Global warming and its implications for conservation.

3. How does it work? Part two: atmospheric science and the layer model

The temperature of the surface of the earth is controlled by the ways that energy comes in from the sun and shines back out to space as IR.

The main points are:

1. The outflow of IR energy from a planet must balance heating from the sun.
2. The planet accomplishes this balance of outflow to match inflow by adjusting its temperature.
3. Absorption of outgoing IR light by the atmosphere warms the surface of the planet as it moves toward an equilibrium of energy fluxes in and out.

The ***layer model***, a simple model of earth's energy balance, is a starting point to understand how this system works. This is not a detailed, ***predictive climate model***, used to forecast climate change (such models do exist: more on them later). It is a simple, ***heuristic model***.

The real world can be out of energy balance for a period, but it tends to equilibrate energy flows in and out. The layer model starts with the assumption that ***incoming energy flux*** and ***outgoing energy flux*** are equal.

$$F_{IN} = F_{OUT}$$

Start with F_{IN}, which is reasonably easy to estimate directly. The intensity of incoming sunlight (at the average distance from the earth to the sun),

$$I_{\mathrm{IN}} = 1350 \text{ W/m}^2$$

A fraction of this is absorbed, and a fraction is reflected. For the purposes of the planet's energy budget, ***reflected*** light bounces off ***without affecting vibrational energy of matter***. With respect to the planet's energy budget, it is as if this light was never received at all.

The fraction of light that is reflected is the surface's ***albedo (α)***. Venus is bright because it has a thick layer of sulfuric acid clouds, with an albedo of 0.70. Mars is less bright because it has no clouds, and its surface albedo is lower, 0.15.   ***Earth's albedo = 0.30*** or so ***depending on the extent of clouds and sea ice cover***.   (Note for later: because these both respond to climate change, feedback loops are created. E.g. ***sea ice positive feedback***: rising temperature reduces ice, which reduces albedo, which increases heating.)

So the ***intensity of absorbed sunlight per unit area*** is

$$1350\frac{W}{m^2}(1-\alpha)\approx 1000\frac{W}{m^2}$$

This light is striking a sphere, so figuring out the area that is illuminated seems difficult.

Ohead: Archer Fig 3.1

Some of it strikes the surface obliquely (polar) some directly (equatorial), which seems to make a complex task. But recognize that all of this EM radiation is coming in parallel, so the area of the shadow is the area that illuminated with equal force.

The area of the shadow is πr^2 (r = radius of the earth).

Assembling these parts, the ***total absorbed incoming energy flux*** is

$$F_{IN} = \pi r_{earth}^2(1-\alpha)I_{IN}$$

Now consider F_{OUT} . To begin, assume a planet with no atmosphere, the ***bare rock model***.

On a real bare rock with no atmosphere, the bright and dark sides at any one moment are incredibly hot and cold, respectively. With a fluid atmosphere to carry heat around, these differences are averaged out. Either way, we're interested in the overall average for the planet as a whole.

The rate of radiation to space follows the Stefan-Boltzmann equation:

$$F_{OUT} = A\varepsilon\sigma T_{earth}^4$$

recall ε = emissivity (0 — 1, no units)
σ = Stefan – Boltzman constant (units of W/m^2K^4)
T = temperature in Kelvins

As before, this equation ***converts the intensity*** per unit area ***to a total flux, by multiplying by the area*** that is involved. ***What is the appropriate area*** in this case? Incoming light does not strike all of the earth, but outgoing IR comes from the ***entire surface area***.

$$A = 4\pi r^2$$
$$so$$
$$F_{OUT} = 4\pi r^2\varepsilon\sigma T_{earth}^4$$

Ohead: Archer Fig 3.3

At equilibrium, $F_{IN} = F_{OUT}$. Replacing F_{IN} and F_{OUT} with their formulas

$$\pi r_{earth}^2 (1-\alpha) I_{IN} = 4\pi r^2 \varepsilon\sigma T_{earth}^4$$

Manipulating

$$\frac{(1-\alpha) I_{IN}}{4} = \varepsilon\sigma T_{earth}^4$$

Or

$$\sqrt[4]{\frac{(1-\alpha) I_{IN}}{4\varepsilon\sigma}} = T_{earth}$$

This is an ***equation for the temperature of a planet in equilibrium***, expressed as a function of:

- ***intensity of incoming solar radiation*** - which is affected by solar activity (indicated by sunspots), which varies in a manner that affects T_{earth}
- ***emissivity*** - greenshouse gasses in the atmosphere are selective in the wavelengths they absorb and emit, and this has important effects on T_{earth}.
- ***albedo*** **–** ice and cloud cover both affect albedo with important consequences for T_{earth}

This gives T = 253K for the earth, or -15^{o}C, which is too cold. The earth is more like +15^{o}C.

Ohead: Archer Table 3.1

The reason for this is that we've used a bare rock model. We need to add an atmosphere, using the layer model, which incorporates the greenhouse effect of the atmosphere. For now, an important point is that ***without the greenhouse effect of the atmosphere, the earth's mean temperature would be well below freezing***. The ***natural greenhouse effect*** is necessary for most species to survive.

The Layer Model

The modeled bare-rock earth is too cold because it doesn't have an atmosphere.

Ohead: Archer Fig 3.3 and 3.4 together

Adding the greenhouse effect of an atmosphere in the simplest manner possible, imagine a layer of gas that works like a pane of glass. This is still ***just a simple heuristic model***, for now. Many of the assumptions would need tweaking to make a realistic, predictive model:

- Incoming solar radiation passes through the atmosphere freely and is absorbed at the surface as before: I_{IN} (influx per unit area)
- The surface radiates IR as a function of temperature: $I_{up,\ ground}$ units of W/m^2
- In the IR range, the atmosphere acts as a blackbody and absorbs the upcoming IR.
- The atmosphere radiates IR as a function of its temperature, both out to space
- $I_{up,\ atmosphere}$ and back to the surface $I_{down,atmosphere}$

As before, ***the system will adjust temperatures to achieve equilibrium between energy fluxes in and out.*** This is ***true for the entire system, and for each component*** of the system. Can use this assumption to make a budget for each component, then combine them.

Energy budget for the atmosphere:

$$I_{up,atm} + I_{down,atm} = I_{up,\ ground}$$

If radiation up and down from the atmosphere layer of the model is the same (as it should be), and replacing each I with its components:

$$2\varepsilon\sigma T_{ATM}^4 = \varepsilon\sigma T_{GROUND}^4$$

Energy budget for the ground:

Looking at the graphical model (Archer Fig 3.4), you see that at equilibrium

$$I_{UP,GROUND} = I_{IN,SOLAR} + I_{DOWN,\ ATM}$$

Replacing these with their components

$$\varepsilon\sigma T_{GROUND}^4 = \frac{(1-\alpha)}{4} I_{SOLAR} + \varepsilon\sigma T_{ATM}^4$$

Energy budget for the earth overall:

Again looking at the graphical model (Archer Fig 3.4), you see that at equilibrium, energy into the system from the sun equals energy out of the system back to space:

$$I_{UP,ATM} = I_{IN,SOLAR}$$

Or

$$\varepsilon\sigma T_{ATM}^{4} = \frac{(1-\alpha)}{4} I_{SOLAR}$$

Solving the equations simultaneously for T_{GROUND} and T_{ATM}

1. There is a pair of values for T_{GROUND} and T_{ATM} that has all three energy budgets in balance. This is the equilibrium for the system.

2. As temperatures of the ground and atmosphere change, they alter the rates of radiation.

3. By heating or cooling, the rate of outgoing radiation (IR earthshine) can balance the rate of incoming absorbed solar radiation.

The ***easiest way to derive the RELATIONSHIP between TATM and TGROUND at equilibrium*** is using the budget for the atmosphere:

$$2\varepsilon\sigma T_{ATM}^{4} = \varepsilon\sigma T_{GROUND}^{4}$$

so

$$T_{GROUND} = \sqrt[4]{2} T_{ATM}$$

$$T_{GROUND} = 1.189 * T_{ATM}$$

In the layer model, the ***surface temperature*** will be ***19% warmer than*** the outer atmosphere temperature that radiates back to space, known as the '***skin temperature***'.

An important point:

1. Although adding an atmosphere to the model warms the surface temperature, the atmosphere itself is not a source of heat.
2. The atmosphere simply affects the rate at which energy from the sun is re-radiated to space.
3. The atmosphere functions like a valve affecting the rate at which energy flows, thus altering the temperature. In terms of regulating a system, similar to a drain in a sink

affecting the level of water at which it equilibrates, given a constant inflow from the tap (sun).

The specific pair of temperatures depends on the amount of solar radiation, as you can see from the energy budget equation budget for the total system. Putting the value for solar radiation in, the simplest layer model does pretty well at predicting actual temperature for the earth.

Ohead: Archer Table 3.1 again.

We're in the ballpark. BUT the layer model assumes that the atmosphere is a perfect blackbody. In reality, different gasses in the atmosphere have different emissivity (and thus absorption) at different frequencies. In particular, they absorb IR.

The last steps to understanding the greenhouse effect are to:

1. Understand how the atmosphere's composition affects absorption and re-radiation of earthshine at different frequencies.

2. Understand how the temperature structure of the atmosphere affects the re-radiation of absorbed earthshine.