3.1 Equilibrium Temperature of a Planet

- Heat in (absorbed solar radiation) balances heat out (emitted Earth radiation)
- Heat in depends on Sun's brightness & distance, and albedo
- Earth absorbs solar radiation as a disk: $S(1-\alpha)\pi r^2$
- Earth emits outgoing longwave radiation as a sphere $\sigma {T_e}^4 4\pi r^2$
- Equilibrium temperature of any planet $T_e = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{1/4}$

3.2 The Greenhouse Effect

- Equilibrium temperature of Earth calculated from solar constant S=1361 W m^{-2} and albedo $\alpha = 0.3$
- Equilibrium temperature of the Earth is 255 K = -18 C = -1 F (very cold!)
- Actual surface temperature is 288 K = 15 C = 59 F (much warmer!)
- Difference between surface temperature and equilibrium temperature due to greenhouse effect
- Gases in our atmosphere (especially CO2 and H2O) absorb emit infrared radiation
- Downward longwave radiation at the surface makes Earth habitable!

3.3 Greenhouse Gases

- Energy is quantized
- Molecules and photons
- Vibrational transitions in the IR
- Charge asymmetry (electric dipole moment)
- Optical thickness and opacity
- IR spectrum of Earth from space
- Radiative forcing by increasing CO2

3.4 Vertical Energy Exchange

- Greenhouse effect depends on vertical temperature differences
- Emission to space comes from cold upper air (sigma COLD^4), but emission down to surface comes from warmer lower air (sigma * WARM^4)
- Air is warmed from below, vertical mixing carries heat aloft
- Vertical mixing opposes (weakens) the greenhouse effect!
- Vertical energy exchange is dominated by radiation
- Atmosphere radiates much more power than received from the Sun!
- Job of winds and ocean currents is to move heat to where it can escape (up & poleward)

3.5 Lateral Energy Exchange

- Absorbed solar radiation is distributed mostly according to latitude (more in tropics, less at poles), details depend on albedo
- Outgoing longwave radiation depends on temperature of emitter (not just latitude)
- OLR greatest over hot deserts, least at poles, but also low from cold clouds over tropical rainforests
- Net accumulation of radiant energy in tropics, net loss at poles
- Winds and ocean currents carry energy from tropics to poles, equalize temperatures
- Massive poleward energy transport responsible for jet streams, Trade Winds, ocean gyres

3.6 Surface Energy Exchange

- Surface is the primary heat source for the atmosphere
- Surface is heated by absorbed solar radiation and cooled by emission of thermal IR
- Residual (incoming SR minus outgoing LR) warms the surface
- Warm surface transfers heat to atmosphere by convection
- Convective heat flux dominated by evaporation (especially over oceans)
- Rising water vapor condenses in the atmosphere, releases latent heat

3.1 Equilibrium Temperature of a Planet

We saw in Module 2 that the only way the Earth can exchange heat with the rest of the universe is through electromagnetic radiation, because there can be no conductive nor convective heat transfer to the vacuum of space. Now we'll look in more detail at the processes of heat in (from absorbed solar radiation) and heat out (by emission of thermal infrared radiation). It turns out to be very simple to calculate the total heating power (rate of absorbed sunlight) and cooling power (rate of heat loss by emission) for the planet as a whole.

The ***only way Earth's average temperature can change is for incoming and outgoing heat to become imbalanced***. When any planet, moon, or other celestial body is in thermal equilibrium, the power of incoming and outgoing radiation are in balance. If an imbalance occurs, then the planetary temperature simply rises or falls until equilibrium is restored.

In words, we can write "Heat in Minus Heat Out equals Change in Heat." In this module, we're just going to consider the equilibrium case where there is no change of heat, where temperature is constant. So "Heat In equals Heat Out." To be more precise we can write

$$F_{in} = F_{out}$$

where F_{in} and F_{out} stand for flux (power) in and out in Watts per square meter (W m^{-2}).

3.1.1 Heat In: Absorbed Sunlight

The power or flux of incoming heat is the rate at which sunlight is absorbed by the planet. This depends on the brightness of the Sun at the distance of Earth's orbit, and the albedo or reflectivity of the Earth. As we learned in Module 2, the albedo of Earth as a whole is about 30%.

So we can write

$$F_{in} = S(1 - \alpha)A_{absorbtion}$$

where S = 1361 W m^{-2} is called the "solar constant" and α is the albedo. S is the average brightness of the Sun on a surface perpendicular to its rays above our atmosphere. In reality this number is not perfectly constant but varies a tiny bit (less than 1%) from year to year through an 11-year sunspot cycle. But for now we can pretend it's exactly constant.

To calculate the total power of absorbed sunlight in Watts we need to multiply by the area A illuminated by the Sun. Sunshine shines straight down at just one location on Earth at any given time. At this "subsolar point," the Sun is precisely at the zenith (highest point in the sky). Everywhere else the Sun is lower and its rays are spread out more

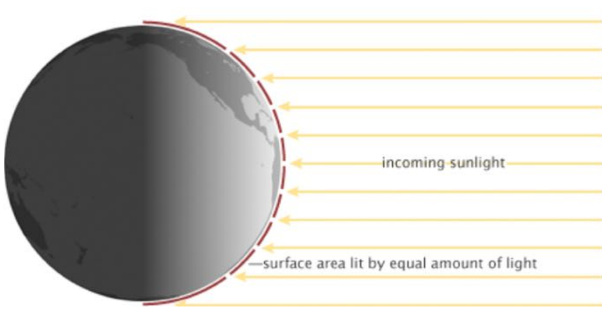


Figure 3-1: Incoming sunlight is spread out according to its angle of incidence to the spherical Earth

and more as it approaches the horizon (Fig 3-1). Of course, it's always night on half the Earth, so that half gets no sunlight at all.

It's possible to use geometry to scale incoming sunlight according to the angle of the Sun in the sky, but we don't need to bother. Instead, we can just use the fact that the Earth casts a cylindrical shadow behind it and calculate the cross-sectional area of that shadow. The total amount of sunlight absorbed is the part that's "missing" in that cylindrical shadow.

The cross-sectional area of the Earth's shadow is a circle whose radius is the same as the Earth's:

$$A_{shadow} = \pi r^2.$$

So the total rate of planetary heat absorption from solar radiation is just

$$F_{in} = S(1-\alpha)\ \pi r^2.$$

We can say that Earth absorbs sunlight exactly as if it were a disk with radius r and albedo α.

3.1.2 Heat Out: Emitted Longwave Radiation

Earth emits thermal radiation (also called ***outgoing longwave radiation*** **abbreviated** ***OLR***) as a blackbody. In Module 2 we learned that blackbodies emit energy according to their temperature:

$$F_{BB} = \sigma T^4$$

So the total power of Earth's OLR is

$$F_{out} = \sigma {T_e}^4 A_{emission}$$

where T_e is the equilibrium temperature of the Earth, $A_{emission}$ is the area emitting thermal radiation, and σ is the Stefan-Boltzmann constant. We saw that Earth absorbs sunlight as if it were a disk, but it emits OLR from the entire sphere. Even the dark night side of the planet emits infrared radiation to space and thereby cools the planet.

The surface area of a sphere is $4\pi r^2$ so we can write

$$F_{out} = \sigma {T_e}^4\ 4\pi r^2.$$

The Earth emits OLR over four times as much area as it absorbs incoming sunlight!

3.1.3 Thermal Equilibrium

Now we can combine our formulas for heat in and heat out by setting them equal to one another:

$$F_{in} = F_{out}$$

$$S(1-\alpha)\ \pi r^2 = \sigma {T_e}^4\ 4\pi r^2.$$

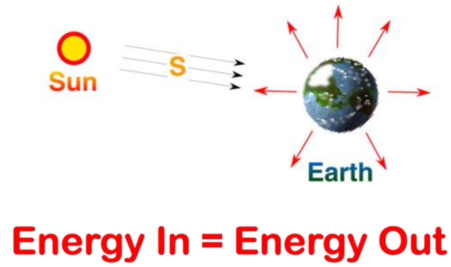


Figure 3-2: Radiative equilibrium of the Earth

Because we have the area of a circle (πr^2) on both sides, we can just cancel it:

$$S(1-\alpha) = \sigma {T_e}^4\ 4.$$

It's easy to rearrange this equation and solve for Earth's equilibrium temperature:

$$T_e = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{1/4}$$

This is pretty amazing! Remember that s is just a measurable physical constant. This means that the temperature of any planet depends only on the brightness of its sun and the albedo of the planet. The brighter the star (or the closer the planet orbits to its star), the hotter it will be. And the more reflective the planet (the higher its albedo), the colder it will be. That's it!

3.2 The Greenhouse Effect

Now we can very easily calculate the Earth's equilibrium temperature.

We use S=1361 W m^{-2} for the solar constant, α=0.3 for the albedo, and of course σ=5.67 x 10^{-8} W m^{-2} K^{-4} for the Stefan-Boltzmann constant. Substituting these values, we get

$$T_e = \left[\frac{S(1-\alpha)}{4\sigma}\right]^{1/4} = \left[\frac{(1361\ W\ m^{-2})(1-0.3)}{4(5.67\ x\ 10^{-8}\ W\ m^{-2}\ K^{-4})}\right]^{1/4} = 255\ Kelvin$$

Recall that water freezes at 273 K, so this calculation shows that the ***Earth is in fact very cold!*** The Earth's equilibrium temperature is 255 K = -18 ºC = -0.4 ºF. That's colder than all but a very few winter nights per year in Fort Collins, Colorado.

By contrast, people have traveled the whole world with thermometers and the temperature is much warmer than the equilibrium temperature. In fact, the global average surface air temperature is about 288 K = 15 ºC = 59 ºF. That's 33 ºC or 60 ºF warmer than the equilibrium temperature!

The ***difference between the global mean surface air temperature and the equilibrium temperature is due to the Greenhouse Effect***. Planetary equilibrium temperature is the effective temperature at which Earth emits photons of infrared radiation to space. It's the radiating temperature required to balance absorbed solar radiation.

Greenhouse gases in Earth's atmosphere (especially carbon dioxide and water vapor) absorb outgoing longwave radiation. This means that the ***infrared photons that actually reach space are emitted from high altitudes in the atmosphere where it's cold – about 255 K***.

Those same greenhouse molecules that absorb infrared photons also emit photons of the same wavelength, in every direction. Gases lower in the atmosphere where it's warmer emit radiation that is absorbed by the surface. This downward longwave radiation adds very substantially to the radiant energy heating Earth's surface. Without downward longwave radiation, the surface would cool so much every night that our planet would be a frozen wasteland like Antarctica!

We can think of the greenhouse effect as being driven by two things:

1) ***the selective transparency of the atmosphere and***
2) ***the fact that its much warmer near the ground than it is at high altitudes.***

Visible light streams right through the atmosphere almost as if it weren't there. Of course, we know that because otherwise we wouldn't be able to see distant objects and it would be dark all the time!

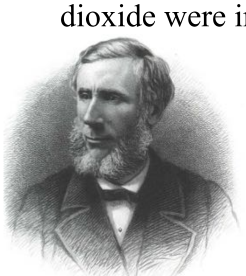
But thermal infrared radiation emitted by objects with temperatures of a few hundred Kelvin (like the Earth) can't get very far through thin air. It gets absorbed by molecules of greenhouse gases. The air is opaque to radiation in thermal infrared wavelengths. This isn't intuitive because we can't see those wavelengths.

Joseph Fourier, 1822: "l'atmosphere functionne comme une serre"

The greenhouse effect was first discovered by the French scientist and mathematician Joseph Fourier in the 1820s. He calculated the radiative equilibrium temperature of the Earth and found that it should be much colder than actual temperatures. He speculated that the atmosphere must function something like a greenhouse used to grow plants (called a *serre* in French). He wrote in 1822 that like a greenhouse, the atmosphere must be able to let heat from sunlight in but then retain it somehow.

Eunice Foote (1856): "the highest effect [is] in carbonic acid gas"

A generation later, American scientist Eunice Foote measured changing temperatures in jars of different gases in sunlight. She concluded that water vapor, methane, and especially carbon dioxide were in fact responsible for the greenhouse effect described by Fourier. Her research was published in 1856. The Irish physicist John Tyndall built on Foote's work by conducting more elaborate experiments in which he quantified the absorption of infrared radiation by different concentrations of different gases. In 1863 he wrote that accumulations of CO_2 from burning coal were likely to warm the climate.



John Tyndall

Svante Arrhenius

In 1896, the Swedish chemist Svante Arrhenius worked out the physics and math of Earth's radiation budget pretty much as we understand it today. He calculated that rising CO_2 would warm the climate by a given amount per doubling of the amount of CO_2 in air and estimated the Earth's climate sensitivity as about 3 ºC per doubling of CO_2 concentration. Remarkably, this is about the same value for climate sensitivity that we find by many methods 125 years later!

Many people mistakenly assume that the relationship between rising CO_2 and global warming was discovered recently, and that it's based on correlation between observed CO_2 and temperature. This is not true.

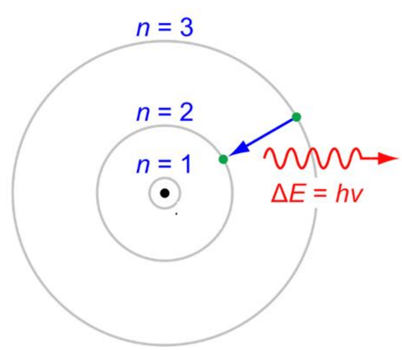
The ***relationship between CO_2 and climate was discovered in the 19th century by laboratory experiment and the resulting global warming was predicted more than 175 years ago.*** It's not based on statistical correlations but on solid physical measurements and the science was part of the explosion of scientific advances of the era of steam locomotives.

3.3 Greenhouse Gases

3.3.1 Matter and Energy Are Quantized

Deep down inside, all matter is composed of molecules which are in turn composed of atoms, which themselves are composed of protons, neutrons, and electrons. There are even smaller things that make these up, but we can ignore them here. At the scale of atoms and subatomic particles, especially when they interact with electromagnetic radiation, stuff is very weird. This is the quantum realm!

Negatively charged electrons "orbit" far above the positively charged nuclei of atoms in a way that analogous to planets orbiting the Sun. They are pulled "down" toward the nucleus by the electromagnetic attraction of the protons, but they have enough kinetic energy to stay "aloft" and not fall in.



Atomic emission

A photon of light can be absorbed by an atom, capturing the radiant energy and using it to "bump" an electron up to a higher orbit. Later, the electron can fall back to its original orbit and a photon of the same wavelength will be emitted as was absorbed in the first place. Both absorption and emission will have exactly the same energy as the difference between the lower and upper electron orbits.

But unlike planets orbiting the Sun, electrons can't just gradually climb to higher and higher or fall to lower and lower orbits. There are only a small number of very specific energies at which they can fly around. This means that the ***atom can ONLY absorb or emit certain very specific wavelengths of light whose photons correspond precisely to the differences in energy levels allowed for its electrons***.

This is what we mean when we say the energy of atoms is quantized: that it can only take certain discrete values. The electron can orbit in shell #2 or shell #3. There is no such thing as an electron orbiting in "shell 2.37." Atomic absorption and emission of discrete quanta of radiant energy like this is the basis of spectroscopy. We say that each element has absorption and emission lines that we can measure. It's how we know what stars and planets are made of, and it's how motor vehicle tailpipe emissions are measured, among many other applications.

3.3.2 Molecules and photons

Atomic absorption or emission that bumps electrons up or down to different orbits typically involves radiation at ultraviolet or visible wavelengths. They're pretty energetic transitions. Molecules interact with weaker electromagnetic fields. In other words, they absorb and emit longer wavelengths, typically in the infrared or microwave parts of the EM spectrum.

Molecules consist of two or more atoms bound together by sharing electrons between them. Some of the electrons from the outer shell of each atom move back and forth between both nuclei in an elongated path we call a chemical bond. When the electrons are far from the positively charged nuclei like this, they are much more susceptible to being knocked around by passing electromagnetic fields (photons) than the electrons in atomic orbitals.

Even a relatively weak photon (low frequency, long wavelength) can disturb a molecule. In the thermal infrared part of the EM spectrum, these disturbances take the form of bending or vibrations of the molecule along the bonds. In other words, the bonds can change their angle or get longer and shorter by absorbing the energy of a weak passing photon.

Just like atomic transitions involving lifting or dropping electrons among orbitals, molecular transitions involving bending or vibration are quantized. That is, there are only a few possible states of vibration and rotation so radiation of only a few discrete wavelengths can be absorbed or emitted. These ***absorption and emission "lines" are the basis of molecular spectroscopy***.

3.3.3 Diatomic vs Triatomic Molecules and Electric Dipole Moments

Nearly every molecule in air is ***diatomic***, composed of two atoms of the same element: nitrogen is N_2 (about 78% of the air) and oxygen is O_2 (about 21%). These molecules form little "barbell" shapes with one nucleus on either end and a line of shared electrons flying back and forth in between making the chemical bond. They are perfectly identical on each end, so the positive and negative charges are distributed evenly throughout. There is no "positive end" or "negative end" for passing electromagnetic fields to grab onto. We say these molecules "***have no electric dipole moment.***"

The symmetric nature of diatomic molecules means that the only way N_2 and O_2 can absorb or emit infrared radiation is to change the frequency at which they get longer and shorter along the axis of the chemical bond. You can visualize these vibrations as balls (nuclei) oscillating back and forth symmetrically on a spring (the bond). This "***symmetric stretch***" of N_2 and O_2 and molecules won't produce any charge asymmetry (electric dipole moment" no matter how fast they bounce. This property makes them very weak absorbers in the infrared.

A very small percentage of the molecules in air are ***triatomic*** (three atoms) rather than diatomic. By far the most abundant of these are water vapor (H_2O) and carbon dioxide (CO_2). The geometry of triatomic molecules allows way more degrees of freedom for them to vibrate and bend than is the case for the vast majority of the gases in air!

Carbon Dioxide (CO_2)

The CO_2 molecule is linear: all three atoms are arranged in a line with carbon in the middle and one oxygen on each end (Fig 3-3). Just like O_2 and N_2, the molecule can absorb a weak IR photon to get longer and shorter via the "symmetric stretch."

But wait, there's more!

Unlike 99% of the molecules in the air (O_2 and N_2), triatomic CO_2 can stretch ***asymmetrically***. In this oscillation the bond at one end gets longer while the bond at the other end gets shorter. In other words, the carbon atom bounces back and forth between the two oxygen atoms.

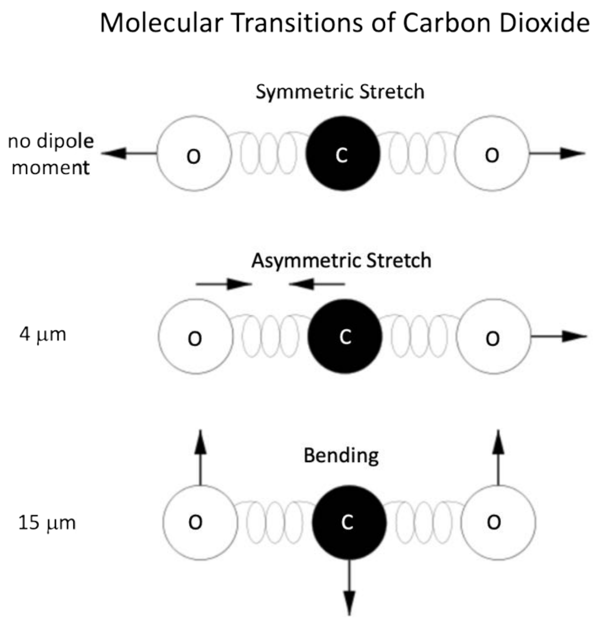


Figure 3-3: Three ways CO2 can wiggle in time with a passing electromagnetic field. Spring symbols represent shared electrons of the chemical bonds between C and O

Oxygen, in the second-rightmost column of the Periodic Table of Elements, "holds on" to electrons like fury and desperately wants two more. Carbon lies in the mellow middle column and can take or leave four electrons. It's this "I can go either way" attitude with respect to electrons that makes carbon the building block of organic chemistry.

When the CO_2 molecule oscillates in an asymmetric stretch, the molecule temporarily gains an electric dipole due to the uneven distribution of charges along its length. The end with the C and O close together becomes a little bit positive and the end with the C and O further apart becomes a little bit negative. This ***"temporary dipole moment" gives the electromagnetic field a handle to grab onto, so the energy associated with the asymmetric stretch is much greater*** than the energy associated with the symmetric stretch.

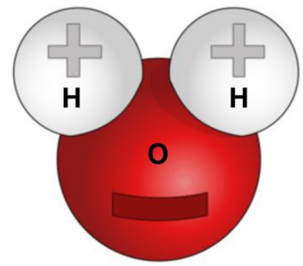
The other important oscillation the triatomic CO_2 can do that O_2 and N_2 can't is ***bending***. The bonds flex back and forth with the central C going one way while the O at each end goes the other. Like the asymmetric stretch, ***bending gives CO_2 a temporary dipole moment because the slightly positive C is at one side of the bend and the slightly negative Os are at the other***. So, like the asymmetric stretch, bending is also associated with strong absorption and emission of infrared photons.

The ***temporary dipole moments associated with bending and asymmetric stretching are what make CO_2 a greenhouse gas***. It's just physics – the simple result of electromagnetic fields acting on positive and negative charges differently.

It's not greed. Not capitalism. Not Al Gore. It's just bad luck that the gas created when carbon is burned in oxygen can oscillate back and forth in resonance with electromagnetic fields emitted by objects at around Earth's temperature. Charged particles and electromagnetic fields don't exercise moral judgements. They just wiggle the way they wiggle.

Water Vapor (H_2O)

Water vapor is an even more powerful greenhouse gas than CO_2 because the H_2O molecule has a permanent dipole moment.



The ***H_2O molecule is bent***, with the hydrogen-oxygen bonds at an angle of about 105º to one another. You can think of H_2O as looking like a cartoon Mickey Mouse head: the small hydrogen atoms make up the ears and the bigger oxygen atom makes up the rest.

The hydrogen ears of the Mickey Mouse H_2O molecule are slightly positive, and the oxygen face is slightly negative because as always oxygen is super-hungry for electrons to fill its outer shell. This asymmetric distribution of electric charge makes water a ***polar molecule***, with a plus end and a minus end.

The polar nature of water is what makes it the "universal solvent" in liquid form and it also makes H_2O a powerful greenhouse gas. Like CO_2, water vapor can stretch symmetrically and asymmetrically. The bonds can spread out and come back together. The polar molecule can even perform flips in time with passing electromagnetic field! Each of these oscillations and every combination of them absorbs and emits a different wavelength of IR radiation. We say that water vapor has a rich absorption spectrum in the IR.

Unlike CO_2, when a lot of water vapor accumulates in the atmosphere, it condenses and falls out as rain and snow. There's no such thing as CO_2 rain on Earth, though CO_2 does condense out as snow in the extremely cold temperature of Mars. The ***amount of water vapor in air is essentially determined by temperature***. Colder air condenses water much more easily than warm air.

But CO_2 can accumulate in the atmosphere almost without any upper bound. It neither condenses nor reacts with other gases in the air. Over geologic time the amount of CO_2 in the air has varied by more than a factor of 100, and climate has warmed and cooled very dramatically. When we make extra CO_2 by burning carbon-based fuel, a lot of it stays in the air for 100s of centuries. There's ***almost no limit to how high the CO_2 can rise***. It only depends on how much carbon is ever burned over all of history.

That's why we are very concerned about rising CO_2, whereas we can rest assured that water vapor is limited by temperature.

3.3.4 Atmospheric Transmission and Absorption

Optical thickness and opacity

Changes in the way molecules wiggle and dance to the tune of electromagnetic fields are responsible for the selective transparency of the Earth's atmosphere at different wavelengths and therefore the greenhouse effect.

The strength of absorption of radiation by a gas is called its opacity or "***optical thickness***." It doesn't take much of an optically thick gas to absorb all the incoming light whereas light can pass through quite a lot of a gas that's optically thin at that wavelength.

The asymmetric stretching mode of CO_2 vibration absorbs and emits IR photons whose wavelength is 4.3 μm. It takes photons with less than 1/3 that much energy (wavelength around 15 μm) to cause the bending transition. Because of its permanent electric dipole moment and the many degrees of freedom for bending and stretching, the H_2O molecule has many absorption and emission lines in the infrared.

Imagine the radiation environment of the atmosphere in the 15 μm wavelength band. Thermal photons are being emitted from the ground, the clouds, and from CO_2 molecules in the air itself. These photons never get very far before being absorbed by a CO_2 molecule. It's like a thick fog, with diffuse light coming from every direction and no visibility of distant objects in any direction. We refer to such an environment as ***optically thick***.

By contrast, there's very little absorption or emission in the atmosphere at a wavelength of 11 μm. Photons emitted from the ground have an excellent chance of passing right through the atmosphere all the way to outer space. We refer to this environment as ***optically thin***.

Figure 3-4 below shows the absorption (in gray) and transmission (in white) of various gases in the atmosphere as a function of wavelength, and then the total optical thickness of the atmosphere in the taller panel. At the top are the emission spectra of the Sun and Earth.

Thankfully, the air is optically thick at ultraviolet wavelengths (shorter than 0.4 μm) due to the ozone layer. Air is almost transparent to visible radiation (0.4 to 0.7 μm). We call this optically thin region an "atmospheric window" because the light just streams through. There are optically thick regions in the infrared especially due to H_2O, with some contributions from methane (CH_4) and nitrous oxide (N_2O) – like CO_2 and H_2O these are also greenhouse gases. Another important atmospheric window is found from wavelengths 8 μm to 11 μm in which there is very little absorption. Earth's thermal radiation peaks in these wavelengths and it is through this window that most of Earth's outgoing longwave radiation (OLR) is emitted. The strong CO_2 bending mode band at 15 μm marks the edge of the IR window, and beyond this band the atmosphere is almost totally opaque due to absorption by water vapor.

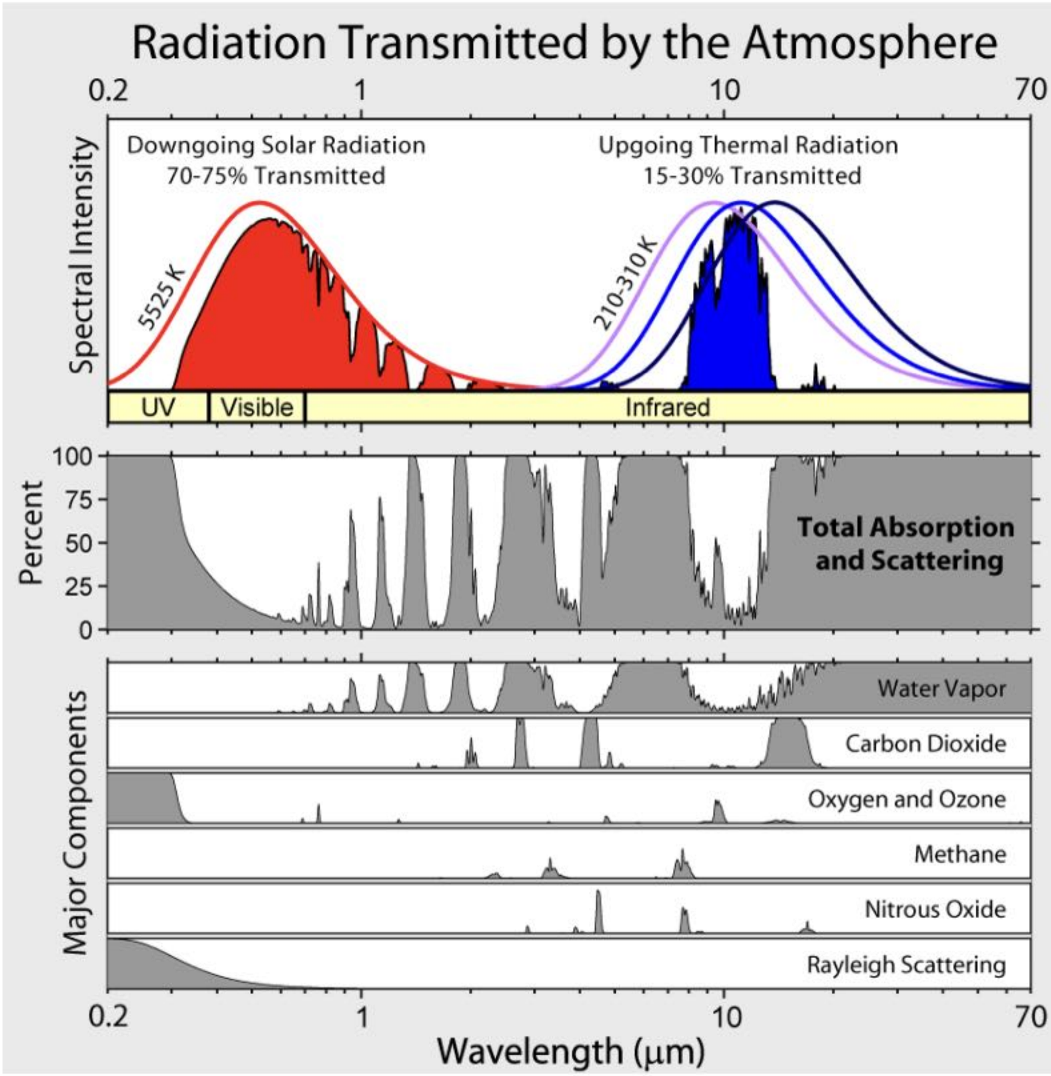


Figure 3-4: Absorption and transmission of radiation by various gases in Earth's atmosphere. Schmittner (2020) Creative Commons License

The IR spectrum of Earth from space

We can measure the upwelling IR radiation from the Earth at each wavelength using spectrometers in orbit (Fig 3-5 below). Earth's surface emits essentially as a blackbody, but radiation received in orbit is much less intense in the optically thick parts of the spectrum indicated with red labeling. Water vapor absorbs much of the outgoing longwave radiation (OLR) at wavelengths between 5 μm and 8 μm and beyond 15 μm. Stratospheric ozone takes a bite out of the spectrum around 9 μm. In the IR window region from 11μm to 14 μm, the orbiting spectrometer observes almost the same spectrum as that emitted by the surface.

Now consider the optically thick region near 15 μm. As we discussed above, the air behaves like very thick fog to these wavelengths due to the bending oscillation of CO_2 molecules. There is a rectangular cut missing from the top-of-the-atmosphere OLR here. Notice that top-of-the-atmosphere radiance in this part of the IR spectrum is about what we'd expect from a blackbody emitting at 225 Kelvin = -48 ºC = -118 ºF!

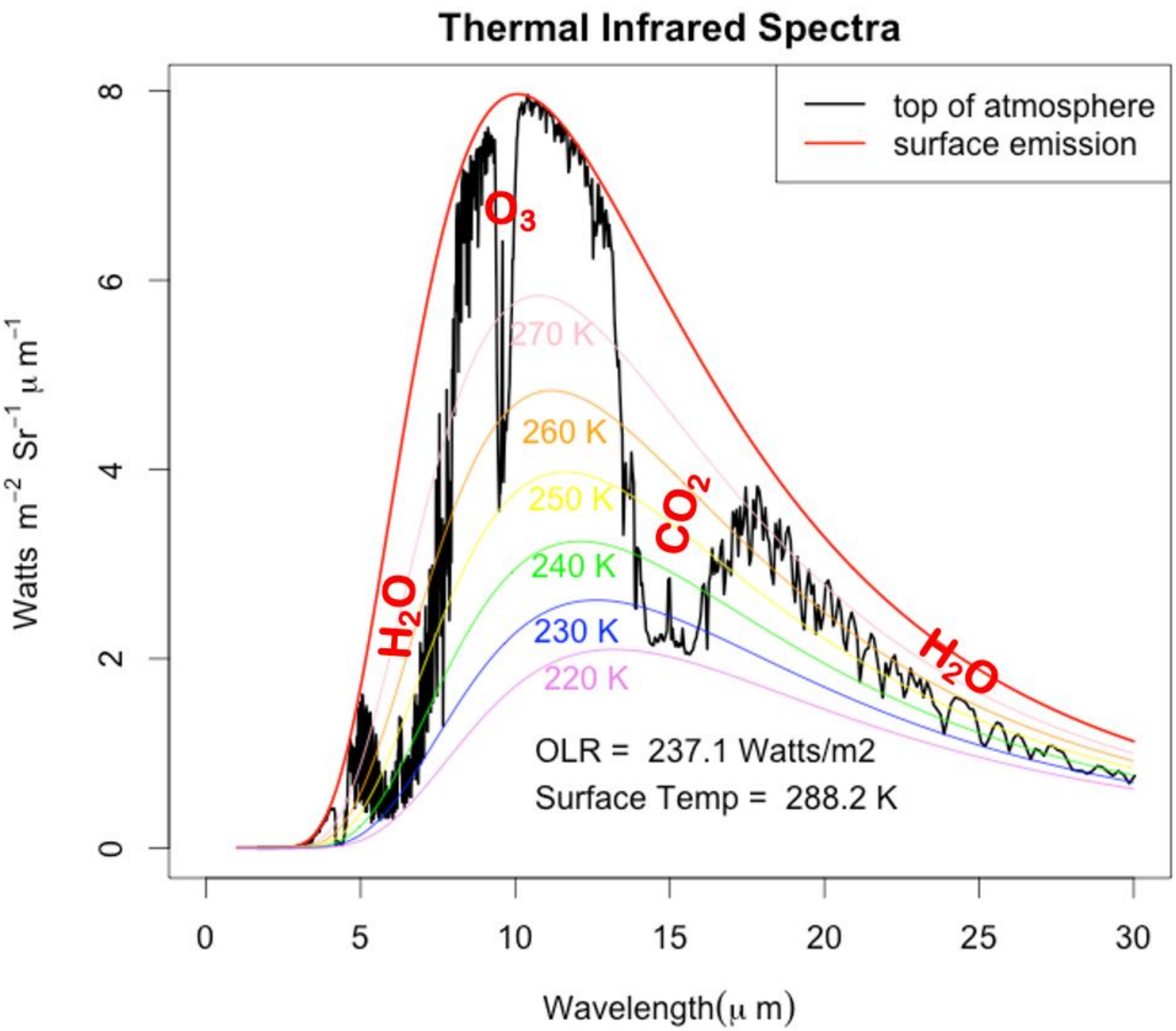


Figure 3-5: Simulated IR spectrum looking down from above Earth's atmosphere (black jagged line). Radiance is shown on the y-axis and wavelength on the x-axis. The red line shows the emission spectrum of a blackbody at 288 Kelvin, meant to approximate Earth's surface. The difference between the red and black lines at each wavelength indicate the absorption of IR radiation by the atmosphere, with major cutouts due to CO_2, H_2O, and ozone (O3) labeled. The area under the curves is the total outgoing longwave radiation (OLR) in Watts per square meter. Pastel curves show blackbody emission spectra for various temperatures colder than the surface to indicate the altitude (temperature) of outgoing emission in the black curve.

The Earth's radiance reaching outer space in the CO_2 bending band is emitted from very high in the atmosphere where it's extremely cold. Below that level, the optically thick CO_2 fog just absorbs all the emitted photons. Only from high up above the bulk of the absorbing CO_2 do the IR photons emitted from the bending transition have a clear path to space.

It's precisely because photons emitted from CO_2 come from such a cold layer of the atmosphere that so little radiation reaches space in those wavelengths. It's easy to see from the plot in Fig 3-5 that the area under the black curve (OLR) is much less than the rate of energy emitted by the surface. This is again the essence of the Greenhouse Effect.

The ***strength of the Greenhouse Effect is determined both by the selective transparency of the atmosphere*** (gases are optically thick at some wavelengths but optically thin at others) ***and by the strength of the vertical temperature profile***. Strong absorption makes the air emit from much higher up at those wavelengths, and strong cooling with height makes the radiation from those layers weak (via σT^4).

3.3.5 Radiative forcing by increasing CO_2

The imbalance between the rate of energy flowing into the climate system from the Sun and flowing out by infrared radiation when CO_2 or other absorbers are added means that the Earth is no longer in thermal equilibrium. Heat in is no longer equal to heat out. The temperature must rise until equilibrium is re-established.

Before the temperature has time to adjust, we define the instantaneous imbalance in radiative power in and out (holding temperature constant) to be the ***radiative forcing of climate***:

$$RF = F_{in} - F_{out}.$$

As CO_2 is progressively added to the atmosphere, the 15 μm bite out of the OLR first gets deeper and then wider. The area under the black curve (OLR) is impacted more and more (Fig 3-6 below). The 4 μm asymmetric stretch feature also gets stronger, but is masked by the strong water vapor absorption at that wavelength.

As noted by Arrhenius in 1896, the overall effect of increasing CO_2 on total OLR increases more slowly as more CO_2 is added. This “band saturation” effect is a classic example of diminishing returns. The more radiant energy that has already been absorbed by earlier additions of CO_2, the less is available to be absorbed at higher concentrations.

Radiative forcing due to CO_2 is a little less than 4 Watts per square meter for every doubling of CO_2 concentration, holding temperature constant. This means that 4 w m^{-2} is added when CO_2 increases from 100 to 200 ppm, an additional 4 W m^{-2} is added between 200 and 400 ppm, between 400 and 80 ppm, and so on. Notice that this means that adding 100 ppm of CO_2 contributes less radiative forcing when the concentration is already high than it does when the concentration is low.

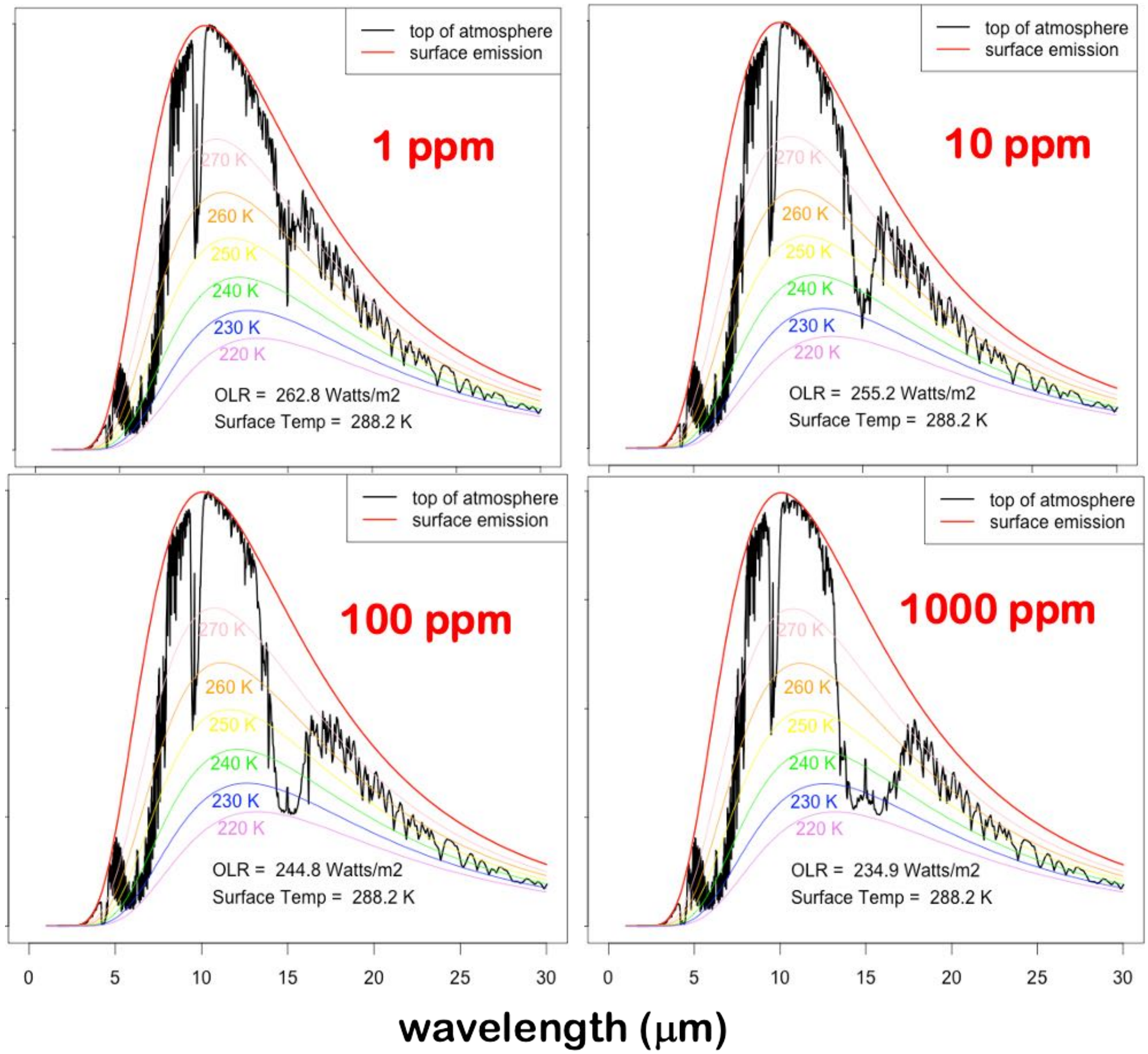
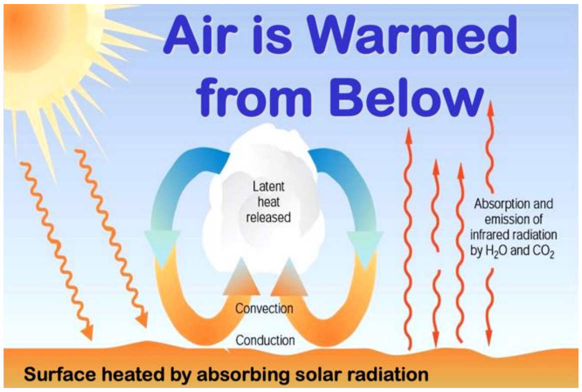


Figure 3-6: Effect of progressive additions of CO_2 to the atmosphere on the IR spectrum of outgoing radiation.

3.4 Vertical Energy Exchange in the Earth System

We've seen that the strength of the Greenhouse Effect depends on the vertical distribution of temperature in the atmosphere. More specifically, the height from which IR photons can be emitted directly to space has to be cold. Ultimately, that's what limits the outgoing longwave radiation (OLR). Now let's explore the way heat energy is transported within the atmosphere to determine the temperature distribution.

Intuitively, we might expect that temperature would increase with height as we get "closer to the Sun." But of course anybody who's ever been to cold snowy mountains knows this isn't the case. As early balloonists learned at great peril, air temperature drops dramatically with height due to falling pressure. "It's cold in them thar hills!"



In fact, the ***air is heated from below by conduction and convection from the surface***. Aside from the heating of the stratosphere by UV absorption in the ozone layer, nearly all atmospheric heat energy is derived from the surface.

Energy transport in the vertical is dominated by electromagnetic radiation, but the key thing to remember is that ***radiant energy is only converted to internal energy (temperature) of the air at the level where it gets absorbed***. High-energy UV photons are absorbed in the ozone layer many miles above the surface where the air is so thin that the sky is dark at mid-day. The air is transparent to visible light, so these wavelengths don't change air temperature at all except when they are absorbed by clouds, dust, or smoke. Instead, the visible sunlight is absorbed at Earth's surface, warming it directly. Lower-energy IR photons emitted by both the hot surface and the cooler air are absorbed very strongly in the atmosphere. This is in fact the main source of energy to warm the air itself, and it is strongest near the surface where the density of air (and the greenhouse gases it contains) is greatest.

Right at the surface, heat is conducted from the soil and ocean water directly to the overlying air. Conductive heat transfer to air is incredibly inefficient so this process doesn't reach very far from the surface. But conduction warms near-surface air enough that it expands and becomes less dense than the air immediately above. The less dense warm air near the surface is buoyant – it literally weighs less than the air adjacent. Buoyancy causes warm surface air to rise and colder air aloft to fall and fill its place. This is thermally driven convection.

Convective heat transfer mixes air in the vertical. We've all seen warm air rising from hot surfaces – rising plumes of dust or smoke, the visible shimmer of hot air rising from a summer parking lot, or a hawk riding a rising column of warm air are all visible manifestations of thermal convection.

Convective mixing is even more powerful when the rising air cools enough due to low pressure aloft that the water vapor contained in the thermal condenses to form microscopic droplets of liquid water. These are clouds, and the condensation of liquid water releases a tremendous amount of heat into the surrounding air (the same heat required to evaporate the water in the first place). Latent heat release in clouds produces even more warming and buoyancy, driving the air even more powerfully upward. Frequently this process feeds on itself strongly enough to produce the violent updrafts known as summer thunderstorms.

Figure 3-7 below summarizes vertical energy transport in the Earth system. Incoming solar radiation at the top of the atmosphere is assigned 100 units, so all the numbers in the diagram represent percentages of incoming unobstructed sunlight.

At the top of the diagram, 30 units of the incoming sunlight is reflected back to space. This represents the Earth's albedo of 30%. The other 70 units pass down into the Earth system. The small branching arrow on this downwelling sunlight shows that 19 units are absorbed by clouds and dust in the air, leaving 51 units to be absorbed at Earth's surface.

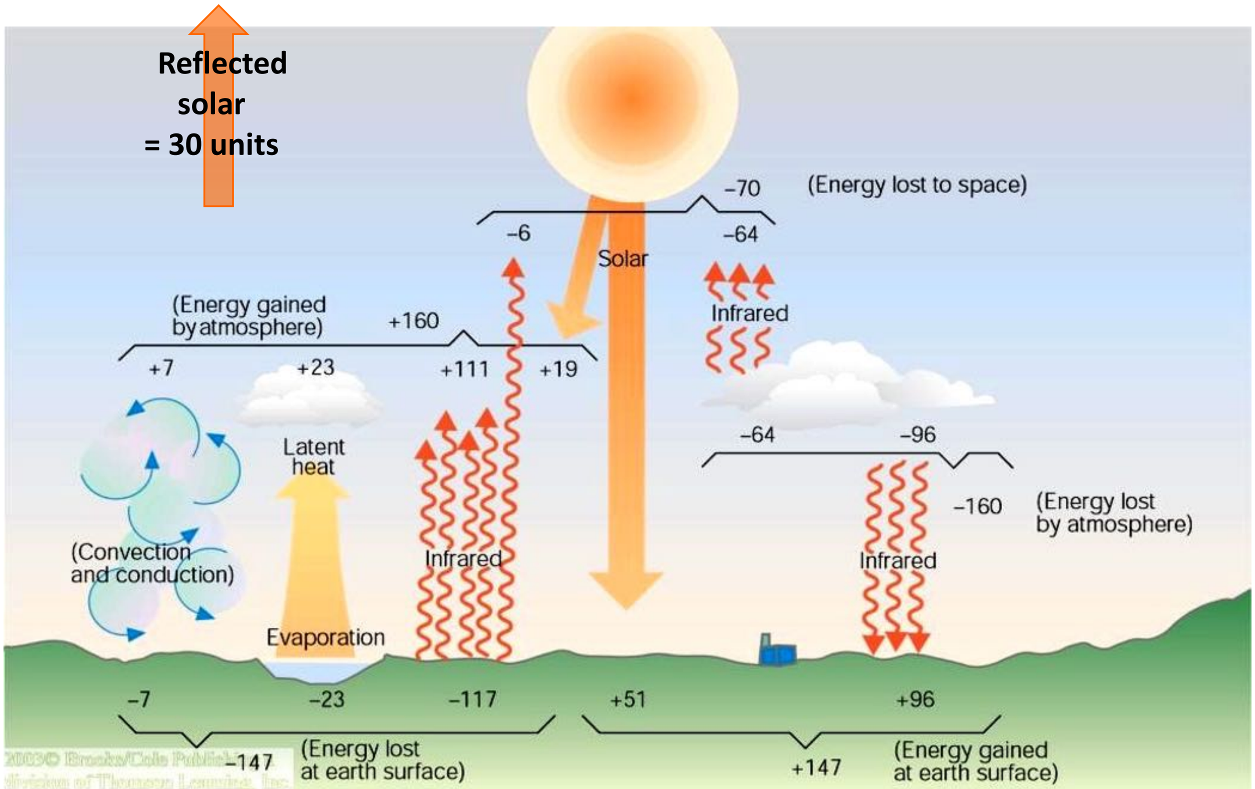


Figure 3-7: Vertical exchanges of heat energy in the Earth system. Incoming solar radiation at the top of the atmosphere (342 W m-2) is defined as 100 units, so each number in the diagram can be read as the percentage of incoming sunlight.

All ***surface energy gains*** are shown on the right-hand side of Fig 3-7, and ***surface losses*** are shown on the left-hand side. Holy moly, look at the surface energy losses from IR radiation – 117 units lost! That's σT_{sfc}^4 and it's way more than the incoming solar radiation at the top of the atmosphere (100 units). How is this possible?

The ***surface only gains 51 units of absorbed sunlight, but it also gains 96 units (nearly twice as much) by absorbing downwelling IR radiation emitted by the warm sky!*** Once again, this is the essence of the Greenhouse Effect.

It may seem bizarre that the surface is warmed twice as much by downward radiation from the warm sky as it is by the Sun, because the Sun feels much brighter and warmer on our skin than the empty sky. But remember that the ***Sun is only up during the day and most of the time it's far from directly overhead. By contrast the warm sky is right over us all the time, 24/7/365***. The instantaneous downward IR is less intense, but that steady skyglow accumulates over time to be the dominant source of heat for Earth's surface.

Overall, the surface gains 147 units of power by absorption of downwelling radiation emitted by the Sun and by the atmosphere (bottom right side of Fig 3-9). But upward thermal radiation only returns 117 of those 147 units (bottom left side of Fig 3-9). The remaining 30 units must be lost from the surface by conduction and convection. Most of this convective heat loss is in the form of evaporative cooling (23 units) and only 7 units are carried away by rising thermals that directly warm the air.

Focus now on the middle of the diagram in Fig 3-9 which shows the energy flows into and out of the atmosphere itself. The atmosphere receives a total of 160 units of power (left center of diagram) and balances this heat gain by emitting 160 units (right center of diagram).

As with the rest of the climate system the primary sources of heat are by absorption of electromagnetic radiation. Out of 117 units of upwelling IR from the surface the atmosphere absorbs 111 (6 units pass through the atmospheric IR window between 8 μm and 11 μm). The 19 units of incoming sunlight absorbed by clouds and particles also adds to the atmosphere's energy gain. Finally, the atmosphere receives the same 7 units of heat lost from the surface by rising thermals of convective warm air, and 23 units of latent heat when the water evaporated from the surface condenses to form clouds and precipitation.

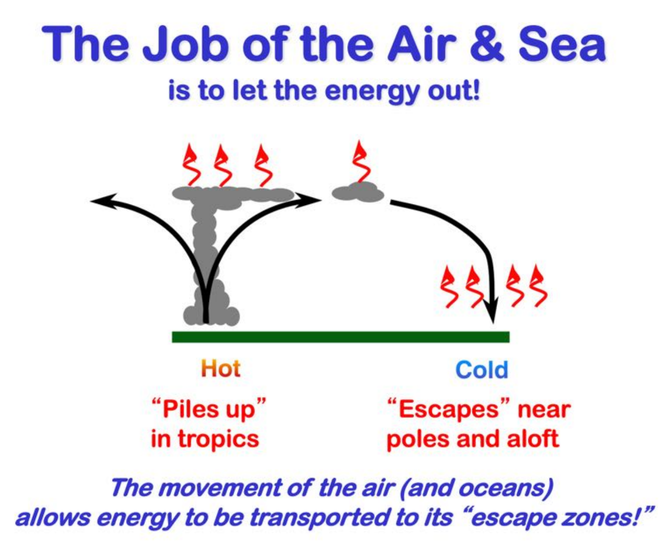
Heat loss from the atmosphere is entirely through electromagnetic radiation. The air radiates both upward and downward in the thermal IR but recall that it is pretty much opaque to these wavelengths. The upper air radiates upward at very cold temperatures for a total loss of 64 units that passes into outer space. But the lower atmosphere radiates downward from warmer layers for a total of 96 units that's absorbed by the surface.

Finally, consider the top of the atmosphere. Sunlight contributes 100 units of downwelling power. With a planetary albedo of 30%, Earth returns 30 units of sunlight directly back to outer space. Nearly all the rest (64 units) is emitted out the top by greenhouse gases in the atmosphere, with only the small residual of 6 units passing from the surface to outer space via the atmospheric IR window.

Each layer conserves energy precisely – there is a perfect balance of power at each layer and for the planet as a whole. The surface receives and loses 147 units. The atmosphere receives and emits 160 units. The top of the atmosphere receives and loses 100 units.

Even though it appears that the surface is "getting something for nothing" because it receives much more heat than the top of the atmosphere, energy is neither created nor destroyed at any stage. This was the fundamental discovery of Fourier 200 years ago – that the air behaves like a greenhouse by letting heat in and holding onto it.

Nevertheless, photons fail to complete the energy balance of the surface. Emission of surface IR loses only 117 of the 147 units the surface receives. The job of atmospheric and ocean circulation is therefore to carry the heat from its accumulation zones (near the surface and in the tropics) to its escape zones (above the greenhouse gases and out to the winter poles).



3.5 Lateral Energy Exchange

Picture in your mind the heaving motion of the air and seas. Every breath of wind, every rising thermal, every cloud and drop of rain, every tiny snowflake. Mighty ocean currents sweeping across the abyss. Thunderstorms and gales and typhoons and blizzards. All of this is the result of lateral imbalances in radiation across the planet.

The job of the atmosphere and oceans is to balance the global energy budget by hauling heat from hot places (tropics, surface) to cold places (winter poles, top of the atmosphere).

3.5.1 Absorbed Solar Radiation

Sunlight is not distributed evenly across the globe. The Sun is much higher in the sky in the tropics than it is at higher latitudes, and days get shorter and shorter as winter approaches. Half the time the Sun is below the horizon at each pole – polar nights are ridiculously long! Furthermore, even when the Sun is up the Earth's albedo depends on clouds (very bright) and the characteristics of the surface (bright snow and deserts vs dark oceans and forests, for example).

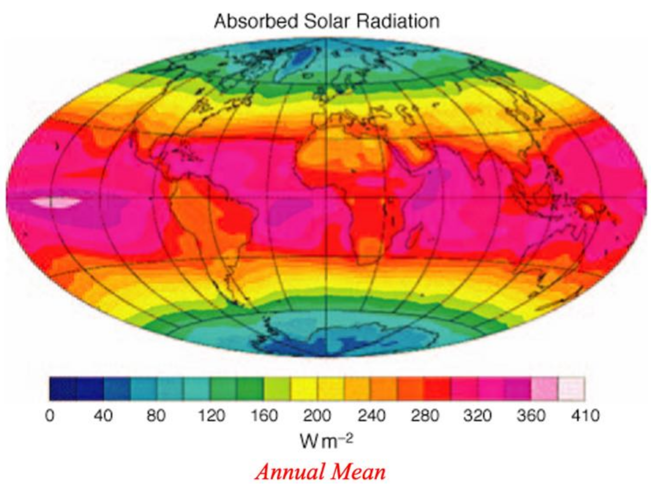


Figure 3-8: Annual average absorbed solar radiation at the top of the atmosphere, in Watts per square meter

Figure 3-8 shows the distribution of solar heat input into the climate system. The global average is $S(1-\alpha)/4 = 342$ W m^{-2} as we saw in section 3.1.

Obviously, there are huge geographical differences in solar heating. Most of the variation is explained just by latitude: the tropics get a lot more solar heat than the poles. That's because the Sun is higher in the sky and the days are longer there. Also remember that half the time there's no Sun at all at the poles.

Along the Equator there are huge areas that absorb more than 400 W m^{-2} But the poles absorb less than 100 W m^{-2} in the annual mean.

The detailed distribution of solar heating is also impacted by planetary albedo. Bright ice and snow near the poles substantially reduces the amount of sunshine that can be absorbed there. The bright sands of the Sahara and the Arabian Peninsula reflect a lot of sunlight too. And clouds over the tropical continents reduce the absorption of solar heat there compared to the tropical oceans.

3.5.2 Outgoing Longwave Radiation (OLR)

From the Stefan-Boltzmann Law we know that OLR is proportional to the fourth power of temperature, so it makes sense that OLR also depends strongly on latitude (Fig 3-9). The warm tropics emit much more IR than the cold poles. But the maximum IR emission is less than the maximum solar absorption, and the lowest emission is greater than the least solar absorption.

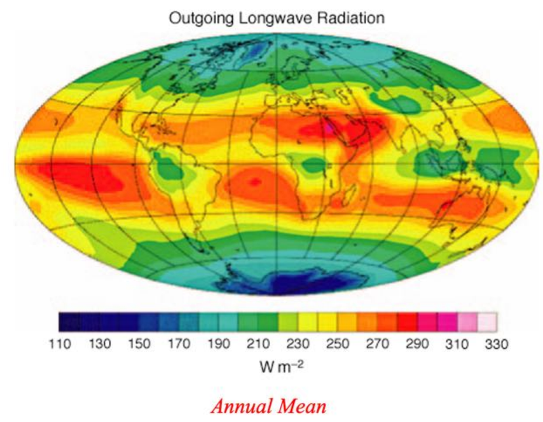


Figure 3-9: Annual average outgoing longwave radiation at the top of the atmosphere in Watts per squarer meter

The geographic distribution of OLR is more "lumpy" than the map of solar heating and it doesn't really look much like just a map of latitude. The strongest IR cooling (red blobs) are located off the Equator in the subtropics. There are regions of lower IR emission over the tropical continents. These are the tropical rainforests, where emission to space occurs from the top of towering storm clouds many miles above the surface where it is extremely cold. By contrast the maximum IR emission originates at the hot surfaces of subtropical deserts and oceans where skies are clear, and photons can escape directly to space through the IR window.

3.5.3 Distribution of Net Radiative Heating

We simply subtract the map in Fig 3-9 from the map in Fig 3-8 to obtain a map of net heating by radiation (absorbed solar minus outgoing IR) in Fig 3-10. Solar heating exceeds IR cooling in the tropics (red colors) and the opposite is true at the poles (blue colors). The pale yellow-green colors indicate regions in which radiation is nearly balanced in the annual mean.

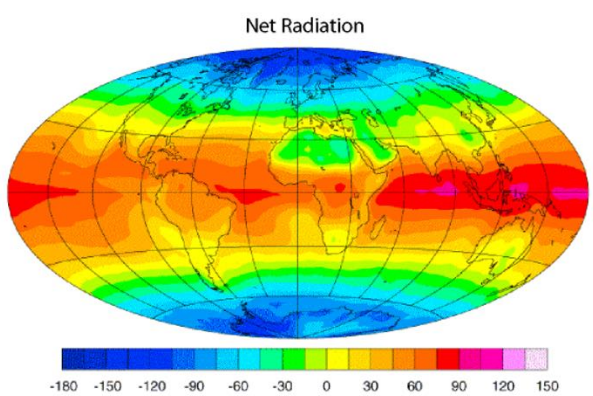


Figure 3-10: Annual mean net heating by radiation (absorbed solar minus emitted IR) at the top of the atmosphere in Watts per square meter

Net radiative heating is more than 100 W m^{-2} over the Equatorial Pacific and Indian Oceans. Similarly net radiative cooling is greater than 100 W m^{-2} over the Arctic and Antarctic. The net accumulation of radiant energy is not exactly a map of latitude because of the complex interactions between radiation and clouds. Clouds reflect a lot of incoming sunshine but also retain a lot of outgoing IR. The Sahara loses radiation in the annual mean because it's both bright (absorbs less sunlight) and hot (emits a lot of IR).

Averaging the maps in Fig 3-8 to 3-10 for each latitude gives a better idea of the planetary distribution of radiant energy (Fig 3-11). Both solar heating and IR cooling are greater at low latitudes and decrease poleward in both hemispheres. But the solar heating drops off much more quickly with latitude than the IR cooling. This leaves a net energy surplus in the tropics and a net energy deficit at the poles.

The ***circulation of atmosphere and oceans must balance out these energy surpluses and deficits by lateral heat transfer in the form of winds, storms, and currents***.

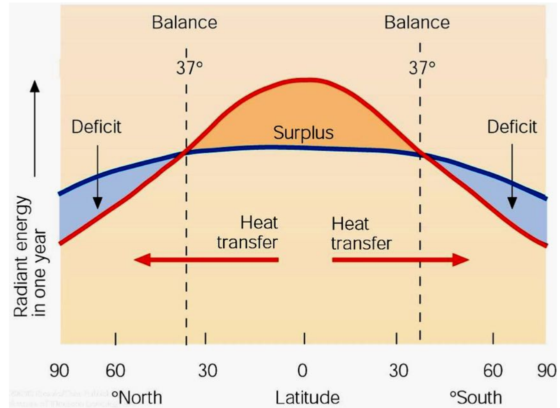


Figure 3-11: Annual total solar heating (red line) and IR cooling (blue line) by latitude at the top of the atmosphere

3.5.4 Circulation of the Atmosphere and Oceans

Net accumulation of radiant energy in the tropics causes the atmosphere and ocean water to expand, making it less dense so that its center of mass is higher than average. By contrast, net loss of radiant energy at high latitudes causes air and water to contract, lowering its center of gravity.

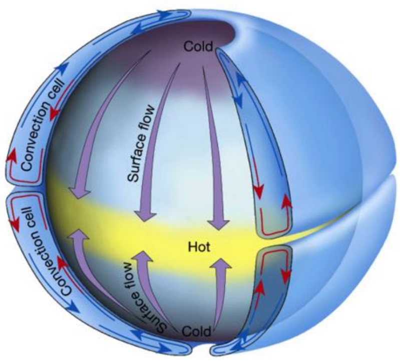


Figure 3-12: Hypothetical poleward heat transports on a planet that doesn't rotate

If Earth didn't rotate, rising warm air and water from the tropics could just flow poleward to displace cold falling air and water at the poles and balance the energy deficits and losses that arise from the uneven distribution of radiant energy (Fig 3-12). Gigantic convective overturning cells could carry vast amount of heat poleward in each hemisphere like the conveyor belts at supermarket check stands that move your groceries toward the cashier and then return for more.

The real Earth spins like a top though, so these convective heat flows get wildly disturbed and twisted around. The actual pathways of winds and storms are more complex due to Earth's rotation, featuring Trade Winds blowing from the east in the Tropics and jet streams blowing from the west at higher latitudes in both hemispheres (Fig 3-13). These ***winds nevertheless compensate about half of the radiative energy deficit*** by moving incredible amounts of heat from the tropics to the poles.

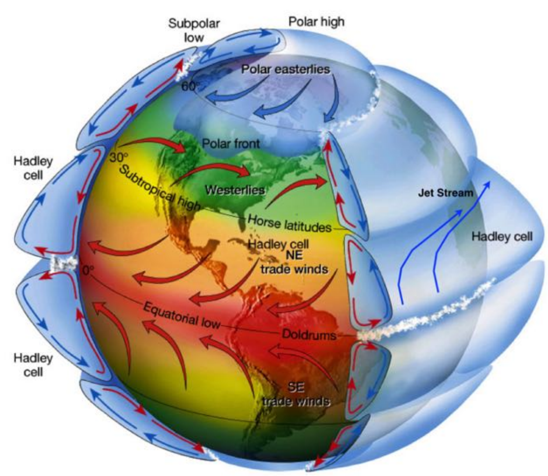


Figure 3-13: Atmospheric circulation on the real (rotating) Earth

The ***remaining half of radiative energy deficits in the tropics and polar regions is balanced by circulation of the oceans*** (currents). The oceans are hemmed in by continents and can only circulate within their basins. So the actual geographic patterns of ocean currents are even more complicated than the winds. Huge ***gyre circulations spin in most oceans carrying warm water poleward on the west sides of each basin and returning cold water equatorward on the east sides*** (Fig 3-14). Some of these are familiar for creating warm climates near the Gulf Stream or cold coastal oceans near the California Current, for example.

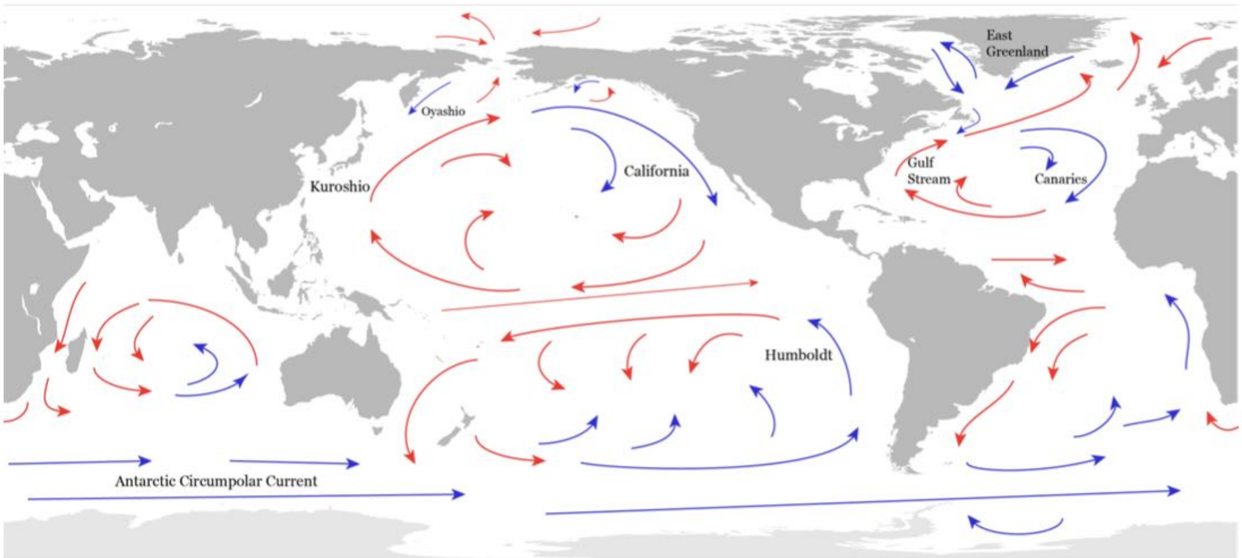
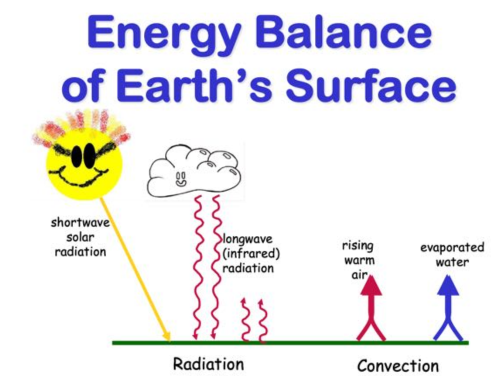


Figure 3-14: Warm (red) and cold (blue) ocean currents transport heat poleward, balancing about half of the annual radiation surplus in the tropics and deficits in polar regions. Schmittner (2020) Creative Commons License.

3.6 Surface Energy Exchange



People on Earth live at the surface, so we care more about energy balances here than anywhere else. It's also important to understand the surface energy budget because it's the primary source of heat that drives the circulation of the oceans and atmosphere.

As with the rest of the climate system, the surface energy budget is dominated by electromagnetic radiation. Absorbed sunshine warms the surface and is mostly compensated by IR cooling. The net accumulation of radiant energy at the surface is only 30 units out of 147 (Section 3.4, Fig 3-7). This net radiation heating is then balanced by convective losses of sensible heat (measured as temperature of rising thermals) and latent heat (evaporation from the surface).

It should come as no surprise that evaporative heat losses happen mostly in wet places (the oceans) whereas sensible heat loss (rising warm air) happens mostly in dry places (on land).

A big part of the reason evaporative cooling is so much more powerful than sensible heat loss is that most of the Earth's surface is open water (Fig 3-15). Evaporative cooling exceeds 100 W m^{-2} over huge areas of the subtropical oceans where sunshine is abundant and steady Trade Winds carry water vapor away. Sensible heat loss from rising warm air approaches 100 W m^{-2} only over the hot deserts of the subtropical continents (Sahara, Kalahari, Australia). Over the continental ice sheets in Greenland and Antarctica, the flow of sensible heat is actually downward from the air to the ice surface.

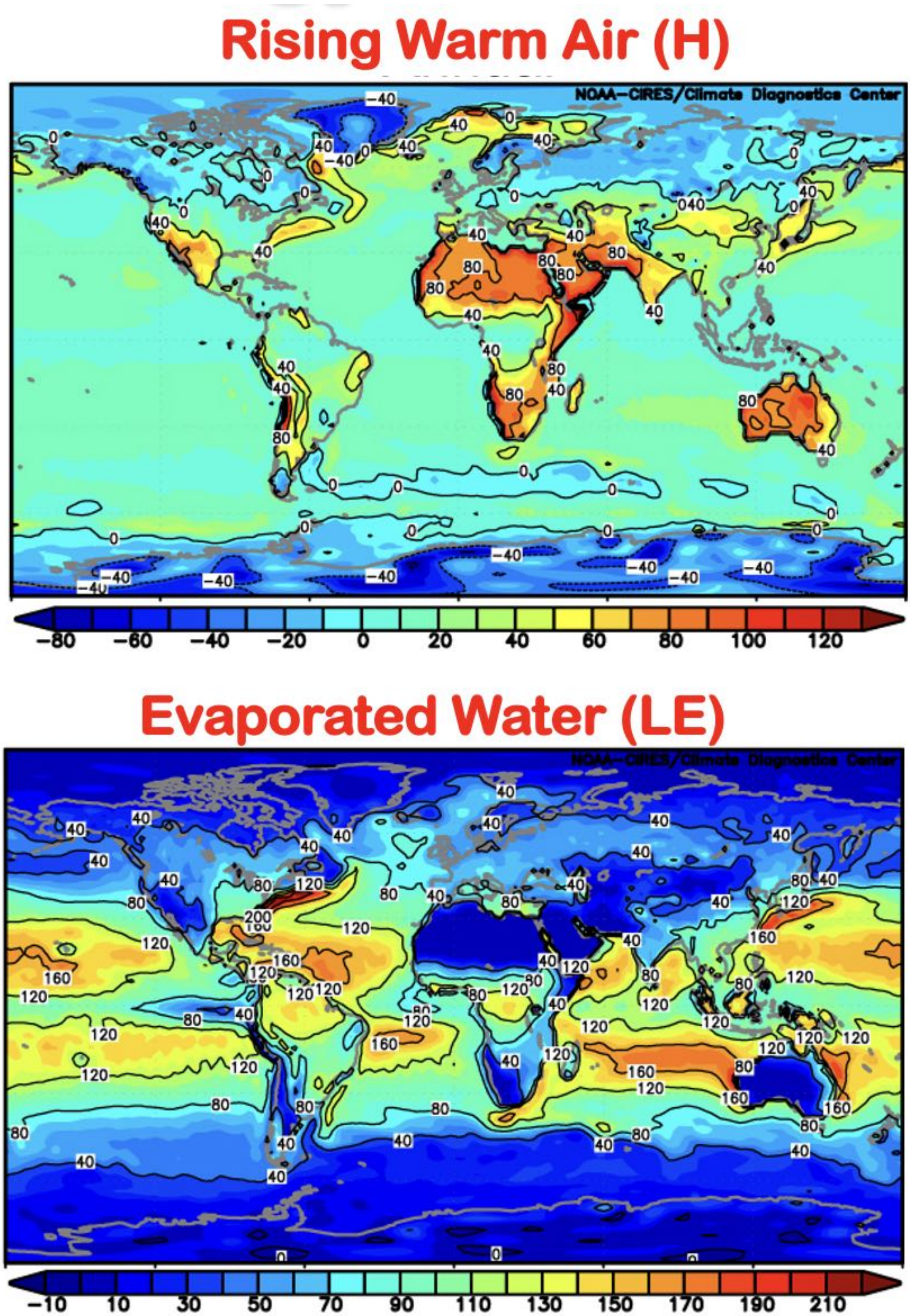


Figure 3-15: Annual average convective energy flows from the surface to the atmosphere due to rising thermals (top) and evaporation (bottom) in Watts per square meter. H stands for sensible heat flux, E for evaporation, and L is the latent heat of evaporation (Joules per kilogram of water). NOAA Climate Diagnostics Center