Summary

Topic 1 covers the way energy flows into and out of the Earth's climate system. If more energy flows into the climate system than leaves it, a fundamental law of physics, the “first law of thermodynamics,” requires that the ocean and atmosphere heat up. A change in the energy balance of the Earth’s climate system is the fundamental driver of climate change. Appendix 1 explores the first law of thermodynamics and related topics in somewhat more detail for those wishing to see how thermodynamic concepts apply to the Earth's climate system.

Energy Balance
And Some Fundamental Laws of Nature

Some Laws of Physics; The First Law of Thermodynamics
The entire physical world is governed by a set of immutable physical laws, discovered over the past several centuries by scientists. To be sure, they are being modified when applied to extreme circumstances. For example, Newton’s laws were modified by Einstein to account for circumstances dealing with relative motions approaching the speed of light and also modified by the “quantum theory” when studying what happens at the tiny dimensions of atoms.

These basic laws apply to the Earth’s climate system just as they do everywhere else in the Universe. Every aspect of the climate system and every change in the Earth's climate, respond to these physical laws: Nothing happens simply "by chance". How the Earth's climate system evolves under these laws can be very complex, and many of the details may not be able to be forecast much in advance (see Topic 4 on Weather and Climate).

Perhaps the most basic law of all governing the Earth’s climate system is called by physicists "The First Law of Thermodynamics". But for our purposes this fancy name can simply be restated as: "Energy is neither created nor destroyed, though it can flow from one place to another and can change its form." A shorthand name for this law is “the conservation of energy”, but here “conservation” doesn’t mean, “turn off your TV set when you are not watching it to save energy.” It simply means energy is neither created nor destroyed, but can change from one form to another. (A somewhat more sophisticated discussion of the First Law of Thermodynamics and its application to the deposition of energy into the Earth’s atmosphere is given in Appendix 1 to this Topic.)
Radiation, some laws that govern it, and different types of radiation.
Before seeing how this law applies to the Earth's climate system, we need to discuss how energy moves from one place to another. Energy flows in various forms. In this Topic we will focus on what physicists call “electromagnetic radiation” (EMR). EMR consists of waves that all travel at the speed of light. What we call “light” is simply EMR with wavelengths in a range that our eyes (and our ordinary cameras) can detect. But if the wavelengths are much shorter than this, the EMR is what we call X-rays, and if they are much longer, they are radio waves. EMR with wavelengths a little longer than what our eyes detect is called infrared radiation (IR), and our skin detects IR as heat, even though our eyes cannot see it. The motion sensors we use outside our houses sense changing amounts of infrared radiation given off by passing people--or animals!

There are a few important laws governing the emission and flow of heat by radiation that we need to discuss.

Radiation from the surface of a solid, liquid or large amount of gas.
We have described electromagnetic radiation as “waves” and for our discussion here that is a convenient description. But one of the remarkable lessons that quantum physics has taught us is that EMR can behave in some instances more like particles (called “photons”) than waves, and that is often the more appropriate way to describe it when dealing with the interaction between radiation and molecules in a gas, as in Topic 3 on the greenhouse effect.

In either description though, the character of the radiation given off from the surface of a solid or liquid (like the ocean) or from the surface of a large amount of gas (like the sun’s surface) depends strongly on the temperature of the surface, and not much else.
If the surface is very hot, as is the case for the sun’s surface, then most of the energy is radiated as visible light, but in the case of cooler surfaces, like the Earth, the energy is instead radiated in the form of infrared radiation. Figure 1 illustrates this, although the range of temperatures shown only covers those for surfaces as hot as the sun and a bit cooler, but it shows two important features:
Figure 1: How the intensity of radiation from surfaces of a fixed area varies with wavelength, depending upon the temperature of the surface. The curve labeled T=6000 K is pretty nearly the temperature of the sun’s surface.

In figure 1, note that the temperatures are measured in “K”, called “degrees Kelvin”. For those not familiar with the centigrade and Kelvin temperature scales, please see Appendix 2.

The dependence of the character of radiation on the surface temperature and the Stefan-Boltzmann Law
The most intense radiation from a surface as hot as the sun is concentrated in those wavelengths (represented by the colored stripes in Figure 1) that our eyes sense as light. For cooler temperatures, notice two things: the most intense radiation is produced at longer wavelengths, and, the total amount of radiation emitted from a cooler surface of 3000K is much less than that from a 6000K surface of the same area—about 1/16th as much. A very important law of radiation (the “Stefan-Boltzmann” law) states that the amount of radiation given off from a given area will increase as the temperature of the surface (expressed in the Kelvin scale) raised to the 4th power.

The temperature of the Earth’s surface varies a lot from the poles to the tropics of course, but the average value is currently about 59F = 15C = 288K. Most of the radiation from the Earth’s surface occurs at very much longer wavelengths (called “far infrared wavelengths”) than the radiant energy we get from the sun.

The Stefan-Boltzmann law is a fundamental result that governs how our climate responds to an energy imbalance: If the Earth’s surface is heated as a consequence of an energy flow imbalance, there will be a tendency of the Earth’s climate system to move in the direction of reaching a new balance at that warmer temperature by emitting more radiation according to the Stefan-Boltzmann law.

A simple description of the energy input and output of the Earth’s climate system
Now we can apply the basic law of “conservation of energy” to the Earth’s climate system. Imagine a large imaginary sphere surrounding the Earth, well above the Earth’s atmosphere. In fact, one can consider that it is on the surface of this imaginary sphere that the numerous satellites are orbiting that are devoted to studying Earth’s climate. Figure 2 (where we have drawn a flat Earth instead of our round globe!) shows several parts of the Earth’s climate system and the arrows represent the flow of energy between them.
A relatively very small amount of energy flows up from the Earth’s interior (due to radioactive decay and residual heat from the Earth’s initial contraction, both manifested as volcanic activity.) However, about 3500 times more energy than that enters the Earth’s climate system from radiant energy from the sun, mostly in the form of visible light, along with some near-infrared radiation.

This inflow of energy from the Sun is represented by the downward green arrows in Figure 2. Some of this energy is reflected back into space, especially by bright surfaces like clouds, snow, ice, and sandy deserts, but also by haze, both natural and man made, all represented by the pale yellow bar labeled “Clouds, Snow & Ice”. This reflected sunlight is represented by the upward yellow arrows. The fraction of the incoming sunlight that is not reflected back into space (about 70%) warms the surface of the Earth, both land and sea.

The warm surface of the Earth (whose, average temperature, as noted above, is about 59 F) sends infrared radiation headed back out into space. This is represented by two wide upward red arrows, one originating from the top layers of the land (the short brown bar), and the other from the ocean’s surface layers, represented by the light blue bar.

Not all of this infrared radiation escapes directly into space, however. Some molecules have a voracious "appetite" for absorbing and then re-emitting infrared radiation, the two most important in the Earth’s atmosphere being water vapor (H₂O) and carbon dioxide (CO₂), but there are several others as well. The upper pale gray bar represents the Earth's atmosphere and the two black "stars" indicate where CO₂ molecules have intercepted some of this radiation.

This intercepted radiation is re-emitted. Some of this re-emitted infrared energy is directed back towards the Earth’s surface, (the downward red arrows) where it is absorbed and further warms the Earth’s surface. This extra warming is the famous "greenhouse effect" which will be discussed in more detail in Topic 3. Some of the infrared
radiation does eventually work its way out into space and this is represented by the topmost upward red arrows.

The blue arrows show the exchange of energy between the shallow and deeper layers of the ocean, not by radiation, but by the circulation of water with different temperatures. In Topic 5 we will talk about the large blue lower area (the deep ocean) as well as the significance of these blue arrows representing the exchange of energy between the ocean surface layers and the deeper ocean.

If the diagram of Figure 2 represented your savings account and you wanted to know whether you would have anything left over to add to your savings account at the end of the year (or whether you had to withdraw some!) you would start with your gross income (the incoming sunlight) then subtract "right off the top" the loss due to taxes (the reflected sunlight) and then further subtract off your net expenses (the escaping upward red arrows). If we pushed the analogy a little further we might say that the downward red arrows were rebates on our purchases, but no analogy is perfect!

So, from the point of view of the satellites orbiting well above the Earth’s atmosphere, if we want to ask the question: Is the Earth gaining or losing energy or is it in approximate energy balance “all we have to do” is ask the satellites to measure the incoming solar radiation, subtract off the reflected sunlight and in addition subtract off the escaping infrared radiation and see if there is an energy imbalance. If, averaged over a few decades, there is an energy imbalance, then the Earth’s surface will either heat up or cool down. This is the inescapable result of the First Law of Thermodynamics.

**What does all of this have to do with climate change?**
It turns out that these are not an easy set of measurements to make, but, as we will discuss in Topic 5, there is very strong evidence that probably for at least a century, and especially for the past several decades, the Earth’s climate system is not in energy balance, and in fact is gaining energy.

Why have we introduced energy balance and the conservation of energy as the first topic in this series? Because energy imbalance is the fundamental cause of climate change: Here is the first sentence from the abstract of a paper by the group of scientists at NASA’s Langley Research Center, who are world leaders in the development of the satellites that make the observations of the energy imbalance noted above, as well the analysis of the data from these satellites:

“Global climate change results from a small yet persistent imbalance between the amount of sunlight absorbed by Earth and the thermal radiation emitted back to space.”

**Some future topics**
To this succinct summary I would only add the slight amendment that a significant change in the geographical distribution of the energy input also initiates profound changes in the climate, as will be discussed in Topic 7, in connection with the Ice Ages.

In Topic 5 we will discuss the evidence that the Earth’s climate system is indeed not in energy balance, but before that we will explore several other important concepts: "Forcings and Feedbacks", which is discussed in Topic 2; the greenhouse effect, which is covered in
Topic 3; and in Topic 4, we emphasize the important distinction between “weather” and “climate.”

Appendix 1: Energy, Enthalpy and the First Law of Thermodynamics

The following material is a bit more technical than the main portion of this Topic, but I hope even readers without any background in science will find it of interest. I hope it will also be useful for teachers and students in seeing how thermodynamic principles can be applied to the Earth’s atmosphere. I also include this appendix because one generally encounters a statement like “heat deposited in the atmosphere increases the heat energy of the atmosphere.” The situation is slightly more nuanced than that and involves the distinction between energy and enthalpy in the context of heat deposited in the atmosphere.

Mathematical Statement of the First Law of Thermodynamics and some historical background

Historically, the sub-discipline of physics known as “thermodynamics” was driven by the desire to understand, and improve on, the efficiency of engines. In such “heat engines” a fluid or gas (e.g. steam) is heated and the increased pressure causes a piston to move resulting in mechanical work being done. (In an actual engine, the gas is repeatedly cycled through stages involving injection of heat from a high temperature source, expansion and subsequent discharge of heat at a lower temperature and compression to complete the cycle.)

The formulation of the first law of thermodynamics took place in the 1800s. We can state it as follows, where we specifically have in mind application to the two gases making up most of the Earth’s atmosphere: About 80% of the molecules are molecular nitrogen (N₂) and 20% are molecular oxygen (O₂).

In symbols, the first law of thermodynamics can be written

\[ \Delta Q = \Delta U + \Delta W \]  
\[ \Delta W = P \Delta V \]

The symbol \( \Delta \) is used to indicate a small and non-abrupt change in the state of the gas. In words, this equation says that the heat energy, \( \Delta Q \), injected into a given quantity of gas results in increasing the internal energy of the gas, \( \Delta U \), plus whatever work, \( \Delta W \), is done by that gas as, and if, it expands. The work, \( \Delta W \), done by the gas (if, for example, it were pushing against a piston) is given by the pressure, \( P \), of the gas, times the increase in the volume of the gas, \( \Delta V \).

In the case of the Earth’s atmosphere, there are several processes involving continual exchange of energy between the atmosphere and the rest of the Earth’s climate system. However, over the last several decades a net amount of energy has been deposited in the Earth’s atmosphere, though far more has been deposited in the ocean, as discussed in Topic 5.
What is the result of that heat deposited into the atmosphere? In particular, what portion of the heat injection, $\Delta Q$, goes into increasing the internal energy, $\Delta U$, and what portion, if any, goes into work associated with the expansion of the gas, $P\Delta V$—and if work is done by the gas, what is the nature of that work?

To answer this, we need to consider two more concepts:

**What is “Internal Energy”?**
What do we mean by “internal energy” and how is it related to the familiar measures of temperature, pressure and volume? In the case of the nitrogen and oxygen molecules composing air, this internal energy consists of the random to-and-fro motions of these molecules in all three spatial directions: the more vigorous the motion, the more internal energy of the gas. But if you picture these molecules as tiny dumb-bells, with each of the two atoms of the molecule at each end of the dumb-bell, the molecules can also spin around each of the two axes perpendicular to the line joining the two atoms in the molecule, and this rotational energy also contributes to the internal energy. (The masses of the atoms themselves are confined to such a small volume that spinning about the third axis of the molecule joining the two atoms makes essentially no contribution to the internal energy.)

It is a fundamental result of the branch of physics related to thermodynamics, “statistical mechanics”, that the amount of internal energy is equally distributed among these five “degrees of freedom”, (three spatial motions and two rotational motions) and the amount of energy associated with each of these motions is given by $\frac{1}{2}kT$ where $T$ is the temperature (measured on the Kelvin scale), and $k$ is a numerical constant. This means that the internal energy for each molecule of air is $5/2kT$.

**The Ideal Gas Law connecting the Pressure, Volume and Temperature of a Gas**

Prior to the formulation of the first law of thermodynamics, earlier work on the properties of gases lead to the *ideal gas law* connecting the pressure of the gas, $P$, the volume, $V$, occupied by the gas, and the temperature, $T$, of the gas, which must measured on the Kelvin temperature scale. (See Appendix 2 for a discussion of the Kelvin scale.) The volume occupied by the gas depends, of course, on how much gas there is in whatever gas sample we are measuring. This is usually expressed in terms of the number of molecules in the sample of gas, and is generally measured in units of “mols”. One mol comprises a specific, but huge, number of molecules, $N$ (called “Avogadro’s number.”) The word “ideal” in the “ideal gas law” simply means that longer-range forces between the molecules of the gas can be ignored—that is quite a good approximation for air. In symbols, the ideal gas law states that for one mol of gas:

$$PV = NkT = RT$$

where the two constant numbers $N$ and $k$ are often combined in the single constant $R$. (Knowing the mass of the nitrogen and oxygen molecules and how many molecules there are in a mol, it turns out that the mass of one mol of air is about 28.8 grams.)

From the result that the internal energy associated with each molecule of air is $5/2kT$, from equation (3) the internal energy of one mole of air is given by

$$U = \frac{5}{2}NkT = \frac{5}{2}RT = \frac{5}{2}PV$$
Pressure balance and the concept of hydrostatic equilibrium

Finally, we need to introduce the concept of “hydrostatic equilibrium”. Applied to the Earth’s atmosphere this simply means that the pressure at the base of the atmosphere (or at any higher level) must be such that, on average, it holds up the weight of the mass of air above it. Imagine that all the air were suddenly removed from below a molecule of air 32,000 feet above the Earth’s surface. It would fall to Earth in only about 45 seconds and strike the Earth’s surface at nearly 1000 miles per hour! So, comparing this short time with many decades, the atmosphere will on average never be far from hydrostatic equilibrium. To be sure, from moment to moment, and from place to place, there will be significant departures from this, as anyone riding an airplane through a thunderstorm can attest. But averaged over a long period of time and over the Earth's surface, since the total mass of air in the atmosphere has not changed significantly, the average pressure at the Earth’s surface will not have changed significantly over many decades, though we know that moderate variations in air pressure are continually occurring from place to place and time to time.

This means that the change in the internal energy of one mol of air at a level supporting a given mass of air above it will be due to any change in its volume, not its pressure, so

\[ \Delta U = \frac{5}{2}P \Delta V \]  

Going back to equation (1) for the first law of thermodynamics this also means that over the course of several decades, an injection of heat \( \Delta Q \) results in a change in volume and temperature of one mol of air of

\[ \Delta Q = \frac{5}{2}P \Delta V + P \Delta V = \frac{7}{2}P \Delta V = \frac{7}{2}R \Delta T \]

where the last relation results from the ideal gas law with the pressure held constant.

The ratio of the amount of heat deposited in one mol of gas to the increase in temperature, when the gas is held at constant pressure, is then just

\[ \frac{\Delta Q}{\Delta T} = \frac{7}{2}R \]

and the simple expression given by equation (7) is a very good approximation to actual measurements. So, it is the specific heat at constant pressure that is relevant to understanding how the atmospheric temperature changes when heat is deposited in it.

Energy, Enthalpy and Work Done by the Atmosphere

Above, we posed the question as to what portion of the heat injection, \( \Delta Q \), goes into increasing the internal energy, \( \Delta U \), and what portion goes into work. From equations (5) and (6) we see that 5/7 (about 70%) of the heat deposited in the atmosphere goes into increasing the internal energy of the air, but about 30% does “work”. What does this work involve since there is no actual piston being pushed against? The answer is that the work is done against gravity—the atmosphere “stands a little taller”, so its gravitational potential energy has increased slightly, in the same way that carrying a rock a little further uphill requires work and increases the rock’s gravitational potential energy.
In addition to the concept of "internal energy", physicists have introduced a quantity called \textit{enthalpy}, defined as the internal energy, $U$, plus the pressure times the volume: $P*V$. It is usually denoted by "$H$", so $H = U + PV$. In the context of changes involving a fluid occurring under constant pressure, $\Delta H = \Delta U + P\Delta V$. Comparing this with the heat input according to the first law of thermodynamics, as written in equations (1) and (2), the input of heat into a fluid under constant pressure is equal to the change in enthalpy of that fluid. (For a nice discussion of enthalpy and its relation to heat deposition at constant pressure, see the following Khan Academy video: \url{https://www.khanacademy.org/science/chemistry/thermodynamics-chemistry/enthalpy-chemistry-sal/v/enthalpy})

Though we have discussed here only the atmosphere, the same general principles apply to the ocean, but water cannot be remotely considered an ideal gas. At constant temperature it is barely compressible when pressure is applied, though at constant pressure its volume changes with temperature. That change is not as simple as for an ideal gas though, and in fact near the freezing point, water actually contracts, but then expands as the temperature is further increased. Though the expansion is not large, as the ocean has been warming, the expansion plays an important role in sea level rise, as discussed further in Topic 9.

\textbf{Some Numbers: About how much net heat as been deposited into the Earth’s atmosphere recently?}

During the 35 years between 1980 and 2015, the average surface temperature has increased by about 0.6 degrees Kelvin. (Satellites began collecting extensive data on all aspects of the climate system since about 1980.) How much heat was injected into the atmosphere to achieve this? Knowing the total mass of the Earth’s atmosphere, we can calculate the number of mols of air, and therefore from the relation between heat input and temperature increase in equation (6) we can make a simple estimate of the heat input. If this surface temperature increase were shared at all levels of the atmosphere, then about $3*10^{21}$ Joules would be required. (A Joule is a unit of energy equal to the energy consumed or transferred in one second at a rate of one Watt.) This estimate should probably be reduced a bit (say, by about 20\%) to about $2.4*10^{21}$ Joules, since we know that the distribution of heat throughout the atmosphere leads to a drop with altitude in the temperature below the surface value. Though still small compared to the total heat input during this time (most of which goes into the ocean) this is still a huge amount of energy. Dividing that amount of energy by the number of seconds over 35 years implies an average power input of about 2000 billion Watts, about 1000 times the power produced at the PG&E nuclear power plant at Canyon Diablo.

This comparison is not meant to imply that the “waste heat” given off from power generation (from whatever fuel source) is responsible for most of the heat deposited in the atmosphere. As we will discuss in further topics, this energy imbalance is due to an increase in the amount of greenhouse gases in the atmosphere, now caused primarily by the burning of fossil fuels.

\textbf{Appendix 2: Scientific Temperature Scales}

Just as we in the US use feet and miles to measure distances while most of the rest of the world uses the metric system—meters and kilometers—so there are three different
temperature scales: Fahrenheit, Centigrade (or Celsius) and Kelvin. In the US we use the Fahrenheit scale (32 °F = freezing water, 212 °F = boiling water) while most of the rest of the world uses the centigrade, or Celsius, scale: 0 °C = freezing water, 100 °C = boiling water. Here is the formula to go from C to F: °F = 1.8°*C +32. So, for example, 20 degrees C is 68 °F. The “K” (the Kelvin scale) used by scientists is related to the centigrade scale by simply adding 273: K = C + 273. The significance of K = 0 (a rather chilly -459 °F!), is that the jiggling motion of atoms in a gas slows to a halt—“absolute zero”. The distinction between the C scale and the K scale becomes important when discussing the laws governing how a gas behaves, as in Appendix 1.