections of water (in liquid or ice phase) in the atmosphere that are often classified by their shape and height.
16._____ The difference between absorbed and emitted radiation. See shortwave and longwave radiation.
17._____ A naturally occurring process that aids in heating the Earth's surface and atmosphere
18._____ The layer of the Earth's atmosphere between the stratosphere and the ionosphere.
19._____ Of or relating to invisible (to the human eye) radiation with wavelengths in the range from about 750 nanometers, just longer than red in the visible spectrum, to 1 millimeter, on the border of the microwave region.
20._____ A standard unit of energy (radiation) or work (mechanics). For energy, one of these is equal to one watt second.
21._____ More incoming energy or less outgoing energy: results in warming.
22._____ Is a form of electromagnetic radiation, with a wavelength that is visible to the human eye (about 400–750 nanometers).
23._____ The transfer of heat energy vertically through a medium through motion of matter. In the atmosphere, it may be seen visibly by cloud formation and thunderstorm development.
24._____ The return of sound or light back to its source. In the atmosphere, the process where incoming solar rays are redirected back upward after striking particles.
25._____ Energy that is emitted from a source in the form of rays or waves.
26._____ Named for Samuel P. Langley (1834-1906), a pioneering solar energy researcher at the Smithsonian Institution, this unit of radiant flux is one calorie per square centimeter (cal/cm2). http://rredc.nrel.gov/solar/glossary/gloss_l.html

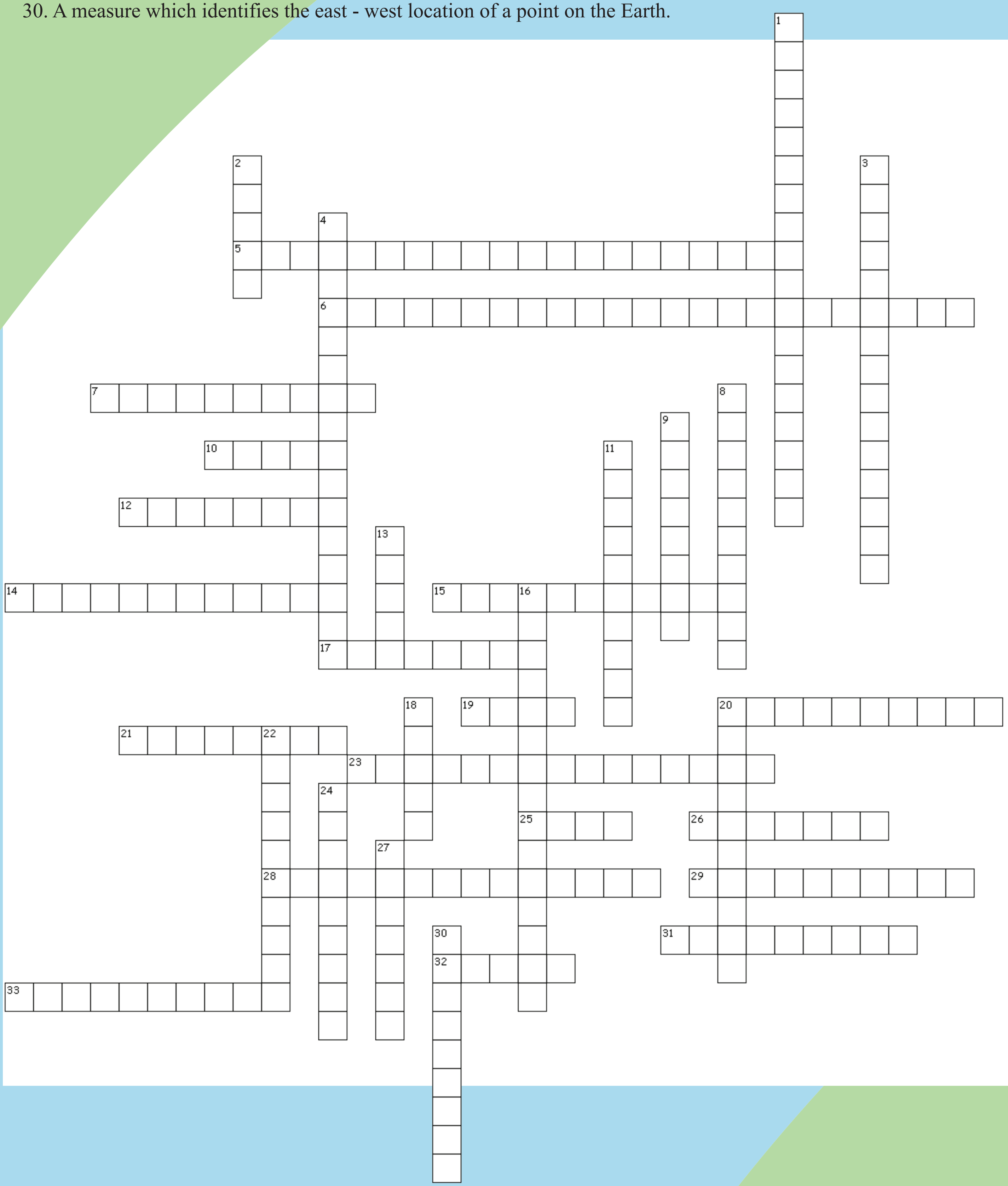
CROSSWORD *Vocabulary*

Across

5. Shortwave electromagnetic waves having wavelengths between 0.1 and 0.4 micrometers that is harmful to plants and animals, including humans.
6. The full range of frequencies, from radio waves to gamma rays.
7. The redirection of light after entering a medium; in the atmosphere, solar rays are redirected by interactions with air, cloud and aerosol particles.
10. The Clouds and the Earth's Radiant Energy System is one of the scientific instruments developed for NASA's Earth Observing System (EOS) satellites.
12. A measure which identifies the north - south location of a point on the Earth. It is the angle between the line connecting a point on the Earth and the Earth's center, and the equatorial plane of the Earth.
14. The second layer of the atmosphere, which contains most of the ozone in Earth's atmosphere.
15. The lowest layer of the atmosphere extending from the surface to an altitude between 8 kilometers (at the poles) and 14 kilometers (in the tropics); most weather occurs in this layer.
17. Columns of rising air caused by uneven warming of the land's surface.
19. A standard unit of power.
20. The transfer of energy through a medium from molecule to molecule due to a gradient in temperature (or electric potential).
21. The continuous distribution of energy in the form of electromagnetic waves, which are arranged in order of their frequencies or wavelengths.
23. More outgoing energy or less incoming energy: results in cooling.
25. The rate of transfer of a fluid, particles or energy across a unit area. In the atmosphere, this can be air, a particular pollutant or aerosol, or light or heat energy (which has units of Watts per square meter).
26. A solid particle suspended in the atmosphere. Volcanic eruptions, salt spray, dust storms and forest fires are natural sources of this.
28. Any change to the Earth's climate system that affects how much energy enters or leaves the system alters Earth's radiative equilibrium and can cause temperatures to rise or fall.
29. The mixture of gases that surrounds the Earth and some other planets. Biogeochemical processes, including human activities, determine the concentrations of the gaseous constituents of this.
32. A molecule consisting of 3 oxygen atoms found primarily in the stratosphere. When created in the troposphere, it can be a harmful pollutant.
33. An abbreviated term for incoming solar radiation.

Down

1. The combined energy transfer from evaporation of water from the surface and transpiration of water by plants growing on that surface.
2. Collections of water (in liquid or ice phase) in the atmosphere that are often classified by their shape and height.
3. The difference between absorbed and emitted radiation.
4. A naturally occurring process that aids in heating the Earth's surface and atmosphere
8. The layer of the Earth's atmosphere between the stratosphere and the ionosphere.
9. Of or relating to invisible (to the human eye) radiation with wavelengths in the range from about 750 nanometers, just longer than red in the visible spectrum, to 1 millimeter, on the border of the microwave region.
11. A process by which energy penetrates the inner structure of a material, causing that material to gain energy.
13. A standard unit of energy (radiation) or work (mechanics). For energy, it is equal to one watt second.
16. More incoming energy or less outgoing energy: results in warming.
18. Is a form of electromagnetic radiation, with a wavelength that is visible to the human eye (about 400–750 nanometers).
20. The transfer of heat energy vertically through a medium through motion of matter. In the atmosphere, it may be seen visibly by cloud formation and thunderstorm development.
22. The return of sound or light back to its source. In the atmosphere, the process where incoming solar rays are redirected back upward after striking particles.
24. Energy that is emitted from a source in the form of rays or waves.
27. Named for Samuel P. Langley (1834-1906), a pioneering solar energy researcher at the Smithsonian Institution, this unit of radiant flux is one calorie per square centimeter (cal/cm2).
30. A measure which identifies the east - west location of a point on the Earth.



Performance Expectation:

HS-PS3-1 **Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.**

HS-PS3-2. **Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative positions of particles (objects).**

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models • Develop and use a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-PS3-2) **Using Mathematics and Computational Thinking** • Create a computational model or simulation of a phenomenon, designed device, process, or system. (HS-PS3-1) **Constructing Explanations and Designing Solutions** • Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.	**PS3.A: Definitions of Energy** • Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. That there is a single quantity called energy is due to the fact that a system's total energy is conserved, even as, within the system, energy is continually transferred from one object to another and between its various possible forms. (HS-PS3-1),(HS-PS3-2) **PS3.B: Conservation of Energy and Energy Transfer** • Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. (HS-PS3-1) Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1) • The availability of energy limits what can occur in any system. (HS-PS3-1)	**Systems and System Models** • Models can be used to predict the behavior of a system, but these predictions have limited precision and reliability due to the assumptions and approximations inherent in models. (HS-PS3-1) **Energy and Matter** • Energy cannot be created or destroyed—only moves between one place and another place, between objects and/or fields, or between systems. (HS-PS3-2)

Performance Expectation:

MS-ESS3-5. **Ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century**

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking Questions and Defining Problems • Ask questions to identify and clarify evidence of an argument. (MS-ESS3-5)	**ESS3.D: Global Climate Change** • Human activities, such as the release of greenhouse gases from burning fossil fuels, are major factors in the current rise in Earth's mean surface temperature (global warming). Reducing the level of climate change and reducing human vulnerability to whatever climate changes do occur depend on the understanding of climate science, engineering capabilities, and other kinds of knowledge, such as understanding of human behavior and on applying that knowledge wisely in decisions and activities. (MS-ESS3-5)	**Stability and Change** • Stability might be disturbed either by sudden events or gradual changes that accumulate over time. (MS-ESS3-5)

Performace Expectation:

5-ESS2-1. **Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.**

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models • Develop a model using an example to describe a scientific principle. (5-ESS2-1)	**ESS2.A: Earth Materials and Systems** • Earth's major systems are the geosphere (solid and molten rock, soil, and sediments), the hydrosphere (water and ice), the atmosphere (air), and the biosphere (living things, including humans). These systems interact in multiple ways to affect Earth's surface materials and processes. The ocean supports a variety of ecosystems and organisms, shapes landforms, and influences climate. Winds and clouds in the atmosphere interact with the landforms to determine patterns of weather. (5-ESS2-1)	**Systems and System Models** • A system can be described in terms of its components and their interactions. (5-ESS2-1)

Using the Earth's Energy Budget to Implement the Next Generation Science Standards