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Energy Budget: Earth's most important and least appreciated planetary attribute

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Basking in the Sun on a warm day, it's easy for people to realize that most of the energy on Earth comes from the Sun; students know this as early as elementary school. We all know plants use this energy from the Sun for photosynthesis, and animals eat plants, creating a giant food web. Most people also understand the Sun's energy drives evaporation and thus powers the water cycle. But many people do not realize the Sun's energy itself is also part of an important interconnected system: Earth's energy budget or balance. This energy budget determines conditions on our planet — just like the energy budget of other planets determines conditions there.

Key Concepts

The energy budget involves more than one kind of energy. People can sense this energy in different ways, depending on what type of energy it is. We see visible light using our eyes. We feel infrared energy using our skin (such as around a campfire). We know some species of animals can see ultraviolet light and portions of the infrared spectrum. NASA satellites use instruments that can "see" different parts of the electromagnetic spectrum to observe various processes in the Earth system, including the energy budget.

The Sun is a very hot ball of plasma emitting large amounts of energy. By the time it reaches Earth, this energy amounts to about 340 Watts for every square meter of Earth on average. That's almost 6 60-Watt light bulbs for every square meter of Earth! With all of that energy shining down on the Earth, how does our planet maintain a comfortable balance that allows a complex ecosystem, including humans, to thrive? The key thing to remember is the Sun — hot though it is — is a tiny part of Earth's environment. The rest is cold, dark space. (See Figure 1.)

Comparing Planets

We know from astronomers and space missions the average surface temperature of the planet

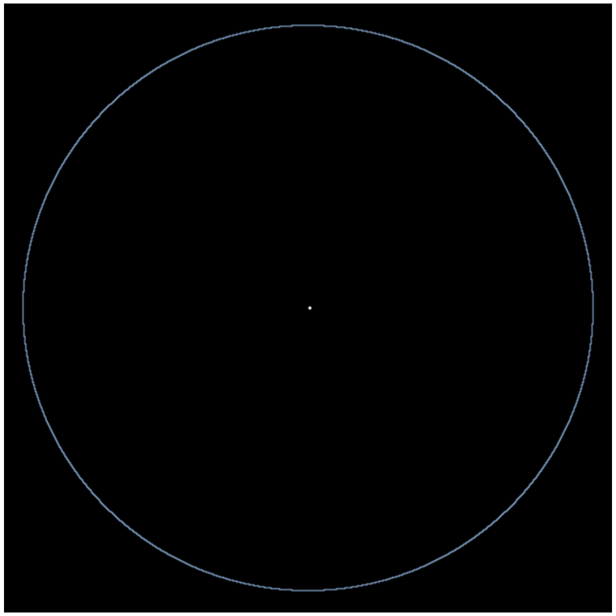

Figure 1. The orbit of the earth around the sun, with all sizes and locations to scale. The white dot near the center is the sun, and the blue line is the path of the earth through-out the year. The earth itself is not visible because at this scale it is only 0.02 pixels wide. The distance of the earth from the sun is more or less constant through-out the year. Image courtesy of Dr. Christopher Baird, University of Massachusetts Lowell.

Mercury is about 167 C (~332 F). It makes sense that Mercury, the closest planet to the Sun, is very hot; certainly too warm for life. We also know the average surface temperature on Mars is about -65 C (~-85 F). Again it makes sense that Mars, 1.5 times farther from the Sun than Earth, is colder and less hospitable. Things get more complicated, however, when we consider Venus. While nearly twice as far from the Sun as Mercury, the average temperature on Venus is considerably hotter: 464 C!

It is clear something other than just distance from the Sun must be important in determining average planetary temperature. Scientists have learned the high temperatures on Venus are due to its thick, carbon dioxide-rich atmosphere and its 100% cloud cover. These factors combine to retain energy within the atmosphere and increase the equilibrium surface temperature of the planet.

On Earth, a calculation as early as the 1820s (Fourier, 1824) indicated the surface temperature of the Earth was higher than expected solely on the basis of its distance from the Sun (-18 C or 0 F). This led to coining of the term "greenhouse effect," for the process by which gases and clouds in Earth's atmosphere increase the average surface temperature to a comfortable 15 C (~59 F).

Energy Budget History

The concept tying together our understanding of conditions on all these planets is termed the "energy budget." This balance between incoming and outgoing energy determines the equilibrium temperature of an object in space, because the object will heat up until the amount of energy it gives off is equal to the amount it is receiving.

For Earth, scientists have been working since the early 1900s to lay out a diagram summarizing the key elements of this budget and to quantify its various components. Hunt et al. (1986) summarizes work in this area prior to the satellite era. Beginning with the launch of Nimbus-7 in 1978, scientists began to study the energy budget from space. (See Figures 2 and 3.) In particular, a series of NASA instruments have been dedicated to understanding and monitoring the energy budget since the mid-1980s: the Earth Radiation Budget Experiment (ERBE; http://science.larc.nasa.gov/erbe/) and the Clouds and the Earth's Radiant Energy System (CERES; http://ceres.larc.nasa.gov/). Kiehl and Trenberth (1997) published an energy budget diagram that has become something of a standard. It uses data from satellites, ground-based instruments, aircraft field campaigns, and computer models to estimate the magnitude of each type of energy flow.

Connecting to the Standards

Ideas related to the energy budget appear in educational standards. For example, in Virginia the concept appears in 6th grade science and in high school

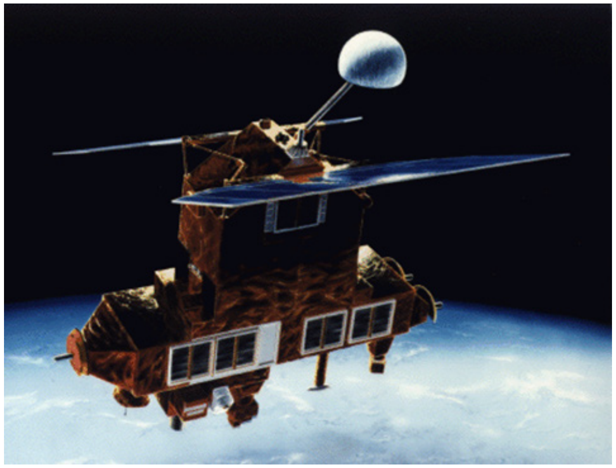

Figure 2. The Earth Radiation Budget Satellite (ERBS) was placed in orbit by the Space Shuttle Challenger in 1984. Image: NASA

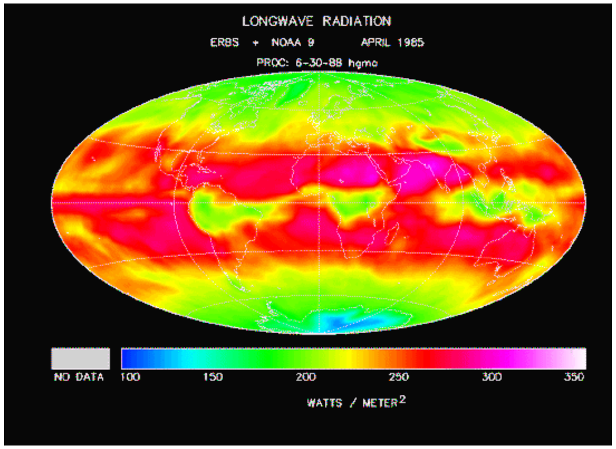

Figure 3. Image of data from ERBS showing long-wave radiation emitted by the Earth. Image: NASA

Earth science. Fragments of the concept, such as energy from the Sun, appear as early as 3rd grade. In the AAAS benchmarks (AAAS, 1993), pieces of the energy budget concept appears across a number of benchmarks in the section titled The Physical Setting, including high school benchmarks about The Earth (4B/H2, H4 and H6); a middle school benchmark on Processes that Shape the Earth (4C/M7); and primary, elementary, middle and high school benchmarks on Energy Transformations (4E/P1, 4E/E2c, 4E/M3 and M6, 4E/H1). In the National Science Education Standards, the topic appears under Transfer of Energy in the middle school Physical Science Standards, and under Energy in the Earth System in High School. In neither of these sets of national standards is the full picture of the entire energy budget process clearly laid out. As a result, few people have a clear grasp of this basic idea.

The energy budget and its component concepts were well-represented in the January 2013 draft of the Next Generation Science Standards (NGSS).

In the final standards (http://www.nextgenscience.org/) the concept is captured in Disciplinary Core Idea ESS2.D Weather and Climate, and in High School standard ESS2-4, with fragments of the concept appearing elsewhere.

The Story of Earth's Energy Budget

Based on 10 years of CERES data, we have created an updated version of the Kiehl and Trenberth (1997) diagram (see Figure 4). To further convey this important concept, we have also developed an energy budget storyboard (http://science-edu.larc.nasa.gov/energy_budget/pdf/EarthsEnergyBudget-Storyboard_031913_sm.pdf) that walks through the budget as follows:

- Energy enters the Earth system from the Sun.
- Some of the energy reflects off of clouds, dust, and other particles and never makes it to Earth's surface. Most of the energy, however, does get to the surface, and once it gets there, the ground, trees, and everything else around us can absorb the energy.
- However, there are some parts of Earth's surface that are highly reflective, like ice or snow, so in addition to absorbing energy, it also bounces off of parts of the surface and heads right back out into space.
- All of the energy the Earth absorbs doesn't just stay there and build up forever. The Earth system radiates this energy out towards space as heat. Cold objects emit less energy; warm objects emit more.
- Most of the heat emitted from the surface is stopped on its way back out. Clouds and certain gases in the atmosphere absorb the energy, preventing it from leaving the system. Only a small "window" allows direct escape.
- Energy emitted from those clouds and gases goes in all directions. Some comes back to further warm the Earth. This is the greenhouse effect.
- Finally, the surface energy budget is balanced by thermals and evaporation.
- Together all of these forms of incoming and outgoing energy have resulted in just the right living conditions for us on Earth.
- Like your house, anything that increases or decreases the amount of incoming or outgoing energy would disturb Earth's energy balance and would cause global temperatures to rise or fall.
- Over the last decade, our best estimate is there is a small positive imbalance – a warming - in Earth's energy budget.
- This observation is consistent with several other *lines of evidence* of a warming planet. See Figure 5.

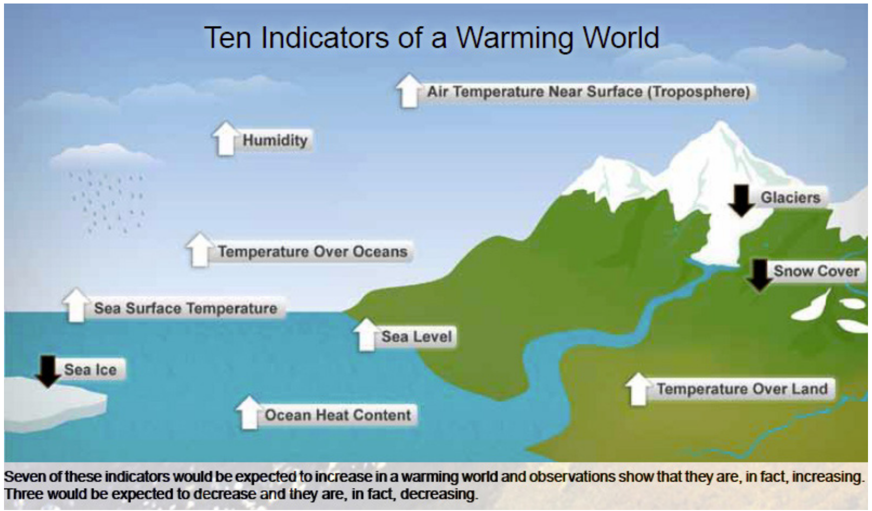

Figure 5. Additional evidence for a warming planet that are consistent with our best estimate of the Earth's energy budget in the last decade. Image: NOAA

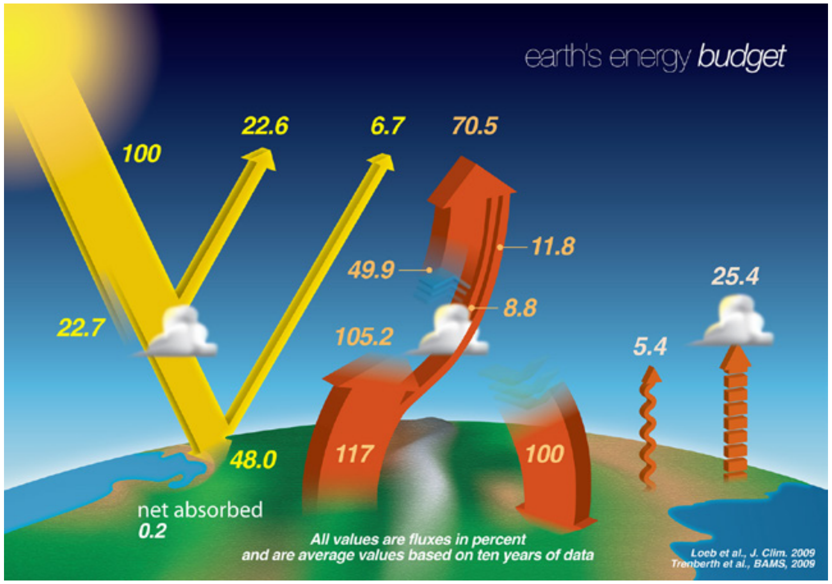

Figure 4. Best estimate of components of the Earth's energy budget, expressed as a percentage of the Sun's energy, based on 10 years of CERES data. Image: NASA

Lessons, Activities and Resources

The diagram in Figure 4 is an annual, global average conception of Earth's energy budget. In reality, the various energy fluxes are constantly changing, from day to night and from season to season. Data on energy budget parameters from the ERBE and CERES instruments are available on the MY NASA DATA website (http://mynasadata.larc.nasa.gov).

To guide exploration of these data, ten peer-reviewed lesson plans are available (http://mynasadata.larc.nasa.gov/lesson-plans/) using these parameters to explore a range of related ideas. A few of these lessons directly address the energy budget concept. These include:

1. Earth's Energy Budget — Seasonal Cycles in Net Radiative Flux
2. Variables Affecting Earth's Albedo
3. How Does the Earth's Energy Budget Relate to Polar Ice?

The rest make use of these parameters for other, sometimes creative, educational purposes:

1. Scientist Tracking Network (Student LAS Version)
2. Solar Cell Energy Availability From Around the Country
3. Correlation of Variables by Graphing
4. Is Portland, Oregon Experiencing Global Warming?
5. Think GREEN – Utilizing Renewable Solar Energy
6. Radiation Comparison Before and After 9-11
7. Phytoplankton in the Gulf of Maine

In addition to these lessons, these data parameters can be used for many other explorations of Earth's energy budget concepts.

For citizen scientists, the MY NASA DATA website also offers science project ideas (http://mynasadata.larc.nasa.gov/804-2/), several of which relate to the energy budget:

1. Measuring the Temperature of the Sky and Clouds
2. Measuring Sunlight
3. Measuring the Earth's Water Vapor Blanket

The NASA/CERES version of the energy budget diagram (Figure 4) is also available in a printable poster size version (http://science-edu.larc.nasa.gov/energy_budget/). This website also features a "Make your own" option for the reverse side of the poster. Six information packed pages were developed to fill the poster reverse, but two word activities and two supplemental pages are also currently available. This variety of information allows teachers the option to customize a poster to better meet the needs of their grade level; or to simply print one or more of the individual sheets for a variety of classroom uses. More supplemental sheets may be added later, as inspiration strikes.

Conclusions

Earth's energy budget is a critical but little understood aspect of our planetary home. NASA is actively studying this important Earth system feature, and sharing data and knowledge about it with the education community.

Featured Activity

How Does the Earth's Energy Budget Relate to Polar Ice?

References

AAAS, 1993: now available online at http://www.project2061.org/publications/bsl/

Fourier, J., 1824: "Remarques Générales Sur Les Températures Du Globe Terrestre Et Des Espaces Planétaires." *Annales de Chemie et de Physique* 27: 136-67.

Hunt, Garry E., Kandel, Robert, Mecherikunnel, Ann T., 1986: A history of presatellite investigations of the Earth's Radiation Budget, Rev. Geo., V. 24, pp. 351-356.

Kiehl, J. T. and K. E. Trenberth, 1997: Earth's Annual Global Mean Energy Budget, Bull. Amer. Meteor. Soc., V. 78, No. 2, pp. 197-208.

Resources for Further Investigation

The Global Climate Change page from NASA
http://climate.nasa.gov/

A lesson plan on The Earth's Energy Budget from the NOAA Ocean Service Education page
http://oceanservice.noaa.gov/education/lessons/earth_energy_budget_lesson.html

The Educational Resource page from the Earth Systems Research Laboratory at NOAA
http://www.esrl.noaa.gov/outreach/education.html

The Outreach and Education page of the Climate Program Office at NOAA
http://cpo.noaa.gov/OutreachandEducation.aspx

A Paleo-Perspective on Global Warming
http://www.ncdc.noaa.gov/paleo/globalwarming/
This website includes pages on the Instrumental Record of Past Global Temperatures, and Paleoclimatic Data throughout history

Earth's Energy Balance from the Climate Change Education page on the website of Stanford University and the School of Earth Sciences
https://pangea.stanford.edu/programs/outreach/climatechange/curriculum/earths-energy-balance-0