

Chapter 4

Earth's Energy Budget

Abstract Earth's energy imbalance is the difference between the amount of solar energy absorbed by the Earth and the amount of energy it radiates to space as heat. If the imbalance is positive, more energy coming in than going out, we can expect Earth to become warmer. If the imbalance is negative, then more energy is going out than is being received and the Earth will cool. Earth's energy imbalance is the single most crucial measure of the status of Earth's climate and it defines expectations for future climate change. The Earth's energy budget is explained in this chapter and the fact that Earth retains more of the electromagnetic radiation incident upon it from the Sun than it radiates back to space. The solar constant and aspects of solar electromagnetic radiation and the electromagnetic spectrum are discussed and illustrated. A distinction between weather and climate is made. Calculations of Earth's temperature with and without an atmosphere are completed. Earth's radiation laws are defined. The outgoing spectral radiance at the top of Earth's atmosphere and the absorption at specific frequencies by greenhouse gases are illustrated.

Keywords World Meteorological Organization • Energy • Radiance • Irradiance • Insolation • Photons • Electromagnetic • Spectrum • Kelvin • Heat • Solar constant • Planck • Wien • Nimbus 7 • Stefan-Boltzmann • TOA • Sunspots • UV • IR • Blackbody • Sunspots

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
The Difference Between Weather and Climate	WMO
TOA	ERM
Photons	6,000 Kelvin
Electromagnetic Radiation	UV
IR	Electromagnetic Spectrum
7,000 ångströms	Heat Energy
Blackbody	Speed of Light
6,000 Kelvin	Irradiance
-19°C	10 ⁻¹² Meter
Insolation	Solar Constant
Visible Light	GSFC
Sunspot Cycles	Wien's Displacement Law
Stefan-Boltzmann Law	ERBS
The Inverse Square Law	1,368 W/m ²
93 Million Miles	Nimbus 7
Indicators of Global Warming	Planck's Law

4.1 Introduction

Climate change science is complex and involves many disciplines. One doesn't need to be an expert in all of them but one does need at least an introductory knowledge and an appreciation of them all. An overview of climate change science includes each of the following:

- Physics of the atmosphere;
- Chemistry of the atmosphere;
- Duration of climatic events;
- The difference between climate and weather;
- Warming of the lower atmosphere (troposphere) and cooling of the upper atmosphere (stratosphere);
- Warming of the World Ocean;
- Warming of the land;
- Melting of sea ice, permafrost, and glaciers;
- Rising concentrations of greenhouse gases in the atmosphere;
- Oceans becoming more acid (acidification);
- Disruption of Earth's weather patterns;
- Animals and plants migrating to higher latitudes and altitudes;
- Rising sea level;
- Diminishing water supplies for millions depending on fresh water from glaciers;
- Encroachment of sea water into fresh water supplies along coastal areas of the world;
- Higher rates of evaporation on land and sea;
- Higher rates of species extinctions;

- Disruption of natural patterns of agricultural growing seasons;
- Disruption of pollination of plants;
- Greater spread of tropical and subtropical diseases;
- Nights warming faster than days;
- Increasing humidity;
- Spring coming earlier and fall later;
- Climate Sensitivity.

All of these topics and more are addressed in the following sections and chapters of this text.

4.2 Weather and Climate

Everyone knows that the climate is always changing! But is it? Or is it weather that is always changing? The climate in southern Florida can be described as tropical and it has been tropical in South Florida for hundreds if not thousands of years. What has the weather been like in South Florida for the past 100 years or so? One can generalize and say that the summers are usually somewhat warmer than the winters but the temperature remains pretty much the same all year long. Every now and then there is a hurricane to disrupt the weather but there are no long-lasting climatic effects from hurricanes. Certainly there is much destruction but the climate soon returns to normal. So maybe the climate is not always changing; maybe it's the weather that changes all the time. Weather and climate are certainly two different things.

Climate in an area has been defined as weather over a long period of time, usually taken to be at least 30 years, according to the World Meteorological Organization (WMO). Weather is what happens today, tomorrow, or predicted for the next week or 10 days. Weather has been defined as the state of the atmosphere at any given time.

Weather is not climate and it is necessary to make that distinction before we consider climate change trends. We cannot speak in terms of global weather, but we can speak in terms of global climate. And the global climate is getting warmer throughout most of the world.

4.3 Solar and Heat Energy

Heat is energy and the majority of Earth's energy comes from the Sun. Some of the solar energy is directly reflected back to space by the top of Earth's atmosphere (TOA), by clouds, by solid particles in the Earth's atmosphere (aerosols), by glaciers, by oceans, and by the solid Earth itself. Solar energy leaves the Sun as electromagnetic radiation (EMR), travels through space, and impinges upon the Earth.

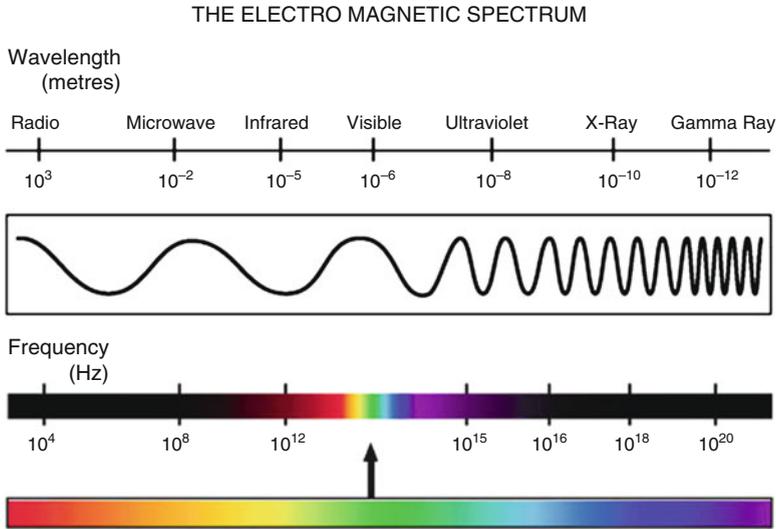


Fig.4.1 The electromagnetic spectrum (From http://www.scienceprog.com/wp-content/uploads/2009/05/electromagnetic_spectrum.jpg)

EMR is a form of energy emitted and absorbed by charged particles, which exhibits wave-like behavior as it travels through space.

The electromagnetic spectrum consists of wavelengths of light varying from long wavelengths (low energy) to very short wavelengths (high energy). The length of a wave is measured from crest to crest or from trough to trough (Fig. 4.1). Light is a type of radiation and behaves as waves of light and as particles of light (photons). Visible light is part of the radiation that comes from the Sun, light bulbs, fires, and other forms of illumination. Visible-light waves range in size from 0.4 to $0.7 \mu\text{m}$ ($4,000$ – $7,000 \text{Å}$), whereas an atom is only a few ångströms in size.

The electromagnetic spectrum and the different wavelengths are shown in Fig. 4.1.

Electromagnetic waves are produced by the motion of electrically charged particles. These waves are also called “electromagnetic radiation” because they radiate from electrically charged particles. They travel through empty space as well as through air and other substances.

Electromagnetic radiation, besides acting like waves, also acts like a stream or packet of particles (photons) that have no mass. The photons with the highest energy correspond to the shortest wavelengths. Electromagnetic radiation travels at the speed of light which is thought to be a universal constant and is on the order of 3×10^8 m/s or $300,000,000$ m/s.

Light produces heat, as one can attest who has ever touched an incandescent light bulb after it has given off light for any length of time. The most common light sources are thermal (heat); a body at a given temperature emits a characteristic spectrum of what is referred to in physics as blackbody radiation. Examples include Sunlight (the radiation emitted by the Sun at around $6,000\text{K}$). About 40% of Sunlight is visible and is the main source of Earth's heat. Other heat

sources are from Earth's interior and incandescent light bulbs and glowing solid particles in flames.

A blackbody is an object that absorbs all the incident radiation that hits it. It in turn radiates heat depending on the temperature of the object.

The peak of the blackbody spectrum is in the infrared for relatively cool objects like human beings. As the temperature increases, the peak shifts to shorter wavelengths, producing first a red glow, then a white one, and finally a blue color as the peak moves out of the visible part of the spectrum and into the ultraviolet. These colors can be seen when metal is heated to "red hot" or "white hot." Blue thermal emission is not often seen.

Over time, the amount of incoming solar radiation (short-wave or ultraviolet) absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation (heat energy or infrared radiation). About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface, by evapo-transpiration, and by longwave radiation that is absorbed by clouds and greenhouse gases. Some of this longwave energy escapes back into space.

The greenhouse gases in the atmosphere radiate longwave energy back to Earth as well as out to space. Certain gases in the atmosphere trap the longwave radiation and re-radiate it back to the Earth's surface. This re-radiation of heat energy is what allows Earth's near-surface temperature to be about 30°C warmer than it would be without the greenhouse gases and these gases have allowed life on Earth to develop over time and thrive. Earth would be a very uncomfortable place at an average global temperature of -15 to -19°C.

4.4 Earth's Radiation Laws

The vast majority of the energy driving Earth systems is solar radiation. Energy from the Sun drives almost every known physical, chemical, and biological cycle on Earth's surface. Beneath the surface, energy derived from the Earth's interior drives volcanoes, fumaroles and geysers, and drives plates and causes continents to drift, but most energy and its results at and near the Earth's surface are radiated from the Sun.

The average properties of the Sun's electromagnetic radiation interacting with matter are given in a simple set of rules called radiation laws. These laws apply when the radiating body is what is referred to as a blackbody radiator (Fig. 4.4).

In order to determine the effects of solar radiation on the Earth, it is first necessary to determine the amount of solar radiation reaching the atmosphere and surface of the Earth. There are three terms which are often used by atmospheric and climate change scientists when dealing with solar radiation impacting Earth, as follows:

- **Irradiance** – The amount of electromagnetic energy incident on a surface per unit time per unit area. In the past this quantity has often been referred to as "flux." When measuring solar irradiance (via satellite), scientists are measuring the amount of electromagnetic energy incident on a surface perpendicular to the incoming radiation at the top of the Earth's atmosphere, not the output at the

solar surface. Total solar irradiance (TSI) is the amount of solar radiative energy incident on the Earth's upper atmosphere.

- **Solar Constant** – The solar constant is the amount of energy received at the top of the Earth's atmosphere on a surface oriented perpendicular to the Sun's rays (at the mean distance of the Earth from the Sun). The generally accepted solar constant of 1,368 W/m² is a yearly average measured by satellite.
- **Insolation** – In general, solar radiation received at the Earth's surface (**In_Sol_Ation**; from **incident solar radiation**). The rate at which direct solar radiation is incident upon a unit horizontal surface at any point on or above the Earth's surface.

The main problem with determining the Earth's surface temperature with calculations made for the top of the atmosphere (TOA) is that up to 70% of incoming radiation can be blocked by gases in the atmosphere and by clouds. Scientists usually estimate the amount of energy actually reaching the surface and this estimate is plugged into climate models.

It must also be assumed that the surface receiving the radiation is perpendicular to the incoming radiation. This is a problem due to the Earth's rotation, its axial tilt (obliquity), the latitude and orientation of the surface relative to the solar radiation, and the season of the year.

All of these factors change the angle of the surface receiving the radiation, which changes the intensity of the energy received.

Assuming that the radiation emission of the Sun is constant is also a problem because this value fluctuates with cycles in solar activity. The Sun has recently (as of June 2012) come out of a long period described as a solar minimum which is a period of reduced solar activity. NASA satellites have measured incoming radiation since 1978 and have recorded changes in solar irradiance (Fig. 4.2). This data can be accessed on the Internet from the Goddard Space Flight Center (GSFC): <http://www.nasa.gov/centers/goddard/home/index.html>.

Energy from the Sun arrives at Earth as electromagnetic waves, or as an electromagnetic spectrum. Electromagnetic waves travel at the speed of light and consist of the entire range of frequencies and wavelengths at which electromagnetic waves can travel from the smallest (a single atom) to the largest (theoretical infinity).

The energy emitted from the Sun is electromagnetic energy. The amount of energy can be expressed by the units of Planck's Law. Planck's Law describes the electromagnetic radiation emitted from a blackbody at absolute temperature T and written as follows:

$$E_{\lambda} = a / [\lambda^5 \{e^{(b/\lambda T)} - 1\}] \quad (4.1)$$

Where E_{λ} = the amount of energy (Wm² μm⁻¹) emitted at wave length λ (μm) by a body at temperature T (in units Kelvin) with a and b as constants.

The wavelength emitted from an object depends on the temperature of the object. This wave length can be calculated according to Wien's Law when the temperature of the object is known. This is also referred to as Wien's Displacement Law.

The wavelength distribution of thermal radiation from a blackbody at any temperature has essentially the same shape as the distribution at any other temperature,

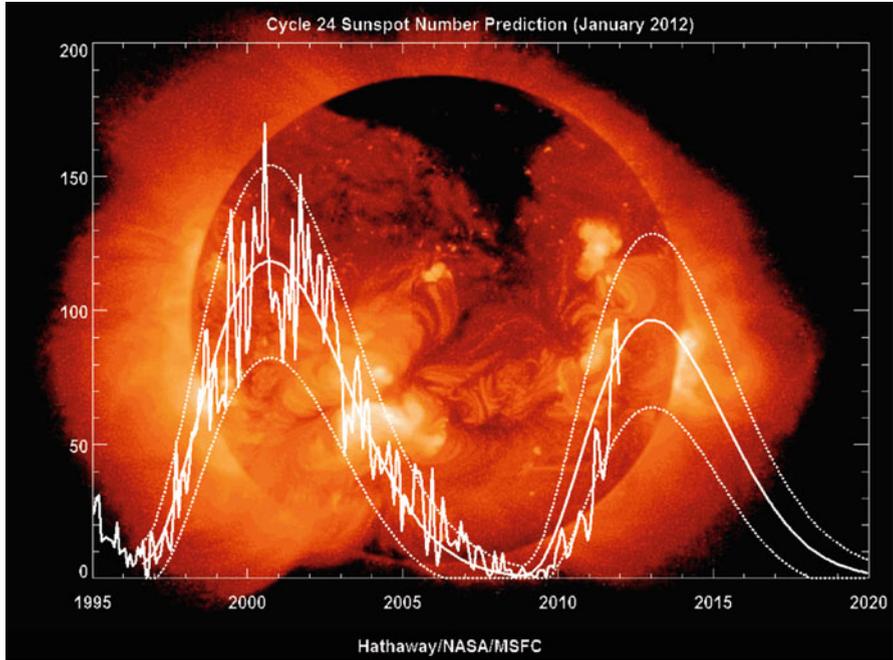


Fig. 4.2 The Sunspot cycle from 1995 to 2020. The *jagged curve* traces actual Sunspot counts. *Smooth curves* are fits to the data and one forecaster’s predictions of future activity (Credit: David Hathaway, NASA/MSFC; From http://science.nasa.gov/science-news/science-at-nasa/2009/01apr_deepolarminimum/; Public Domain)

except that each wavelength is displaced on the graph. This is the reason it is called Wien’s Displacement Law.

By differentiating Eq. 4.1 (Planck’s Law), it is possible to determine the wavelength of maximum radiation emission from the Sun using Wien’s Law:

$$\lambda_{\text{maximum}} = 2897 / T$$

λ_{maximum} = the peak wavelength of energy in micrometers

T = Temperature of the object radiating energy.

2897 = Wien’s Displacement Law Constant

Using Wien’s Law, the peak wavelength of radiation emitted from an object is inversely proportional to the temperature of that object. The radiation output of an object can be calculated using the Stefan-Boltzmann Law when the temperature is known. The Stefan-Boltzmann Law states that the total energy radiated per unit surface area of a blackbody per unit of time is directly proportional to the fourth power of the blackbody’s thermodynamic temperature T (also called the absolute temperature). The Stefan-Boltzmann Law is written as follows:

$$E = l \sigma T^4$$

E = Surface irradiance of the object

ϵ = Emissivity of the object

σ = Stefan-Boltzmann Constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$)

T = Temperature of the object

The Inverse Square Law is used to calculate the decrease in radiation intensity due to an increase in distance from the radiation source. The Inverse Square Law is written as follows:

$$I = E(4\pi \times R^2) / (4\pi \times r^2)$$

I = Irradiance at the surface of the outer sphere

E = Irradiance at the surface of the object (the Sun)

$4\pi \times R^2$ = Surface area of the object

$4\pi \times r^2$ = Surface area of the outer sphere

In order to be able to calculate the solar constant the following equation is used:

$$S_o = E(\text{Sun}) \times (R(\text{Sun}) / r)^2$$

S_o = Solar Constant

E = Surface irradiance of the Sun

$R = 6.96 \times 10^5 \text{ km}$ = Radius of the Sun

$r = 1.5 \times 10^8 \text{ km}$ = Average Sun – Earth distance

The solar radiation reaching the Earth's surface can be found with the following equation:

$$I = S \cos Z$$

I = Insolation

$S \sim 1,000 \text{ W/m}^2$ (clear day solar insolation on a surface perpendicular to incoming solar radiation. This varies a great deal due to atmospheric variables).

Z = Zenith Angle (Zenith Angle is the angle from the point directly overhead to the Sun's position in the sky. The angle is dependent on latitude, solar declination angle, and the time of day).

$$Z = \cos^{-1}(\sin \phi \sin \delta + \cos \phi \cos \delta \cos H)$$

ϕ = Latitude

H = Hour Angle = $15^\circ \times (\text{Time} - 12)$ (Angle of radiation due to time of day. Time is given in solar time as the hour of the day from midnight)

δ = Solar declination angle

Solar declinations can be found for each hemisphere on NASA's websites such as the following for the Northern Hemisphere: <http://edmall.gsfc.nasa.gov/inv99Project.Site/Pages/science-briefs/ed-stickler/ed-irradiance.html>.

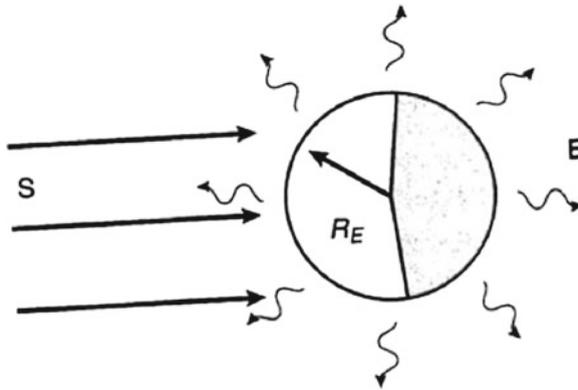
In addition to making calculations for solar irradiation based upon physics concepts, the public can access and analyze solar irradiance data that is collected by orbiting satellites and ground-based pyranometers (a pyranometer is an instrument for measuring solar radiation). Satellite irradiance data is available from 1978 to the present on the Internet. The irradiance data has been collected by the following NASA satellites:

- Nimbus 7 (Earth Radiation Budget) 1978–1993;
- Solar Maximum Mission: Active Cavity Radiometer Irradiance Monitor I (ACRIM I) 1980–1989;
- Earth Radiation Budget Satellite (ERBS) Solar Monitor Measurements 1984–1996;
- Upper Atmosphere Research Satellite (UARS) ACRIM II Measurements 1991–1997.

Data and further information related to these satellites and others are available to the public through the NASA Goddard Space Flight Center Data Archive Center: <http://daac.gsfc.nasa.gov/>.

A few simple calculations will illustrate the effect that the physics of the atmosphere has on Earth's surface temperature as shown by the following steps:

Step 1 – Assume that the Earth has no atmosphere. Calculate the average global surface temperature.



To calculate the Earth's average surface temperature, you can use the Stefan-Boltzman Law for a blackbody.

$$E = \sigma T^4$$

where the Stefan-Boltzman constant, $\sigma = 5.67 \times 10^{-8} \frac{\text{Watts}}{\text{m}^2 \cdot \text{K}^4}$

In this equation, E is the rate of incident solar irradiance, which can be taken to be about 1,368 W per square meter (as an average measured by satellites).

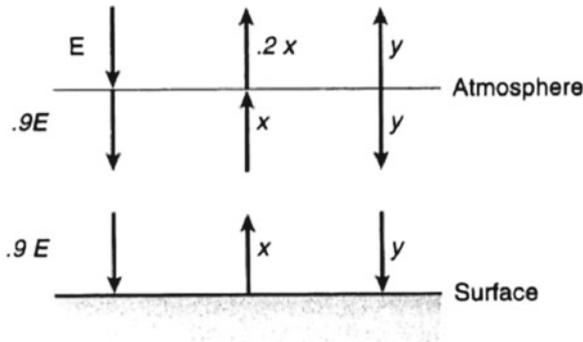
Solving for temperature:

$$T = \left(\frac{E}{\sigma}\right)^{1/4} = \left(\frac{1,360 \frac{\text{Watts}}{\text{m}^2}}{5.67 * 10^{-8} \frac{\text{Watts}}{\text{m}^2 * \text{K}^4}}\right)^{1/4} = 254.5 \text{ K} = -19 \text{ }^\circ\text{C}$$

Step 2 – Next add in the atmosphere. Recalculate the average global surface temperature.

For this calculation, the atmosphere can be regarded as a thin layer with an absorptivity of 0.1 for solar radiation and 0.8 for infrared radiation. Let x equal the irradiance of the earth's surface and y the irradiance (both upward and downward) of the atmosphere. E is the irradiance entering the earth-atmosphere system from space averaged over the globe (E=342 W/m²) (solar constant = 1,368/4 = 342 W/m²).

At the Earth's surface, a radiation balance requires that:



Doing a radiation balance for the surface and the atmosphere, e.g., energy into the surface equals energy out of the surface and energy into the atmosphere equals energy out of the atmosphere gives you the following equations, respectively:

$$0.9E + y = xE + x = 0.9E + 2y + 0.2x$$

Solving these equations simultaneously reveals that x=377 W/m² and y=163 W/m².

Again, by using the Stefan-Boltzman Law, you can now calculate the temperature of the surface of the earth.

$$T = \left(\frac{E}{\sigma}\right)^{1/4} = \left(\frac{x}{\sigma}\right)^{1/4} = \left(\frac{163 \frac{\text{Watts}}{\text{m}^2}}{5.67 * 10^{-8} \frac{\text{Watts}}{\text{m}^2 * \text{K}^4}}\right)^{1/4} = 286 \text{ K} = 13 \text{ }^\circ\text{C}$$

You can see that with an atmosphere, the average surface temperature of the earth is actually 13°C . Taking it one additional step, you can calculate the increase in absorptivity that would be needed to increase the global average surface temperature by 1°C . Using the equations above, you can see that the increase would only need to be about 0.02.

No matter how you decide to describe it, through hands on experiments and measurements, or through the calculations, climate change is happening and the global climate is very sensitive to change. The sooner we all accept it, the sooner we can start working together to both reduce our emissions and adapt to the changes that are already happening.

The problem presented above is adapted from Wallace and Hobbs, 1977 as it was stated by Scott McNally, in *Scientific American*, February 16, 2012 (used with permission).

4.5 Earth's Energy Imbalance

If the Earth emitted the same amount of energy as it was receiving, it would be in energy equilibrium or balance. But there is more energy coming into the Earth system than is going out, so the system compensates by warming. It has to warm because of the energy imbalance. Prior to the Industrial Revolution the atmospheric concentration of carbon dioxide had been stable for hundreds of years and the Earth's temperature had had normal fluctuations due to a balance of energy received with energy emitted by the Earth.

The Sun is ultimately responsible for virtually all energy that reaches the Earth's surface. Direct overhead Sunlight, as measured by satellite, at the top of the atmosphere provides $1,368\text{ W/m}^2$; however, much of the Sunlight is reflected off the top of the atmosphere so that the light which is absorbed at any typical location is an annual average of $\sim 342\text{ W/m}^2$. If this were the total heat received at the surface, then, neglecting changes in albedo (Earth's reflectivity), the Earth's surface would be expected to have an average temperature of -19°C . Instead, the Earth's atmosphere recycles heat coming from the surface and delivers an additional 324 W/m^2 , which results in an average surface temperature of roughly plus 15°C . This is the greenhouse effect which keeps the Earth's surface habitable for living organisms.

The total solar energy is determined by the temperature of the Sun's visible surface, or photosphere, which is about $6,000^{\circ}\text{K}$ (Kelvin). Like the Sun, the Earth emits an amount of energy determined by the temperature of Earth's lower atmosphere, the troposphere, which is about 255°K (or about -18°C). But this in turn is determined by Earth's need to balance the incoming solar energy which it absorbs, by emitting an equal amount of energy back to space, in order to remain in equilibrium.

The troposphere not only radiates out to space, but also radiates downward to the surface, and that "back-radiation" from the atmosphere adds to the fraction of solar energy which penetrates to the surface, to heat the surface to about 288°K (or about $+15^{\circ}\text{C}$). The figure below shows how Earth's energy balance is achieved for a

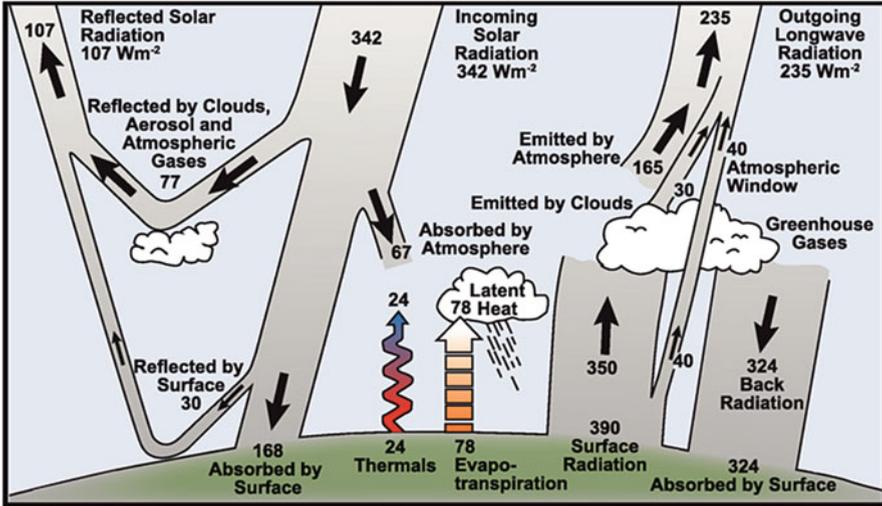


Fig. 4.3 Estimate of the Earth's annual and global average energy balance (from IPCC AR4 2007)

typical square meter at the top of the atmosphere (TOA) and how it depends on the solar constant of about $1,368 W/m^2$ divided by 4 (because Earth's cross section which absorbs the solar energy is 1/4 of its emitting surface area) as well as the Earth-atmosphere albedo, which is the fraction of solar energy reflected by a combination of the land, ice and especially clouds which compose the Earth-atmosphere system. ($1,368 W/m^2$ divided by 4 equals $342 W/m^2$).

Incoming solar radiation is $342 W/m^2$ at the top of the atmosphere (TOA) and if Earth was in energy balance, $342 W/m^2$ would also be outgoing. The majority of incoming solar radiation is shortwave ultraviolet radiation. The outgoing radiation is longwave infrared radiation. In Fig. 4.3 above, $324 W/m^2$ are reflected back to Earth by greenhouse gases and absorbed by Earth's surface and $235 W/m^2$ are emitted back to outer space (Fig. 4.3).

Although the Earth and Sun behave approximately as black bodies, this is not the case for the gases that make up the Earth's atmosphere. Certain atmospheric gases absorb radiation at some wavelengths but allow radiation at other wavelengths to pass through. Black bodies are objects that absorb all electromagnetic radiation impinging upon them and radiate amounts depending on their temperature.

Absorption of energy by a particular gas occurs when the frequency of the electromagnetic radiation is similar to that of the molecular vibrational frequency of the gas in question. The atmosphere is mostly transparent in the visible part of the spectrum but significant absorption occurs of ultraviolet radiation (incoming shortwave solar radiation) by ozone and absorption of infrared radiation (longwave outgoing terrestrial radiation) by water vapor, carbon dioxide and other trace gases.

The absorption of terrestrial infrared radiation is particularly important to the energy budget of the Earth's atmosphere. Such absorption by the trace gases heats

the atmosphere, stimulating it to emit more longwave radiation. Some of this is released into space while the rest is re-radiated back to Earth. The net effect of this is that the Earth stores more energy near its surface than it would if there was no atmosphere, consequently the temperature is higher by about 33 K (+15°C).

This process is popularly known as the greenhouse effect as was defined earlier in this text. Glass in a greenhouse is transparent to solar radiation, but opaque to terrestrial infrared radiation. The glass acts like some of the atmospheric gases and absorbs the outgoing energy. Much of this energy is then re-emitted back into the greenhouse causing the temperature inside to rise. In reality, a greenhouse is warmer than its surroundings principally because of the shelter it offers rather than because of any radiative considerations. Nevertheless, the term has stuck largely as a result of media reporting and the analogy is useful.

Consequently, the gases in the atmosphere which absorb the outgoing infrared radiation are known as greenhouse gases and include carbon dioxide, water vapor, nitrous oxide, methane, and ozone. All the greenhouse gases have molecules whose vibrational frequency lies in the infrared part of the spectrum. Despite the considerable absorption by these greenhouse gases, there is an atmospheric window through which terrestrial infrared radiation can pass. This occurs at about 8–13 μm , and its gradual closing is one of the effects of anthropogenic emissions of greenhouse gases. As this window closes the Earth's temperature will rise even more rapidly than it is rising at present.

Energy arriving at the top of the atmosphere starts an energy cascade involving numerous energy transformations. On entering the atmosphere, some of the solar shortwave radiation is absorbed by gases in the atmosphere (e.g., carbon dioxide, water vapor), some is scattered, some is absorbed by the Earth's surface and some is reflected directly back into space by either clouds or the surface itself. The amount of shortwave radiation reflected depends on a factor known as the albedo (or reflectivity). Albedo varies according to the surface. Ice and certain clouds have a high albedo (0.6, or 60% to 0.9, or 90%) while the oceans generally have a low albedo (0.1, or 10%). For the whole Earth this averages at about 0.30, meaning that 30% of the incoming solar radiation is reflected.

Of the terrestrial longwave radiation re-emitted from the Earth's surface, most is re-absorbed by the greenhouse gases and only a little escapes directly through the atmospheric window. Long-wave radiation re-emitted from the atmosphere (greenhouse gases, clouds) is either returned to the Earth's surface or released into space. The net result of this greenhouse effect is to increase the amount of energy stored near the Earth's surface, with a consequent increase in temperature. There are also additional heat fluxes associated with evaporation and transpiration which balance the energy fluxes into and out of all parts of the Earth-atmosphere system.

A blackbody is an object which absorbs all radiation falling upon it and does not reflect any, but will emit radiation as it is heated. As the blackbody is heated, it will emit radiation according to Planck's Law. All radiation emitted by a blackbody is due to its temperature; the higher the temperature, the more radiation that will be emitted.

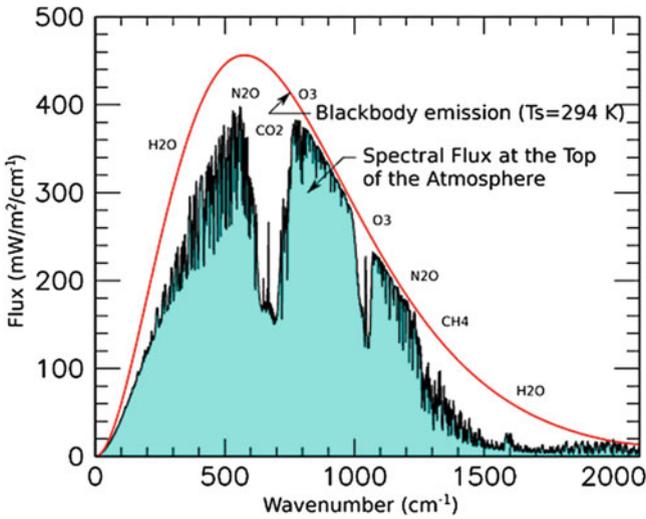


Fig. 4.4 Outgoing spectral radiance at the top of Earth's atmosphere showing the absorption at specific frequencies and the principle absorber. For comparison, the red curve shows the flux from a classic "blackbody" at 294 °K ($\approx 31^\circ\text{C} \approx 69.5^\circ\text{F}$) (NASA/GISS, Public Domain)

The figure above (Fig. 4.4) shows two curves, one from a classical blackbody and the other looking down at the atmosphere from outer space. The red curve is radiation of a blackbody at $T_s = 294\text{ K}$. The black curve is spectral flux at the top of the atmosphere. The large reduction in flux is at the wavelengths absorbed by carbon dioxide (CO_2).

Solar radiation is emitted uniformly in all directions. After travelling 93 million miles only a tiny fraction of the energy emitted by the Sun toward the Earth is intercepted by the Earth. Therefore, the energy flux arriving at the top of the Earth's atmosphere is many orders of magnitude smaller than that leaving the Sun. The latest satellite measurements indicate a value of $1,368\text{ W/m}^2$ for the energy received at the top of the atmosphere on a surface perpendicular to the solar beam. This is known as the solar constant, which is a misnomer as the "solar constant" varies with the amount of energy produced by the Sun and this varies over time. It has been found to vary in an 11-year sunspot cycle but this is also variable.

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