earth's energy *budget*

incoming
solar radiation
340.4

reflected by
clouds &
atmosphere
77.0

total reflected
solar radiation
99.9

reflected by
surface
22.9

total outgoing
infrared radiation
239.9

atmospheric
window
40.1

emitted by
atmosphere
169.9

emitted by
clouds
29.9

absorbed by
atmosphere
77.1

absorbed by
atmosphere
358.2

greenhouse gases

latent heat
(change of state)

thermals
*(conduction/
convection)*

18.4

86.4

absorbed by
surface
163.3

emitted by
surface
398.2

back
radiation
340.3

evapotranspiration

net absorbed
0.6

***All values are fluxes in Wm^{-2}
and are average values based on ten years of data***

Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009

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 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 (explore at: http://phet.colorado.edu/simulations/sims.php?sim=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 (~50%) to water vapor in the atmosphere. Clouds (25%), carbon dioxide (20%), methane and other infrared-absorbing gases (5%) 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 ten years from 2000-2010. Approximately 0.6 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.

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:

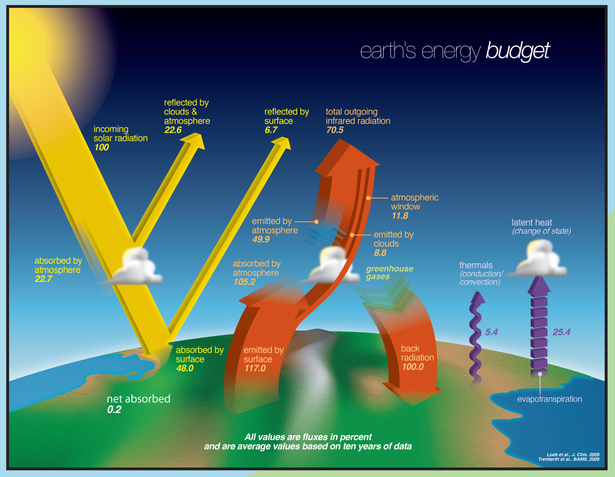
Sunlight In = Sunlight reflected from clouds/atmosphere + Sunlight reflected from surface + IR emission

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 absorbed + Thermals + Evapotranspiration = 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.
(Explore: http://cleanetet.org/resources/43016.html)

Energy Budget Changes Since *1950*

In more recent years, changes in the atmosphere have also caused unbalance in these equations, with another departure from equilibrium. At least part of these changes is due to human activities.

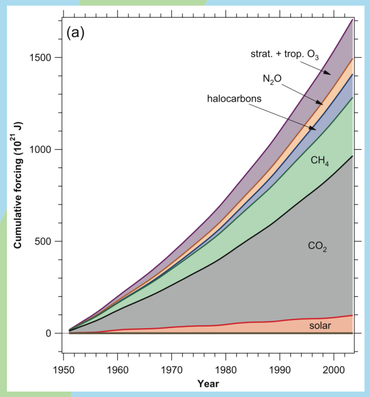
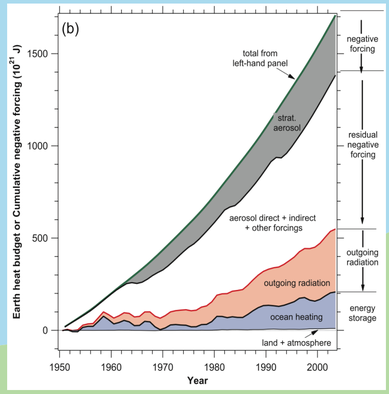


Figure (a) depicts items that have caused changes in the energy budget since 1950. Called forcing agents, these absorb additional energy in the atmosphere (enhanced greenhouse effect). The greenhouse gasses shown in the figure:

- 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 also shown 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? Figure (b) 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 – 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., 2009 in Geophysical Research Letters

Seasonal Cycles in Net Radiative *Flux*

Purpose:
To use CERES radiation data to understand seasonal variations in the pattern of net energy input to the Earth system.

Grade Level:
6, 9 - 12

Estimated Time for Completing Activity:
One 50-minute class period

Learning Outcomes:
- Understanding how Earth's tilt causes seasonal differences in incoming solar energy
- Using the Live Access Server to investigate the Earth's radiation budget
- Locating map locations using latitude and longitude coordinates
- Understanding how features of the Earth system, such as clouds and deserts, modulate the reflection of energy from the Sun

Prerequisite:
- Familiarity with accessing websites on the Internet
- Familiarity with locating given geographical locations using latitude and longitude and a world map
- Prior lesson about seasons and Earth's tilt

Vocabulary:
Flux, Latitude, Longitude, Radiation

Lesson Links:
- Animation of Earth Net Radiative Flux as Observed by the CERES Instrument
  http://mynasadata.larc.nasa.gov/images/mnet.avi
- http://mynasadata.larc.nasa.gov/images/Seasonal_Net_01.JPG (Dec 2003)
- http://mynasadata.larc.nasa.gov/images/Seasonal_Net_02.JPG (March 2004)
- http://mynasadata.larc.nasa.gov/images/Seasonal_Net_03.JPG (June 2004)

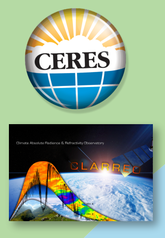
Background:
The net amount of energy received by different parts of the Earth at different times of year determines the type of weather and climate they will experience. The net radiative flux shows the combined effect of the Sun's location and the conditions in the Earth system. The two primary components of the Earth system that affect the net radiative flux are: 1) the type of surface and 2) clouds. This lesson will allow students to explore these variations.

Procedure:
1. Open the image of Monthly Top-of-Atmosphere All-sky Net Flux for December 2003.(see Links section) Discuss whether the patterns you observe are consistent with your prior knowledge about seasons and Earth's tilt. Based on this, write down a prediction of how the pattern would be different in March.
2. Open the image of Monthly Top-of-Atmosphere All-sky Net Flux for March 2004. (see Links section) Does the pattern in this image fit your prediction? If not, revisit your earlier discussions and write down a prediction for the pattern in June.
3. Open the image of Monthly Top-of-Atmosphere All-sky Net Flux for June 2004. (see Links section) Does this pattern agree with your prediction?
4. Open the animation of Earth's net radiative flux (see Links section) as observed by the CERES instrument during March 2000 through Feb 2001. The file is a Windows Media clip. Observe the seasonal shifts in the net energy received by the Earth. Does the annual cycle agree with your previous understanding and predictions?

Questions:
1. Looking back at the images for December, March and June, write down two locations where you think the surface has a noticeable impact on the pattern of net radiative flux, and two locations where you think clouds have a noticeable impact.
2. Open the images for Clear-sky Net Flux (Note - these images are created by taking only the satellite observations during the month when an area is cloud-free. White areas denote areas of persistent cloud cover where no clear-sky information could be obtained.). Compare these images to the All-sky images and, for the four locations you selected in question 1, discuss whether your prediction was correct. Support your arguments by comparing the patterns in the All-sky versus Clear-sky image.

For the complete lesson go to :
http://mynasadata.larc.nasa.gov/preview_lesson.php?&passid=44

The Earth's Energy *Budget*



The energy budget diagram on the front shows our best understanding of energy flows into and away from the Earth. It is based on the work of many scientists over more than 100 years, with the most recent measurements from the Clouds and the Earth's Radiant Energy System (CERES; http://science.larc.nasa.gov/ceres/) satellite instrument providing high accuracy data of the radiation components (reflected solar and emitted infrared radiation fluxes).

This energy balance determines the climate of the Earth.
Our understanding of these energy flows will continue to evolve as scientists obtain a longer and longer record using new and better instruments (http://clarreo.larc.nasa.gov/).

Did you know?

Units:

Energy fluxes are measured as Watts per square meter.
Watt: a standard unit of power.
Joule: a standard unit of energy
1 Watt = 1 Joule / sec



Standards

National Science Education Standards - http://www.nap.edu/html/nses/
Content Standard D: Earth and Space Science: Energy in the earth system
Content Standard F: Science in Personal and Social Perspectives: Science and technology in local, national, and global challenges

National Council of Teachers of Mathematics Standards (grades 9-12) – http://standards.nctm.org/
Number and Operations: Understand numbers, ways of representing numbers…
Measurement: Understand measurable attributes of objects and the units, systems, …
Data Analysis and Probability: Develop and evaluate inferences and predictions …
Connections: Recognize and apply mathematics in contexts outside of mathematics.
Representation: Use representations to model and interpret physical…

AAAS Benchmarks (grades 9-12) - http://www.project2061.org/publications/bsl/online/
The Physical Setting: Weather and Climate
Transfer of thermal energy between the atmosphere and the land or … 4B/H2
Greenhouse gases in the atmosphere... 4B/H4
Climatic conditions result from … 4B/H5
The earth's climates have changed in the past, are currently changing, and are expected to change in the future… 4B/H6

Climate Literacy Framework Principles - http://climateliteracynow.org/
Principle 3: The Sun is the primary source of energy for the climate system.
Principle 4: Earth's weather and climate systems are the result of complex interactions.
Principle 6: Evidence indicates human activities re impacting the climate

You can find more information, resources, and activities on this concept at:
http://science-edu.larc.nasa.gov/energy_budget

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. More are highlighted on the web page.



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."



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."



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.



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.