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Guide to the Science of Climate Change in the 21st Century

Chapter 4
Earth's Energy Budget

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4.1 Introduction

Earth's energy budget forms the framework with which it is possible to discuss the science of climate change. All of the energy that 'fuels' planet Earth comes from the Sun – solar radiation. All energy is measured in Watts per square metre or Wm^{-2}. (Recall, the brightness of light bulbs is measured in Watts. Visible light is short wave radiation.) Short wave radiation that is not immediately reflected back into space is absorbed by the atmosphere and the surface of the Earth. The exchange of energy between the surface of the Earth and the atmosphere results in all of the absorbed energy being emitted into space in the form of long wave radiation. In the process both the surface of the Earth and the atmosphere warm. The amount of warmth will depend on the ability of the atmosphere and the Earth's surface to reflect short wave radiation and the ability of the atmosphere to absorb long wave radiation. Human activities can affect the amount of short-wave energy absorbed by changing land use and the ability of the atmosphere to absorb long wave radiation by changing the composition of the gases and aerosols that form the atmosphere. In so doing human activities influence how warm the Earth's surface and the atmosphere must become to return the absorbed solar energy to space and preserve the energy balance.

4.2 Concept of energy

It is very important to understand the concept of energy before discussing the Earth's energy budget.

Definitions and descriptions can be found in the following web sites, United States Energy Administration, Britannica, and Wikipedia.
https://www.eia.gov/energyexplained/what-is-energy/
https://www.britannica.com/science/energy
https://en.wikipedia.org/wiki/Outline_of_energy

The table below, taken from the US Energy Administration web site, identifies the different forms of energy.

Forms of energy

Many forms of energy exist, but they all fall into two basic categories:

- Potential energy
- Kinetic energy

Potential energy

Potential energy is stored energy and the energy of position.

Chemical energy is energy stored in the bonds of atoms and molecules. Batteries, biomass, petroleum, natural gas, and coal are examples of chemical energy. Chemical energy is converted to thermal energy when people burn wood in a fireplace or burn gasoline in a car's engine.

Mechanical energy is energy stored in objects by tension. Compressed springs and stretched rubber bands are examples of stored mechanical energy.

Nuclear energy is energy stored in the nucleus of an atom—the energy that holds the nucleus together. Large amounts of energy can be released when the nuclei are combined or split apart.

Gravitational energy is energy stored in an object's height. The higher and heavier the object, the more gravitational energy is stored. When a person rides a bicycle down a steep hill and picks up speed, the gravitational energy is converting to motion energy. Hydropower is another example of gravitational energy, where gravity forces water down through a hydroelectric turbine to produce electricity.

Kinetic energy

Kinetic energy is the motion of waves, electrons, atoms, molecules, substances, and objects.

Radiant energy is electromagnetic energy that travels in transverse waves. Radiant energy includes visible light, x-rays, gamma rays, and radio waves. Light is one type of radiant energy. Sunshine is radiant energy, which provides the fuel and warmth that make life on earth possible.

Thermal energy, or heat, is the energy that comes from the movement of atoms and molecules in a substance. Heat increases when these particles move faster. Geothermal energy is the thermal energy in the earth.

Motion energy is energy stored in the movement of objects. The faster they move, the more energy is stored. It takes energy to get an object moving, and energy is released when an object slows down. Wind is an example of motion energy. A dramatic example of motion energy is a car crash—a car comes to a total stop and releases all of its motion energy at once in an uncontrolled instant.

Sound is the movement of energy through substances in longitudinal (compression/rarefaction) waves. Sound is produced when a force causes an object or substance to vibrate. The energy is transferred through the substance in a wave. Typically, the energy in sound is smaller than in other forms of energy.

Electrical energy is delivered by tiny charged particles called electrons, typically moving through a wire. Lightning is an example of electrical energy in nature.

Table 4.1 Forms of energy taken from https://www.eia.gov/energyexplained/what-is-energy/

Perhaps the best way to start to understand the concept of energy is how we use it or experience it. Consider the following examples?

1. Using a fuel burning stove to boil water. Natural gas, propane, kerosene, wood, coal, paraffin or some other fuel is burned to create heat which is transferred to the bottom of the kettle that then heats the water. The water temperature increases and steam is produced. The energy in the fuel is a 'chemical form' of potential energy. When burned the chemical energy produces 'heat or thermal energy' and 'radiant energy', forms of kinetic energy, which are transferred to the bottom of the pot which conducts it through the walls of the pot (a form of thermal energy transfer) to the water which warms ('thermal energy increasing') until it starts to steam (thermal energy leaving the water) by the process of evaporation.
2. An incandescent light bulb uses 'electrical energy' to produce 'radiant energy'.

3. A fuel burning car uses the ‘chemical energy’ in the fuel transformed to ‘mechanical energy’.
4. The sun uses ‘nuclear energy’ to produce ‘radiant energy’ which the earth and our skin absorbs and turns it into ‘thermal energy’.

Energy is measured in terms of the ‘work’ it can do (potential energy) or the work it is doing (kinetic energy).

Work is defined in mechanical terms as equal to force times the distance over which is applied. Force is measured in Newtons (SI units) and distance is measured in metres. One unit of work is equal to one Newton times one metre. One unit of work is known as one Joule.

Potential energy is measured in Joules (J). Potential energy is the amount of work the energy can produce when transformed into kinetic energy.

Kinetic energy is measured in terms of rate of energy transfer or Watts (W). One Watt equals one Joule per second (J/s or Js^{-1}).

Energy, any form, passing though a unit area, e. g. one square metre, is known as the energy flux. One unit of energy flux equals one Watt per square metre (These units, W/m^2 or Wm^{-2} mean Watts per square meter). Energy flux is a measure of the movement of energy. If all the light from a 1000-Watt light bulb is shone through an area 1 m by 1 m, the energy flux is 1000 W per square meter. If the light bulb only produced 10 Watts, the energy flux would be 10 W per square meter. This is the most important term to understand.

4.3 Solar energy

The flux of radiant energy from the Sun to the outer surface of the Earth’s atmosphere is 342 Wm^{-2}. The layer of gases covering the Earth (the air we breath) is called the atmosphere. The ‘top’ or ‘outside’ of the atmosphere is 100 kilometers from the surface of the Earth. (Passenger jet fly about 10 kilometers above the surface of the Earth.) This is the average energy per square metre over the whole planet. It is very important to realize that the solar radiation is the sum of radiation of energy from the invisible ultraviolet, light that is visible to the human eye, to the thermal infrared as shown in Figure 4.1. The radiation moves in waves and a particular radiation is identified by its wavelength (See Figure 4.2). The energy of radiation with a specific wavelength is called spectral irradiance measured in Watts per square metre per wavelength (measured in micro metres, one millionth of a metre or microns which has the symbol, µm).

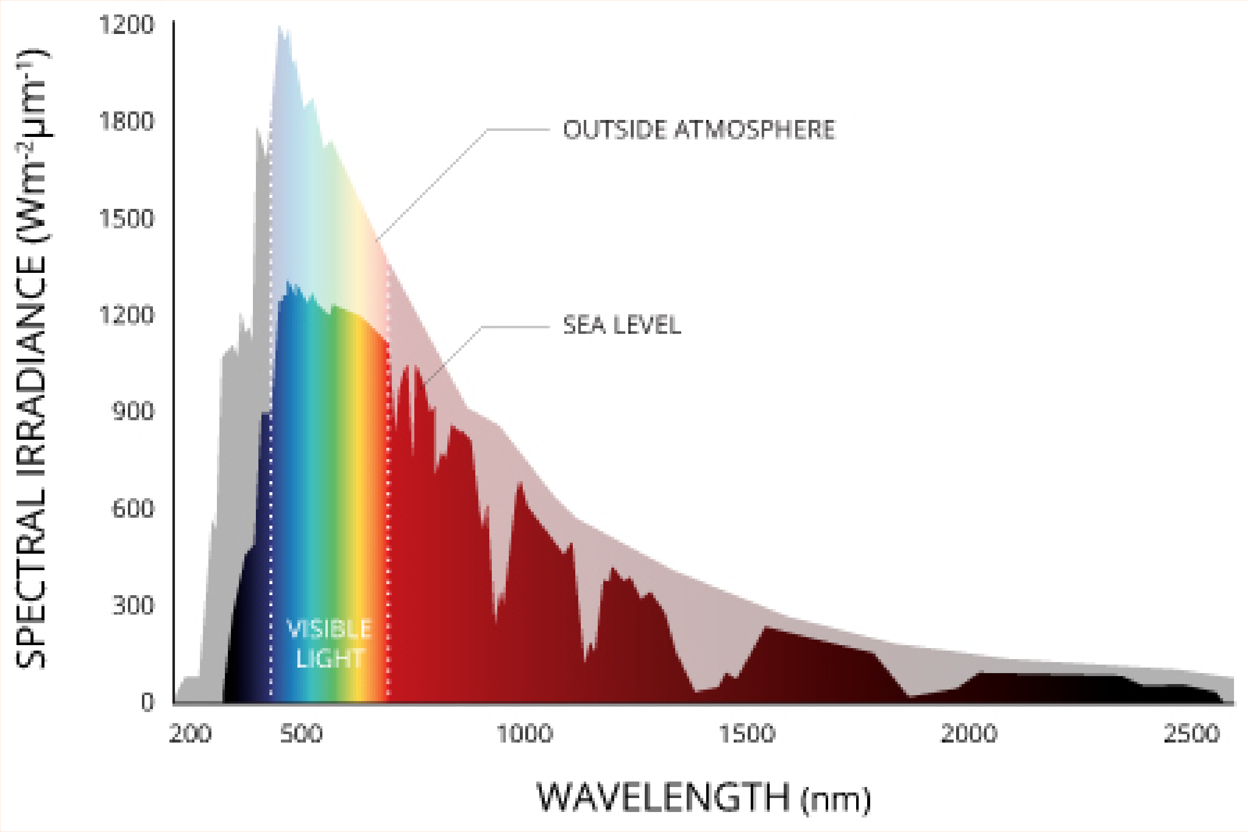

Figure 4.1 Sun's radiant energy that reaches Earth's atmosphere and surface.
https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/

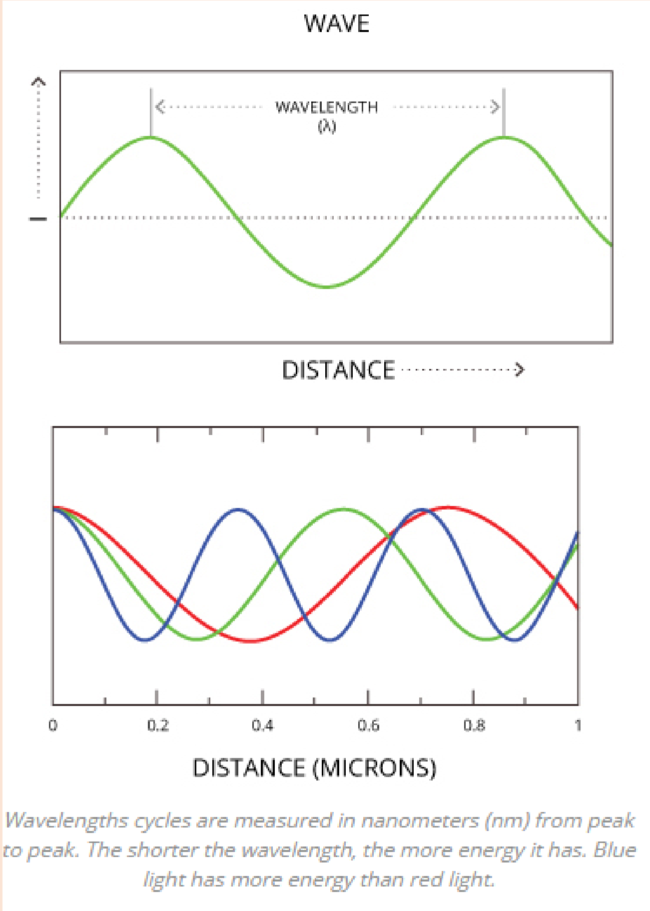

Figure 4.2 Wavelength description of radiant energy.
https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/

As shown in Figure 4.1 not all of the radiation reaches the earth's surface. As the radiation moves through the Earth's atmosphere certain wavelengths of radiation are absorbed by the different gases and particles (aerosols) that comprise the atmosphere. This includes nitrogen, oxygen, hydrogen, the inert gases such as helium (, water, carbon dioxide, gases produced by volcanoes, industrial pollutants and particles from a variety of natural and industrial sources. So called greenhouse gases (GHG), like carbon dioxide, water vapour and gases and aerosols emitted by volcanoes are a natural part of the atmosphere. Different substances absorb specific wavelengths of radiation. Human activity resulting in changes in land use, burning of fossil fuels and introduction of a variety of industrial processes over the past two hundred years have greatly contributed to the variety and increase in greenhouse gases.

The distribution of radiation with wavelength is known as the solar radiation spectrum. As shown in Figures 4.1 and 4.3 this is typically divided into ultraviolet or UV, visible light and near infrared (where almost all of the Sun's radiant energy occurs). The spectrum of solar radiation outside or above the atmosphere, without atmospheric absorption (coloured yellow) is significantly different than that at sea level (coloured red). The visible radiation is a narrow band of the radiation received from the Sun. Infrared radiation refers to radiation with wavelengths greater than visible light. It is felt as warmth or heat because water (human body) is particularly effective in absorbing infrared radiation. Ultraviolet radiation, UV, is high intensity invisible radiation that is potentially damaging to living organisms (sunburns and melanoma type cancer).

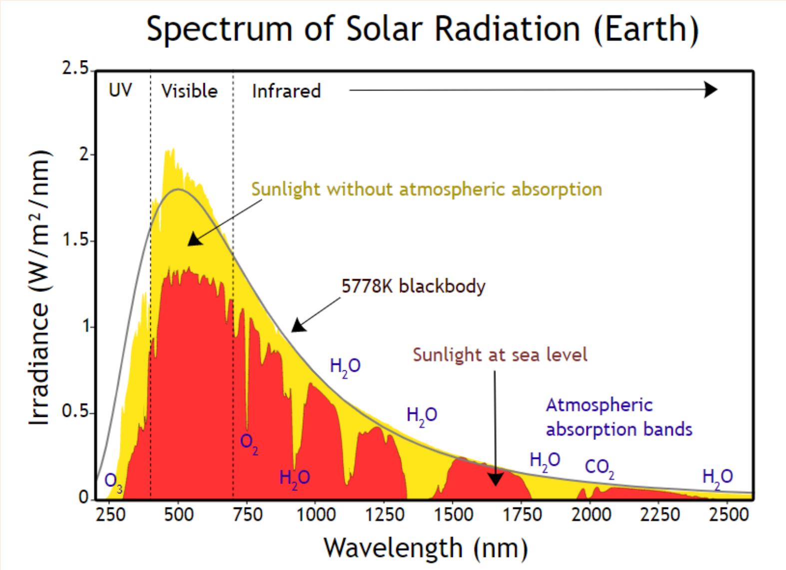

Figure 4.3 Absorption of Sun's radiant energy that reaches Earth's atmosphere and surface.
https://energyeducation.ca/encyclopedia/Solar_energy_to_the_Earth

Note that ozone, O_3, a molecule of oxygen made up of three atoms of oxygen, absorbs UV. (Ozone existing in a layer of the layer of the atmosphere high above the surface of the Earth protects Earth from harmful UV). Water and carbon dioxide absorb much of the infrared radiation. The absorption of all wavelengths of solar radiation is described in greater detail in Figure 4.4.

When radiation energy is absorbed the effect is to increase the thermal energy of the substance absorbing the radiation – typically observed by increases in temperature of the substance absorbing the radiation.

The thermal energy (heat energy) of a substance is lost by emission of radiant energy in the form of long wave or infrared radiation (similar to the radiant energy one feels from the surface of hot stove). The rate at which the energy is emitted varies with the temperature of the substance. The radiation is sent in all directions. The warmer the substance, the greater the rate of emitted radiant energy (the greater the energy flux). The Earth is warm and so emits long wave or infrared radiation. This latter characteristic is very important to the understanding of global warming because water, carbon dioxide, sulfur dioxide and many industrially generated gases are very effective absorbers and emitters of longwave radiation.

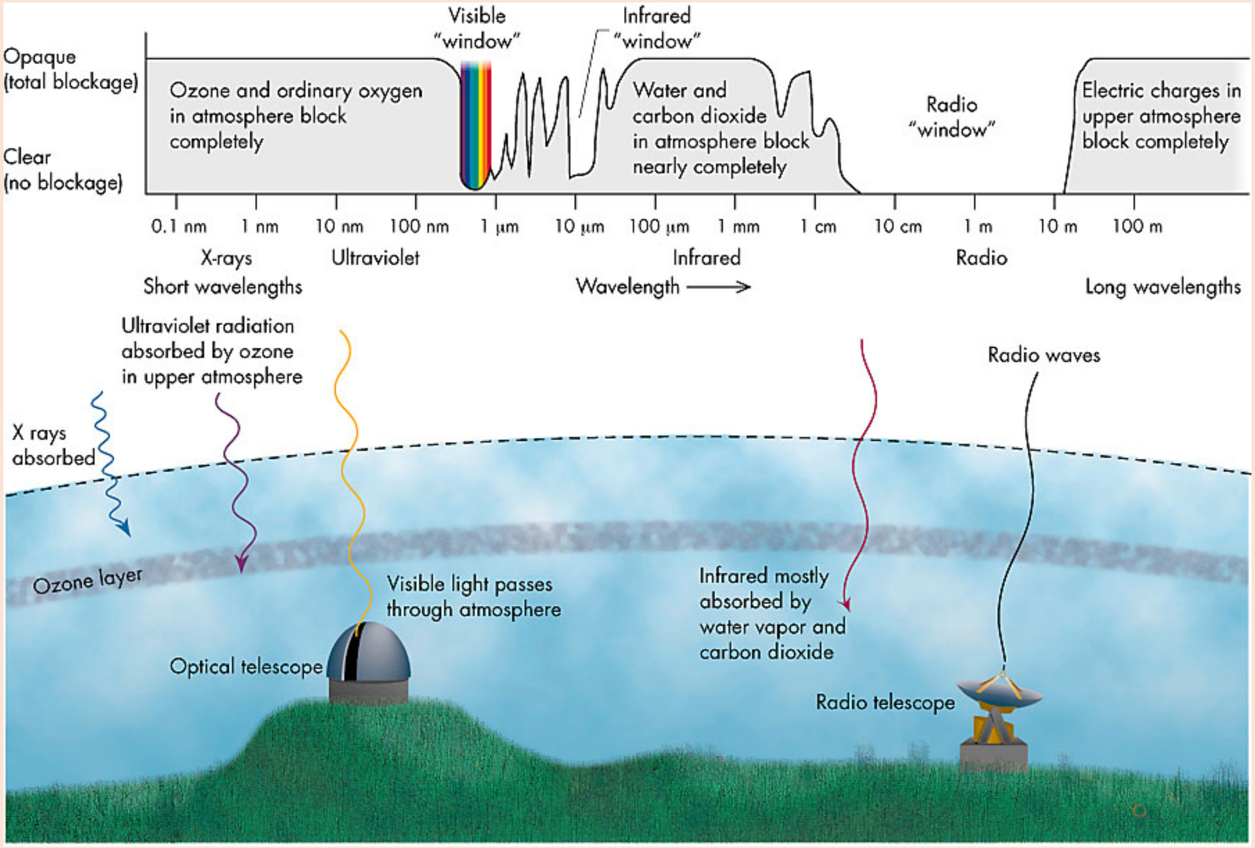

Figure 4.4 Absorption of solar radiation by Earth's atmosphere.

4.4 Energy budget

The study of the science of climate change must start with developing a thorough understanding of the 'global energy budget'. This might be the most complicated part of the science. A simplified but complete version of the global energy budget taken from Kiehl and Trenberth 1997 is shown in Figure 4.5. It shows the 'long term average' values taken over the whole surface of the planet.

Much of the radiant energy received from the Sun is reflected by substances in the atmosphere or the surface of the Earth. Reflected radiant energy is typically scattered in all directions. Reflected radiation may leave the atmosphere completely or be reflected again or absorbed (changed into thermal energy) and emitted. The amount of radiation reflected is unique to the substance.

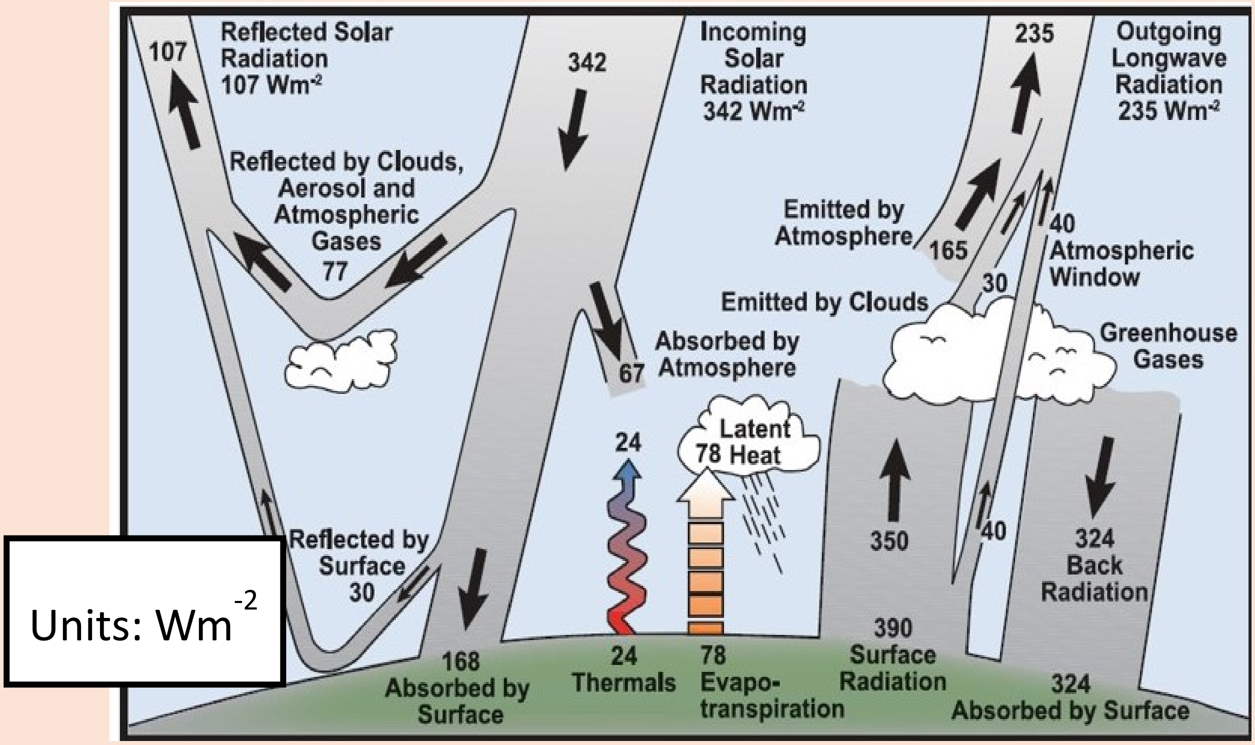

Figure 4.5 Global Energy Budget taken from http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/Kiehl_Trenberth_Radiative_Balance_BAMS_1997.pdf.

When the air is warmed by the surface of the Earth, it is less dense than the surrounding air and it moves upward (like a hot-air balloon). The effect is a transfer of energy from the Earth's surface to the air high in the atmosphere (warm air mixes with cool air). The vertical upward movement of the warm air occurs in the form of thermals – like the vertical cloud formations seen as part of storm or 'thunder' clouds. A similar effect occurs when air warmed by the Earth is recirculated into the atmosphere by wind. Energy transfer from the surface of the Earth by thermals and wind are the principal elements of atmospheric circulation.

'Evapotranspiration' refers to the use of energy to convert liquid water to water vapour by evaporation or by transpiration by plants. This is a significant amount of energy. Water vapour and the energy it contains leaves the surface of the Earth and becomes part of the atmosphere. When the water vapour condenses, the energy it contained warms the atmosphere. The effect is a transfer of energy from the Earth's surface to the atmosphere (cooling of the Earth's surface and warming of the air).

4.5 Conservation of Energy

The **principle of conservation of energy in a closed system** states that energy cannot be created or destroyed but may change from one form to another. The closed system is Earth, like the inside of the box shown in Figure 4.5. Energy reaching Earth and its atmosphere from the Sun (on top of the atmosphere) MUST equal the amount of energy leaving Earth and its atmosphere **plus** the amount of energy stored by Earth and its atmosphere. The energy balance of a closed system is said to be stable if the energy going into the system equals the amount of energy leaving the system which implies that the energy stored within the system is constant. However, much may be happening in terms of how the energy is moving around or being transformed from one type to another **within** the system.

The sides of Figure 4.5 represent the closed system considered when assessing conservation of energy and system stability. **Energy will only move vertically in or out of the system as shown. No energy moves horizontally (sideways).**

The top of Figure 4.5 (one side of our system) shows incoming solar radiation (energy from the sun) is equal to 342 Wm^{-2}. Of this 77 Wm^{-2} is reflected by the atmosphere (atmospheric gases, clouds, and aerosols) back into space, 67 Wm^{-2} is absorbed by the atmosphere, 30 Wm^{-2} is reflected by the surface of the Earth back into space and 168 Wm^{-2} is absorbed by the Earth. Note that the water vapour in the atmosphere is not part of the clouds where the water particles, liquid or ice, behave like other aerosols.

Energy that is absorbed by the Earth, 168 Wm^{-2}, warms the Earth and energy that is absorbed by the atmosphere, 67 Wm^{-2}, warms the atmosphere. The absorbed energy from the sun is transformed into thermal energy (warm Earth and warm air).

The warm Earth loses some of its thermal energy by thermals, 24 Wm^{-2} and by evapotranspiration, 78 Wm^{-2}. This energy warms the atmosphere.

The warm atmosphere and clouds will radiate 324 Wm^{-2} of long wave radiation back to the Earth and 165 Wm^{-2} plus 30 Wm^{-2} into space.

The warm Earth will lose thermal energy in the form of long wave radiation, 390 Wm^{-2}. The atmosphere and clouds will allow some of the long wave radiation to pass through without being absorbed, 40 Wm^{-2}.

The warm atmosphere and clouds will radiate 324 Wm^{-2} of energy back to the surface of the Earth. The warmed Earth will radiate a total of 390 Wm^{-2} back into the atmosphere.

Consider the energy budget for the Earth. The sum of the reflected solar radiation, 107 Wm^{-2}, and the amount of out going long wave radiation, 235 Wm^{-2},equals the amount of incoming solar radiation, 342 Wm^{-2}. The energy budget of the Earth is stable.

Consider the energy budget of the surface. The sum of the energy being absorbed and leaving the surface of the Earth must be equal or the Earth would be steadily warming. The amount of energy being absorbed by the Earth equals portion of solar energy absorbed, 168 Wm^{-2},plus back radiation from the atmosphere, 324 Wm^{-2},equals 492 Wm^{-2}. The amount of energy leaving the surface of the Earth equals the sum of thermals, 24 Wm^{-2}, evapotranspiration, 78 Wm^{-2}, and surface radiation, 390 Wm^{-2}, equals 492 Wm^{-2}. The energy budget of the surface is stable.

Consider the energy budget for the atmosphere as an internal system as shown in Figure 4.6. Energy into atmosphere equals the sum of solar radiation absorbed by atmosphere plus thermals plus evapotranspiration plus long wave radiation from the surface equal to 67 Wm^{-2} + 24 Wm^{-2} + 78 Wm^{-2} +390 Wm^{-2} = 559 Wm^{-2}. Energy out of the atmosphere equals the sum of outgoing longwave radiation and back radiation equal to 235 Wm^{-2} + 324 Wm^{-2} = 559 Wm^{-2}. The amount of energy entering the atmosphere and the amount leaving are the same. The energy budget of the atmosphere is stable.

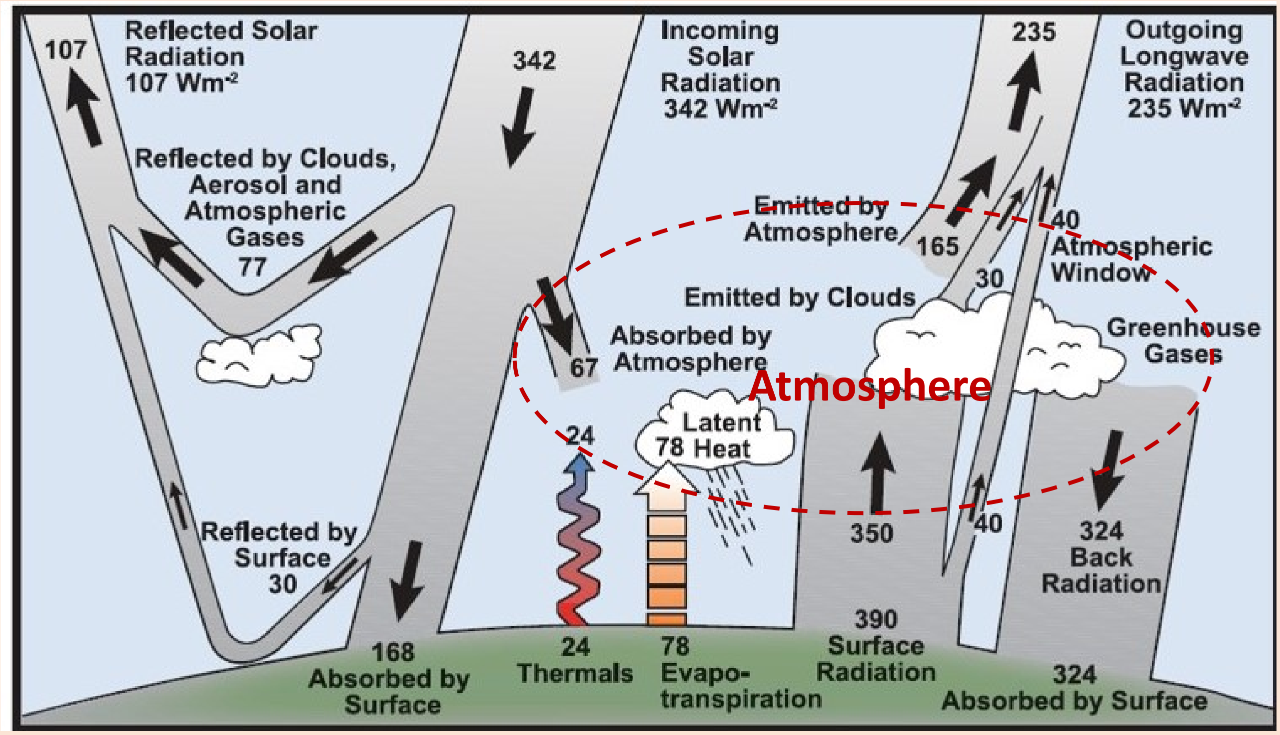

Figure 4.6. Energy budget of atmosphere.

4.6 Greenhouse effect

The ‘greenhouse effect’ refers to the increased warming of the Earth’s surface when an atmosphere and clouds are present. Without the atmosphere and clouds all of the solar energy will reach the surface, 342 Wm^{-2}. Of this 30/198 x 342 Wm^{-2} = 52 Wm^{-2} will be reflected from the surface (assuming per centage reflected remains the same). This means that 342 – 52 = 290 Wm^{-2} will be absorbed and ultimately emitted back into space as long wave radiation (assuming the energy budget is stable). This is considerably less than the amount emitted from the surface of the Earth when an atmosphere and clouds are present (492 Wm^{-2}) which implies that the surface is warmer with an atmosphere and clouds – the so-called greenhouse effect.

4.7 Impact of human activities on the energy budget.

It is very important to remember that the global energy budget as shown is in Figure 4.5 is the ‘long term average’ for the whole planet. The energy budget does in fact vary considerably locally and regionally and with time.

Also, even for a stable system, the energy movement within the system can vary significantly.

Humans affect the energy budget by modifying the Earth surface and the atmosphere by contributing to the accumulation of greenhouse gases and aerosols as shown in Figure 4.7. Essentially, **any modification** in the Earth’s surface or change in composition of the atmosphere will impact all of the components of the energy budget. While the amounts of reflected solar radiation and outgoing longwave radiation may vary their sum will always equal the amount of incoming solar radiation.

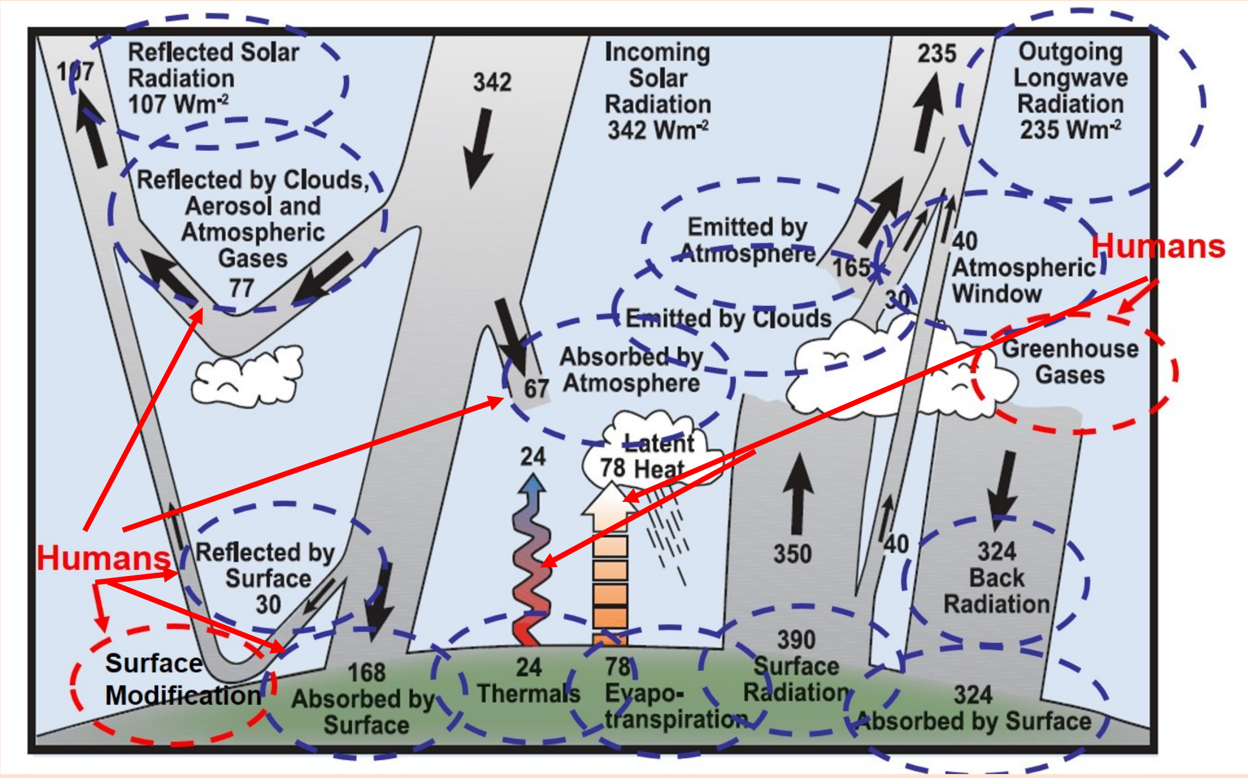

Figure 4.7. Components of energy budget affected by human activities.

4.8 Information support

Key web sites:

1. What is energy. https://www.eia.gov/energyexplained/what-is-energy/

2. Energy defined. https://www.britannica.com/science/energy

3. Forms of energy. https://en.wikipedia.org/wiki/Outline_of_energy

4. Overview of climate system. https://www.ipcc.ch/site/assets/uploads/2018/03/TAR-01.pdf

5. Earth's energy budget. https://en.wikipedia.org/wiki/Earth%27s_energy_budget

6. Earth's annual global mean energy budget. http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/Kiehl_Trenberth_Radiative_Balance_BAMS_1997.pdf

7. Sunlight. https://en.wikipedia.org/wiki/Sunlight

8. Solar radiation and photosynthetically active radiation. https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/

9. Energy education. https://energyeducation.ca/encyclopedia/Insolation

10. Solar energy to the Earth. https://energyeducation.ca/encyclopedia/Solar_energy_to_the_Earth

11. Black-body radiation. https://en.wikipedia.org/wiki/Black-body_radiation

12. Greenhouse gases. https://en.wikipedia.org/wiki/Greenhouse_gas#Atmospheric_lifetime

13. Greenhouse effect. https://en.wikipedia.org/wiki/Greenhouse_effect

14. Greenhouse effect. https://www.nrdc.org/stories/greenhouse-effect-101

Videos:

1. Greenhouse effect. https://www.youtube.com/watch?v=SN5-DnOHQmE