Environmental Transport and Fate

Chapter 10

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Climate Dynamics

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First off, a definition is in order.

There is a fundamental difference between **weather** and **climate**.

Definition:

The **climate** is the mean state of the earth's atmosphere, that obtained after averaging over several years.

This mean state of the atmosphere is unstable, and the instabilities are manifested as the **weather**.

The main difference between climate and everyday weather is best summarized by the popular phrase:
"Climate is what you expect, weather is what you get." (Quote attributed to Mark Twain)

To understand terrestrial climate, we ought to begin with the source of its heat, the sun, and the laws of radiative heat transfer. There are two basic laws:

<u>Law #1</u>: All bodies emit radiation. The hotter they are, the more they radiate.

The emitted radiation flux, E, is given by:

$$E = \sigma T^4$$

where T = absolute temperature in degree Kelvin (= ^oC + 273)
σ = 5.67 x 10^{-8} W/(m^2.K^4)

<u>Law #2</u>: The radiation emitted by a body at absolute temperature T fills a spectrum, with peak at wavelength λ given by:

$$\lambda = \frac{2898\ \mu m . K}{T}$$

<u>Consequence of Rule 1:</u>

Because the sun is so hot (T = 5750 K), it emits a lot of radiation:

$$E_{sun} = \sigma T_{sun}^4 = (5.67 \times 10^{-8})(5750)^4 = 61.98 \times 10^6\ W/m^2$$

Given the size of the sun (R_{sun} = 696,000 km), the enormous distance between the sun and the earth (d = 149,476,000 km), only a very small fraction of solar energy is intercepted by the earth.
Divided by the surface of the earth exposed to the sun (πR^2 = 127.3 x 10^6 km^2), this intercepted radiation amounts to:

1372 W/m^2.

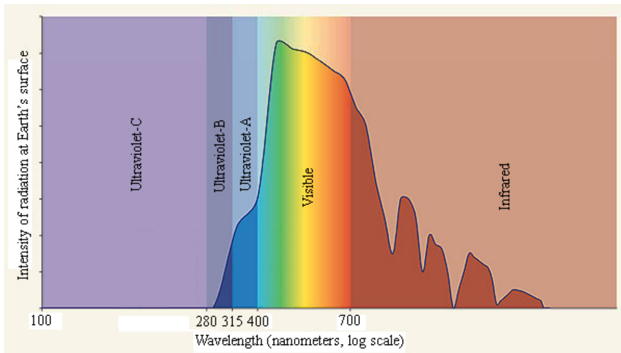
The earth turns around and does not always show the same side to the sun.
Thus, we need to distribute the amount received over the entire surface of the earth ($4\pi R^2$ = 509.3 x 10^6 km^2). This gives

I = 343 W/m^2

as the globally and seasonally averaged energy received from the sun.

Consequence of Rule 2:

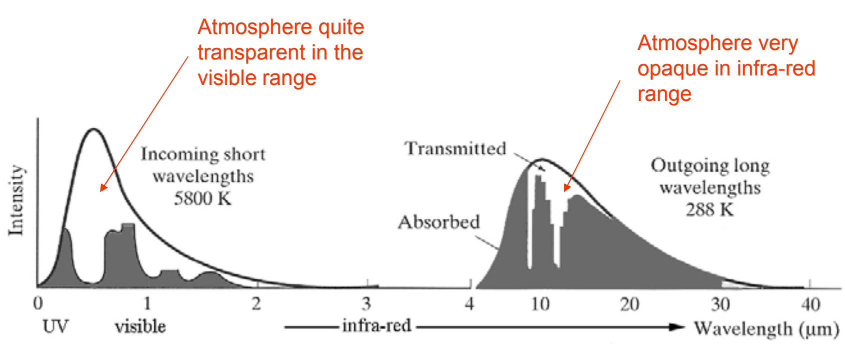
Because the sun is at T = 5750 K, it emits most of its radiation around λ = 0.50 µm, in the visible range.



(http://www.nature.com/)

In comparison, the earth is much cooler (with around T = 15°C = 288 K) and emits its radiation around λ = 10 µm, in the infra-red range. This radiation is not seen but is felt by us as heat.

Radiation from sun and from earth on same wavelength axis



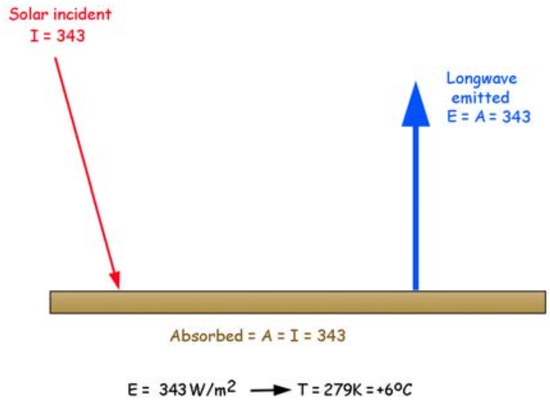
↑ from sun

↑ from earth

Conclusion:
The atmosphere is mostly transparent to visible light (lets the sun in) but is quite opaque in the infra-red range (traps the heat).

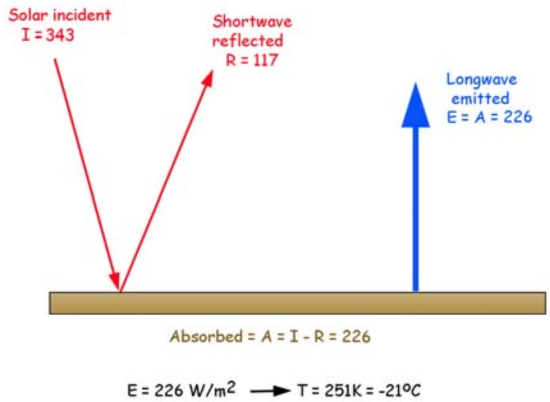
Now, let's construct the heat budget for the earth, piece by piece.

First, imagine that there is no atmosphere. What is received from the sun is absorbed by the earth and, in steady state, returned back to space in equal amount.



Not bad as a first guess, albeit a little too cold.
The globally averaged temperature is more like 15^{o}C.
But, as we will see this is right for the wrong reason…

It happens that surfaces such as clouds, ice, snow, shiny leaves *etc*. are partly reflective, and not all the incoming radiation from the sun is absorbed by the earth. A fraction α, called the *albedo*, is reflected out to space. With α = 0.34, we have



This temperature is obviously much too low.
Something else must keep us warmer than that.

There is an atmosphere, and it is not very transparent to outgoing infrared radiation from the ground surface.

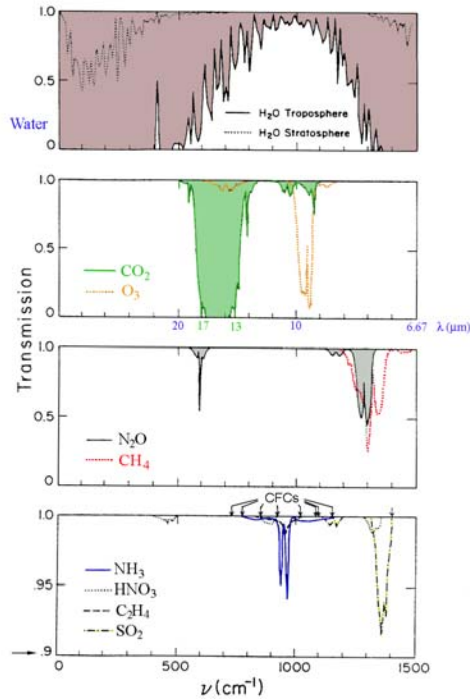
Shown here is the transmission coefficient of various elements found in the atmosphere.

Any transmission less than unity means absorption, and zero transmission implies complete absorption.

Blocking elements are called greenhouse gases.

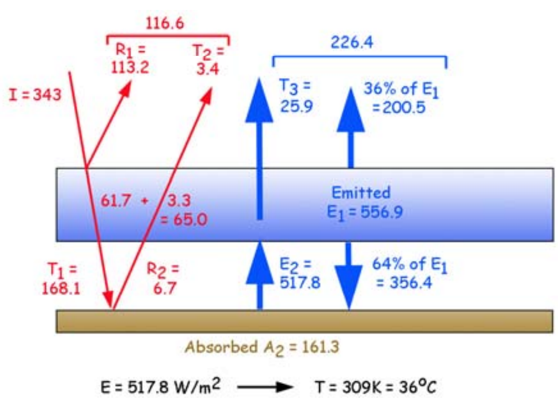
Note that water vapor is by far the most significant greenhouse gas, followed by carbon dioxide.

A major difference between water vapor (H_2O) and carbon dioxide (CO_2) is that water vapor comes and goes, and varies greatly from desert areas to rainy areas, whereas carbon dioxide tends to stay in the atmosphere and be well mixed.



Let's us now add the blanketing effect of the atmosphere, the so-called *greenhouse effect*.

Part of the solar radiation is reflected by clouds and particulate matter in the atmosphere (33%) and part is reflected by shiny surfaces on the earth surfaces (4%).



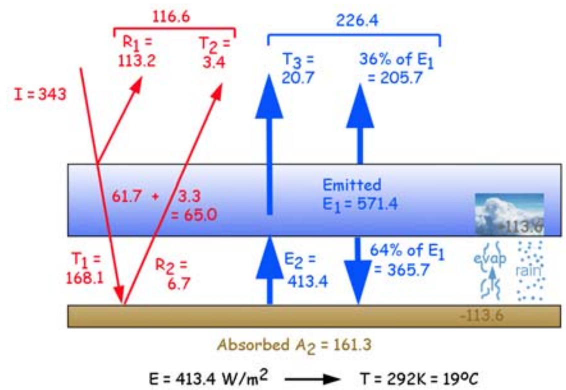
Then, the atmosphere is also relatively opaque to infrared radiation from the ground (absorbing 95% and transmitting only 5% of it).

Finally, the amount intercepted by the atmosphere, both in short and long waves is re-emitted, with 64% going downward and 36% upward.

The downward portion is absorbed by the ground, creating an infrared echo.

This predicts a significantly higher temperature, one that is actually too high.
So, there must be a cooling mechanism…

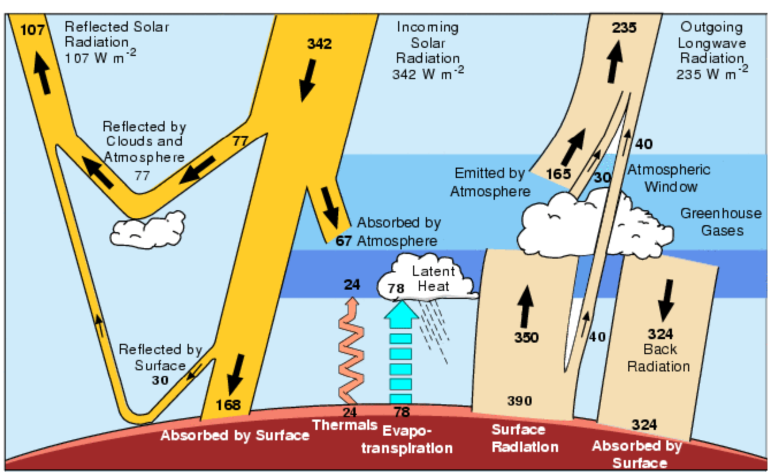
The cooling mechanism is the hydrological cycle.
Indeed, evaporation of water at the earth's surface uptakes latent heat, which is then released in the atmosphere at the time of condensation.



Thus, the hydrological cycle partly short-circuits the greenhouse effect.

The resulting temperature is still a little too high but there are more effects than those shown up to here.

With more details, yet.



Source: Kiehl and Trenberth, 1997, *Bulletin of the American Meteorological Society*, 78, 197-208.

Note that the earth's surface emits more (390 w/m^2) than what is coming from the sun (342 W/m^2)

In sum, the earth's averaged ground temperature is a **balance** between

- two major cooling processes, **reflection** (albedo effect) and **hydrological cycle**, and

- one major warming process, the **greenhouse effect**.

A change in anyone of these three processes is bound to affect our climate.

As it turns out, the three processes are linked, so that a change in one of them will create a change in the other two.

For example, an enhanced greenhouse effect increases the ground temperature, which in turns melts ice and decreases the albedo (positive feedback) while also enhancing evaporation and intensifying the hydrological cycle (negative feedback).

The terrestrial climate has always been changing over the decades, the centuries, the millennia, and beyond.

Paleoclimatology is the study of past climates. Since thermometers and other instrumentation were not around in the distant past, paleoclimatological studies rely on proxies, such as sediment strata, coral, tree rings, and tiny air bubbles in ancient ice sheets, to provide indirect evidence of what the temperature used to be on earth.

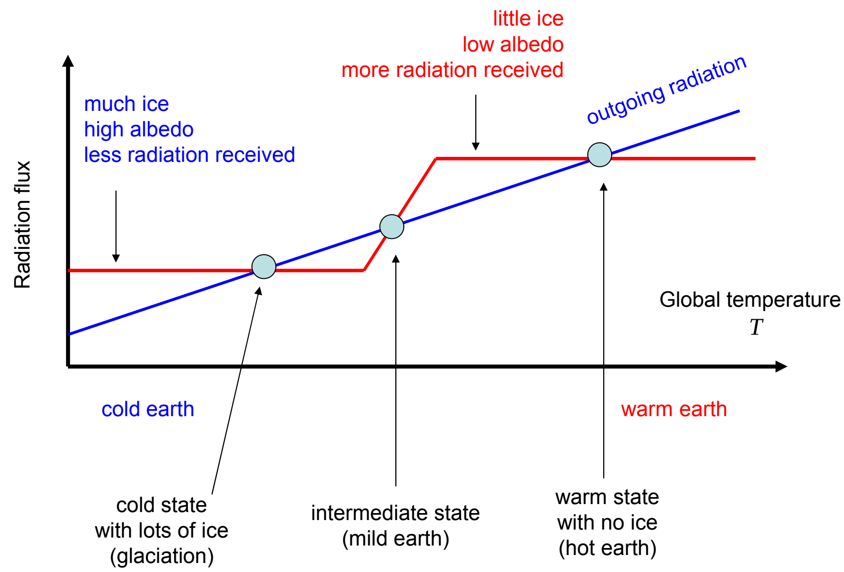
There are essentially three main states that the earth's climate may take:

- An extreme cold state with lots of ice and high albedo (so-called glaciation state)

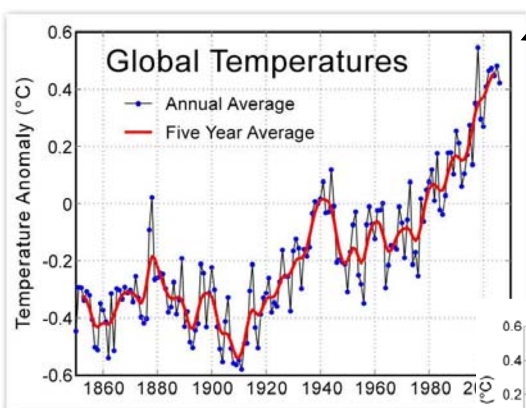
- An extreme warm state with almost no ice and low albedo, and

- An intermediate and relatively precarious state with some ice and moderate albedo.

Our present climate is in this intermediate state.

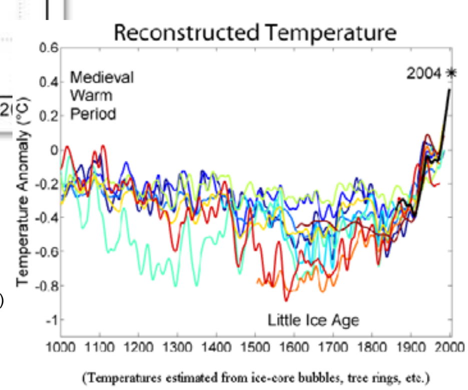


The temperature record over the past



from thermometers
(adjusted for urban heat island)

reconstructed from proxies
(such as tree rings and ice-core bubbles)



Little Ice Age
of the late medieval period
as seen in paintings by
Peter Brueghel (1525-1569)

Winter Landscape with a Bird Trap (1565)

The Hunters in the Snow (1565)

Going somewhat further back in time

We note a strong correlation between temperature (ΔT), carbon dioxide (CO_2) and methane (CH_4).

<u>Major questions are</u>:

What is causing what else? Does CO_2 lead ΔT or is it the other way round?

Or, could it be that all three indicators are responding to a fourth variable?

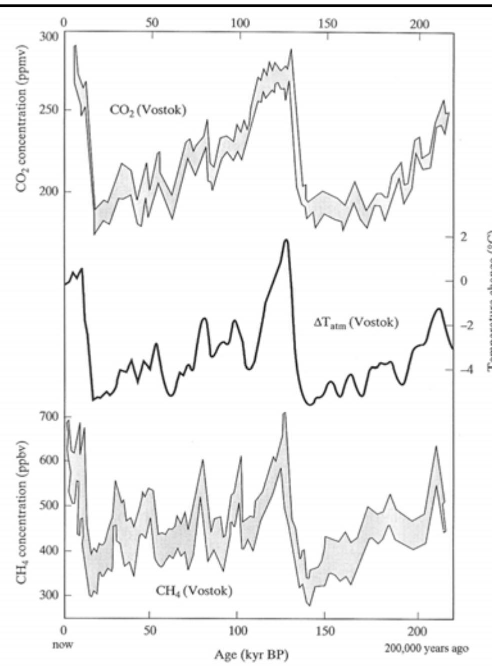
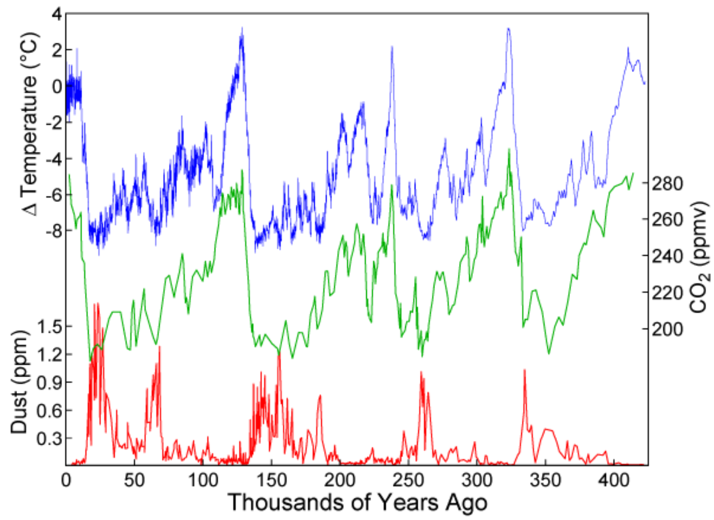


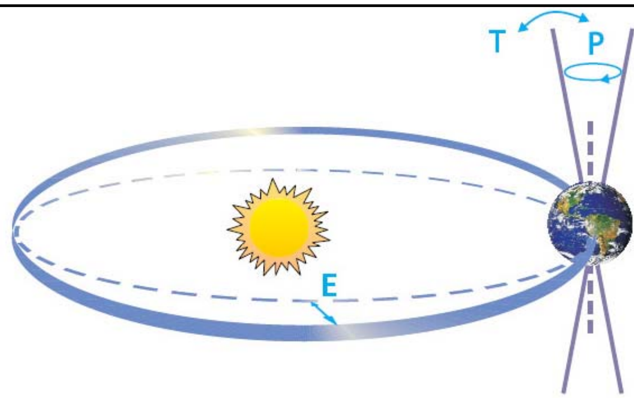
FIGURE 8.3. Carbon dioxide and methane concentrations (ppmv) and Antarctic temperature change (°C) over the past 220,000 years. Temperatures are referenced to current Vostok surface temperature. (*Source:* IPCC, 1995)

Going further back still.

We now discern cycles.



Ice core data for the past 400,000 years. Note length of glacial cycles averages ~100,000 years. Blue curve is temperature, green curve is CO_2, and red curve is windblown glacial dust (loess). Today's date is on the left side of the graph. (*Source*: wikipedia/paleoclimatology)



Eccentricity (E)
period of 400,000 years

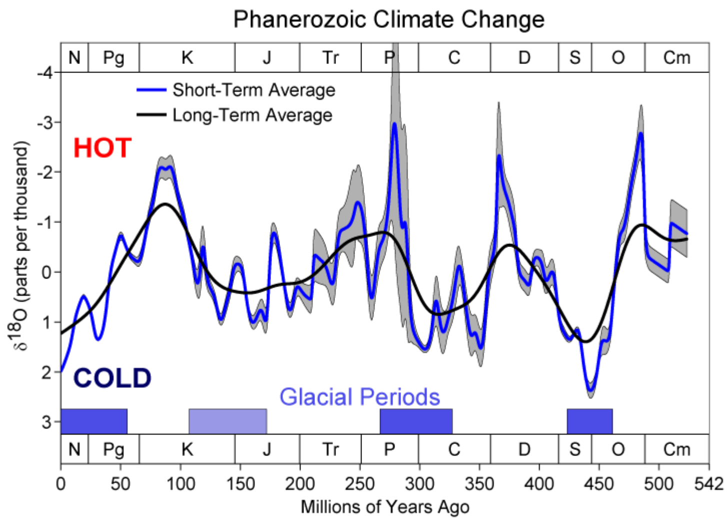
Tilt (T)
22° to 24.5°
period of 41,000 years

Precession (P)
± 60 W/m^2
19,000 to 23,000 years

Milankovitch Cycles. *Schematic of the Earth's orbital changes (Milankovitch cycles) that drive the ice age cycles. 'T' denotes changes in the tilt (or obliquity) of the Earth's axis, 'E' denotes changes in the eccentricity of the orbit (due to variations in the minor axis of the ellipse), and 'P' denotes precession, that is, changes in the direction of the axis tilt at a given point of the orbit. Source: Rahmstorf and Schellnhuber (2006).*

(http://www.global-greenhouse-warming.com/Milankovitch-cycles.html)

And even further back…



(*Source*: wikipedia/paleoclimatology)

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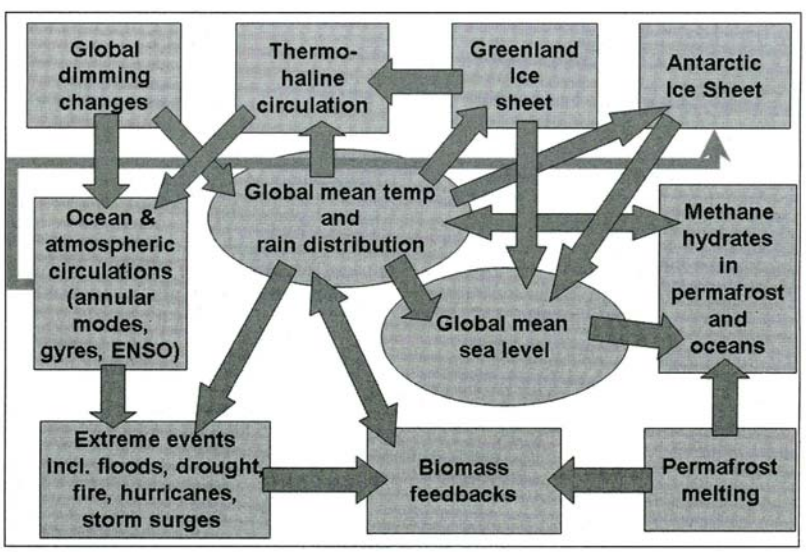
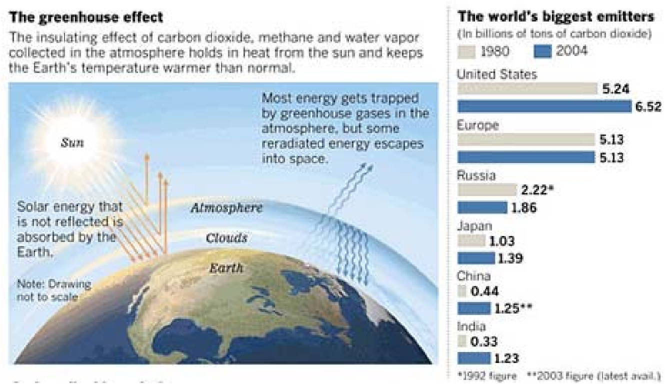


Fig 1. Links between parts of the climate system include feedbacks that may accelerate climate change and its impacts.

An example of non-scientific and incorrect presentation of climate dynamics.



http://jcwinnie.biz/wordpress/?p=2288

Find at least three things that are fundamentally wrong with this presentation.