Global Distributions of Heat and Temperature

Objectives

- Demonstrate understanding of the concept of Earth’s heat budget
- Demonstrate understanding of the processes that affect temperature distributions: solar radiation, black-body radiation, surface properties (e.g., albedo, absorption), location (e.g., latitude), and heat transfer processes (radiation, convection, and conduction)

What would the distribution of temperature on Earth be if the planet were a homogeneous ball of rock without fluids (i.e., no oceans or atmosphere)? (Draw a cartoon)

*Incoming solar radiation*

The source of heat energy for Earth’s atmosphere is the sun. Total energy received from the sun per unit time is \(\pi R^2 S\), where \(R\) is the Earth’s radius and \(S\) is the solar constant (the annual average radiative solar flux at the top of the atmosphere) and is equal to 1368 Wm\(^{-2}\). \(S\) is referred to as a constant because it has not changed by more than a few percent over the last few hundred years (*note that \(S\) has varied over longer time scales*). The factor \(\pi R^2\) denotes the Earth cross-sectional area.

Over the entire Earth’s surface area (\(4\pi R^2\)), the average amount of energy received per unit area (m\(^2\)) per unit time (s) is \(S/4 = 344\) Wm\(^{-2}\), since the Earth’s surface area is four times its cross sectional area.

The energy flux (the rate of transfer of energy across a unit area) reaching the Earth’s surface at a given location depends on the angle of illumination and is proportional to the cosine of the sun angle relative to the local vertical at a given latitude (that is when the sun is at zenith at the equator, at 60 degrees North or South only half the flux arrives, as \([\cos(60) = 0.5]\). If the Earth was a homogeneous ball of rock and its axis was perpendicular to the plane of orbit around the sun (and the direction of incoming solar radiation), radiation would have been maximal at the equator and minimal at the poles. Earth, however, tilts with respect to its plane of orbit around the sun and the angle of incidence of solar radiation received at its surface changes with month of the year, resulting in seasonal variations in the input radiative energy flux.

*Class demonstration: energy flux as a function of latitude (for this demonstration you will need an inflatable globe and a flashlight)*

1. Place a flashlight or a laser pointer at a given distance from the globe and shine it directly on the equator. Then, slowly move the globe down (keeping
approximately the same distance from the light source) until the region near the pole is illuminated.

2. Where is the amount of radiative flux per unit area the largest (i.e., where is the area illuminated by the laser smallest)?

**WorldWatcher Activity:**
(Download the program (free) from: http://www.worldwatcher.northwestern.edu/softwareWW.htm)

I. Annual average of incoming solar radiation
- Click on the “energy balance” icon
- Select “incoming solar energy”
- Select average data sets and highlight all the months in the year 1987
- Click OK
What is the average energy received per unit area?
How does it vary with latitude? Why?

II. Seasonal variations of incoming solar radiation
- Select “incoming solar energy”
- Select “open data sets”
- Select incoming solar radiation for December 1987 and click open
- Select incoming solar radiation for June 1987 and click open
Explain the differences you observe between the two maps.

III. Create a movie of the seasonal variability in incoming solar radiation:
- Select “incoming solar energy”
- Select “make movie from data sets”
- Highlight the months in 1987 and drag them to the box of chosen data sets
- Click animate

What is the fate of the solar energy impinging on the earth?

**WorldWatcher Activity: Absorbed solar energy**

Click on the “Absorbed solar energy” icon
- Select average data sets and highlight all the months in the year 1987
- Click OK

Compare the map of “absorbed solar energy” to the map of “incoming solar energy” created in the previous step.
What do the differences tell you? Make sure both maps are on the same scale [Check the user’s guide (in the help menu) for instructions on how to adjust data range (Colorscheme)]
Reflectivity
Not all the energy reaching the Earth’s surface is absorbed; part of it is reflected back. This is quantified by the ratio of outgoing to incoming short wavelength radiation and is termed albedo (α). Albedo has no units because it is defined as the fraction of the impinging radiation that is reflected. Albedo depends on the color and structure of the surface interacting with the incoming solar radiation and the angle of incoming radiation. The Earth’s albedo has an average value of 0.3 (that is, 30% of the incoming radiation is reflected back). Below are some values for the reflectance of different substrates.

- Snow ~80-90%
- Desert sand ~35%
- Vegetation ~10-25%
- Bare soil or rock ~10-20%
- Asphalt ~5-10%

What do you think would be an average value of albedo for the ocean? (broad-band ~ 20% - 30%)

WorldWatcher Activity: reflectivity (albedo)
- How do you expect reflectivity to change with latitude? Why?
- Where would you expect lower than average values? Why?
- Where would you expect higher than average values? Why?
- Do you expect to see variations between seasons? Why?

- Click on the “Reflected solar energy” icon
- Select average data sets and highlight all the months in the year 1987
- Click OK

Do the data agree with your predictions?

Obtain the mean value for the reflected solar energy, and the mean values for the incoming solar energy and the absorbed solar energy (previous maps).

Does the energy budget balance?

It follows that the average amount of solar energy absorbed by the Earth, per unit area per unit time is: \( \frac{1}{4}(1-\alpha)S = 240 \text{ Wm}^{-2} \). Note that in the analysis of heat budget of Earth we neglect heat emanating from the interior of the Earth as it accounts for less than 0.2% of the heat provided by the sun.

Upward radiation from Earth
Every body radiates out energy based on its temperature (referred to as a “black body” radiation). Incoming solar radiation (energy) absorbed by the Earth’s surface causes it to
warm up and radiate energy. An equilibrium temperature is reached (i.e., temperature is no longer rising) when the incoming radiation equals the outgoing radiation (the warmer a body is the more energy it emits as black body radiation). Earth emits radiation at longer wavelengths (infrared spectrum) compared to the wavelengths of incoming solar radiation (most is in the visible, UV and shorter infrared wavelengths; Figure 1). To compute the emission from the Earth’s surface we use the formula for black body radiation: 
\[ E = \sigma T^4 \]
where \( \sigma \) is the Stephan’s-Boltzmann constant \( \sigma = 5.7 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \) (0K = -273°C). The temperature at equilibrium between incoming solar energy and outgoing black body radiation can be calculated by equating incoming and outgoing energy:
\[ \sigma T^4 = \frac{1}{4}(1-\alpha)S = 240 \text{Wm}^{-2} \]

**Figure 1**: Radiative flux as a function of wavelength for the sun and Earth. Note the differences in the quantity and quality (wavelength) of the radiative flux between the sun and Earth.
Source:http://www.ldeo.columbia.edu/~kushnir/MPAENVP/Climate/lectures/energy/blackbody.gif
WorldWatcher Activity: Earth’s surface temperature based on black body radiation

I. Click on the “Absorbed solar energy” icon
- Select average data sets and highlight all the months in the year 1987- Click OK
- Calculate the mean annual temperature (based on absorbed energy; K= -273°F, to convert from °C to °F: 1.8*°C+32)

II. Create a surface temperature map from absorbed solar energy data
- Select analysis
- Select window math operation
- Under math operation: choose convert to temperature
- Click OK

II. Create a map from surface temperature data
- Click on the “earth’s surface temperature” icon
- Select average data sets and highlight all the months in the year 1987
- Click OK

Compare the two maps (make sure the data have the same units and same scale).

Why is the Earth’s surface much warmer and the differences between the equator and poles smaller, compared to your calculations in I and II?

Simple calculations of the greenhouse effect:

Now let’s add the atmosphere. The atmosphere is transparent to incoming radiation at short wavelength’s (UV and visible light) but partially absorbs at longer wavelength (infrared, i.e., energy radiated from earth).

As downward flux of solar radiation is absorbed by the ground (at short wavelengths), the ground warms up and emits an upward radiation flux at longer wavelength. Similarly to the downward flux, the upward emitted flux (U) equals:

\[ U = \sigma T^4 \]

A fraction \( (1 \geq e \geq 0) \) of this radiated energy is absorbed by the atmosphere and the atmosphere heats up and also emits radiation, but at longer wavelengths (the greenhouse
effect, Figure 2), which we denote as 2B (a flux B upwards and a flux B downwards back to the Earth).

From the principle of conservation of energy, the upward flux must balance the downward flux of incoming solar radiation (Gill 1982):

\[ I = (1-e)U + B = U - B \]  

(radiative equilibrium solution)

\[ \Rightarrow U = \sigma T^4 = I/(1-e/2) \]

Since \( 1 \geq e \geq 0 \) (it is a fraction of a whole), T is higher than if there was no atmosphere (the case where \( e = 0 \)).

\[ \text{Figure 2: the greenhouse effect.} \]
\[ \text{Source: http://star.arm.ac.uk/climate/images/greenhouse.gif} \]

Note: the term ‘greenhouse effect is actually not accurate to describe the way the atmosphere acts. Greenhouses are warmer because the glass suppresses heat transfer by advection and convection. If you open the doors/windows of a greenhouse you will lose most of the heat in the greenhouse.
World watcher Activity:

I. the green house effect

Use the WorldWatcher tool to plot the mean annual greenhouse - effect (click on greenhouse effect, select average data sets, select all the months for the year 1987 and click “OK”) Is this effect uniform? Why or why not?

II. Closing the budget

Compare values of the mean annual incoming solar energy to the mean annual reflected solar energy (short wavelengths) + the mean annual space bound energy (longer wavelengths). Does the budget balance?

In reality, calculations of fluxes involve many wavebands and the absorption of each band is calculated separately. Also, such models must take into account reflection and scattering by clouds (which depends on distributions and albedo of clouds).

Heat transfer by the atmosphere and oceans (conduction, convection, and horizontal transport)

Until now our treatment of the heat budget did not take into account fluid motion.

How is the heat balance affected by fluid motion?

Heat can be transported by conduction, that is, by adjacent molecules passing vibrational energy to each other, and by convection and advection, that is by fluid motion. [Note that in oceanography advection relates to horizontal flow (e.g., the Gulf Stream) while convection involves vertical flows (e.g., deep water formation in Antarctica and near Iceland)]. The contribution of conduction to heat transport is relatively small in the total heat budget and convection is the dominant mechanism of vertical heat fluxes (i.e., in the atmosphere, in the oceans, and between oceans and atmosphere). Convection carries up the atmospheric heat and water vapor that is produced by evaporation. In fact, evaporation is the main mechanism by which oceans lose heat. Water vapor affects heat balance in several ways:

1. When the amount of water vapor reaches a saturation level (function of temperature and pressure, that is height), it condenses and forms clouds. Clouds reflect and scatter a significant amount of incoming radiation and thus affect the total amount of energy absorbed by the atmosphere.
2. Water vapor absorbs a fraction of the incoming solar radiation and thus determines the temperature at the lower atmosphere.
3. Cloud formation results in the release of latent heat at the cloud height. This latent heat was taken from the ocean during evaporation and this path of heat transfer accounts for about 75% of the convective transport.

Final equilibrium therefore depends on the BALANCE between radiative and convective processes (Figure 3).
Figure 3: Radiative and convective processes that determine global distributions of heat and temperature
Source: http://eosweb.larc.nasa.gov/EDDOCS/images/Erb/components2.gif

What would the global distributions of surface isotherms be in the absence of horizontal transport?
Go to http://www.osdpd.noaa.gov/PSB/EPS/SST/sst_anal_fields.html. Click on the 50 KM global analysis climatology (for an additional map see http://www.abc.net.au/science/slab/elnino/img/gsst.gif). Are isotherms distributed according to your prediction? Where do they match your prediction and where do they not match? What are some of the processes responsible for the observed deviations?

The radiative-convective model we discussed so far considers only vertical gradients in temperature and vertical motion of fluids (air and water). Latitudinal variation in solar energy flux and radiative absorption result in large horizontal gradients in temperature (Figure 4). Lateral fluid motion tends to reduce these gradients (horizontal fluid motions are sometimes termed advection to separate them from vertical motions).
**Figure 4:** Balance between average net shortwave (solar radiation) and longwave (radiation emitted from Earth) radiation from 90° North to 90° South (Source: http://www.physicalgeography.net/fundamentals/7j.html)

The overall contributions of oceans and atmosphere to meridional heat transport are similar, but the oceans dominate the horizontal transport at 20°N while atmospheric processes dominate transport at approximately 50°N (Figure 5).

**Figure 5:** Source:http://www.seafriends.org.nz/oceano/ocean48.gif
In the absence of meridional transport, ocean surface temperature will gradually decrease with increasing latitude and isotherms would be horizontal lines parallel to the lines of latitude. The pattern of isotherms indeed shows the generalized latitudinal distribution of solar radiation, but variations from horizontal lines, parallel to latitude lines, are also apparent. Several processes contribute to the observed deviations. For example, a band of relatively colder water lies along the equator on the eastern side of the Pacific and Atlantic Oceans. This band is a surface water divergence where deep, cold water is upwelled to the surface. In mid latitudes, isotherms are inclined toward higher latitudes at the west side of ocean basins. This is a result of warm surface ocean currents (western boundary currents) that transport water and heat poleward. Due to the Coriolis, western boundary currents move into the oceanic interior at the boundary between the subtropical and subpolar gyres. As the current moves east it spreads and cools. So the warmest water at these latitudes tends to be toward the west of the ocean basin. Interactions between land, ocean, and atmosphere also contribute to the deviation from horizontal parallel isotherm lines. Land masses block or stir air and water masses that move along latitudes. Land masses have different thermal properties than oceans because soil and rocks have a lower heat capacity than water. As a result, land warms up and cools down much faster in response to solar radiation, compared to oceans.