Fundamentals of Climate Change (PCC 587): Radiation

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DAY 1: 9/25/13
Readings

- Archer Chap 2: Blackbody Radiation
- Archer Chap 3: The Greenhouse effect
- Archer Chap 4: Greenhouse Gases
Today: Radiative Transfer

- Radiation = light
  - Visible or otherwise...

Shorter wavelengths => more energetic
Today: Radiative Transfer

- The sun
- Solar radiation interacting with the Earth
  - Reflection, absorption
  - Effects of clouds, volcanoes, etc
- How the Earth radiates away heat
  - Greenhouse effect
  - Effect of CO2, water vapor, etc
- All this discussion will be globally averaged
  - Later we’ll start talking about tropics vs poles, etc...
Solar Radiation

- Driver of everything in the climate system!
We Are Small!

Sun is
~100 x Earth radius
~1e6 x Earth volume
~3e5 x Earth mass

10 light minutes away from Earth (100 Sun diameters away)
Basics of Radiative Transfer

- "Black-body" radiation
  - A body that absorbs all light

- Temperature of black body determines everything
  - Intensity and color (wavelength) of radiation
  - Hotter => shorter wavelengths and much more intense

Stefan-Boltzmann Law:

$$E = \sigma T^4$$

- $E$ = total intensity
- $T$ = temperature
- $\sigma$ = Stefan-Boltzmann constant
  - $\sigma = 5.67 \times 10^{-8}$ W/m$^2$/K$^4$

Wien’s Displacement Law:

$$\lambda_{max} = \frac{b}{T}$$

- $T$ = temperature
- $\lambda_{max}$ = wavelength at which maximum emission occurs
- $b = 2.897 \times 10^{-3}$ m K
Black-body Radiation

- Planck’s Law tells the intensity as a function of wavelength for each temperature:

- Stefan-Boltzmann Law tells you the integral under the blue curves (total emission over all wavelengths)

- Wien’s Displacement Law tells you the peak emission wavelength (dashed red)
Thermal Radiation

- At normal Earth temperatures, the thermal emission is infrared (we can’t see it)

Infrared imaging shows us the temperatures of stuff:
  e.g., cold nose, warmer eyes and ears

A WARM CAT....

IZ A HAPPY CAT
Thermal Radiation

- At temperatures around 800 K, solids glow a dim red
- 1000 K => red
- 6000 K => white (this is around the temperature of the sun’s photosphere)

Can tell the temperature of lava from its color
Solar Radiation

- 5780 K blackbody is a good approximation to solar radiation

**Fig. 7.2** The spectrum of the sun (---) and a black body at 5780 K (---). Note that in this representation the area under the curve is not proportional to irradiance. [Adapted from *Quart. J. Roy. Meteor. Soc.* 84, 311 (1958).]
Spectrum of the Sun’s Radiation

- Solar radiation is mostly in the visible bands

Also significant UV and infrared emission by the sun
Solar Radiation

- Sun emits way more radiation than the Earth!

Blackbody radiation curves for Sun and Earth

Sun ~6000K
Earth ~290K
Solar vs Terrestrial Radiation

- Normalize the curves so maximum intensities are equal:

Very little overlap: solar (“shortwave”) and Earth (“longwave”)
Variability of Solar Output

- Solar constant varies over 11 year sunspot cycle:
  - Variability is around 0.07% over 11 yr period
  - Affects global temperatures by 0.2 K? (research of KK Tung, Applied Math)
  - We are just recovering from a prolonged minimum in solar activity

- Note high frequency variability as well
Sunspot Cycles over Time

- Sunspots have longer period variability than just the 11 year cycle:
Sunspot Cycles over Time

- Maunder minimum coincides with “Little Ice Age”?

There was also enhanced volcanic activity at this time.

Source: Global Warming Art
Solar Radiation and Earth

- Insolation felt on Earth depends on distance from the Sun

  Solar radiation at Earth-sun distance (solar constant) = 1364 Watts/meter$^2$

  Average radiation on Earth:
  half of Earth is dark always and most locations don’t receive direct radiation

  Average radiation on Earth
  $= \frac{\text{solar constant}}{4}$
  $= 341 \text{ W/m}^2$

- Total power from sun: $1.7 \times 10^{17}$ Watts (170 PW)
  - Comparisons: Grand Coolee Dam $= 6.8 \times 10^9$ W
  - Total power consumption of globe $= 1.6 \times 10^{13}$ W
What happens to the Sun’s radiation when it reaches the Earth’s atmosphere?

The atmosphere is made up of:
- 78% nitrogen
- 21% oxygen
- 1% argon
- 0.4% water vapor (varies a lot with location though)

The important ones for radiation are all a tiny fraction of atmospheric mass (trace gases):
- Water vapor, CO2, ozone, etc
When the Sun’s radiation reaches the Earth’s atmosphere, several things can happen:
- Scattering/reflection of solar radiation
- Absorption
- Transmission

Most solar radiation makes it straight to the surface:
- **50%** of top-of-atmosphere (TOA) radiation is **absorbed at the surface**
- **20%** is absorbed in atmosphere (17% in troposphere, 3% in stratosphere)
- **30%** is **reflected** back to space (25% by atmosphere, 5% by surface)
What does the reflection?

- **Clouds** reflect the most solar radiation by far
  - 2/3 reflection by clouds
  - 1/6 reflection by clear sky atmosphere
  - 1/6 reflection by surface

(Remember poles are exaggerated in Mercator projections like this)
Albedo

- Albedo: reflectivity of a surface
  - Black = 0, white = 1
- Cloud albedo depends primarily on thickness (0.2-0.7)
- Snow albedo: 0.4-0.9 (depending mostly on age)
- Ocean is very dark (< 0.1)
- Desert ~ 0.3, forest ~ 0.15

(Remember poles are exaggerated in Mercator projections like this)
Albedo of Surfaces

- Albedos of different surfaces/clouds:

Surface reflects relatively small percentage of TOA solar radiation (~5%), but albedo is very important for local climate.
Aerosols

- Atmospheric reflection is partially due to air molecules
- **Aerosols** (fine particles suspended in air) also make a large contribution to atmospheric reflection
  - Dust (e.g., from the Sahara)
  - Sea salt
  - Sulfur dioxide (from volcanoes, coal burning)
  - Soot
  - And others
Dust

- Saharan dust transported across Atlantic:
  
  Dust also absorbs solar in addition to reflecting (slightly different climate impacts)

Dust can be anthropogenic: Desertification/land use changes contribute ~30% of current dust levels
Volcano Effects on Climate

- Volcanoes can have large climate impact
  - Esp. if they get material into stratosphere & have sulfates

Mount Pinatubo, Philippines, erupted June 1991, resulted in 0.5 C global temperature decrease

Volcanic climate impacts are through dust or aerosols:

Direct heating of atmosphere by volcanoes is small.

CO2 emission by volcanoes is <1% of anthropogenic emission.
Pinatubo Eruption Impacts

- Large increase in aerosols, decrease in temperature

Before →

2 months after →

14 months after →

Observed (dashed) vs modeled (solid) temperature change (from Hansen et al 1996)
“Global Dimming”

- Solar radiation reaching the Earth’s surface has declined by ~4% from 1961-1990
  - This has coexisted with large increases in the global temperature. Why?
- Increased aerosol concentrations partially to blame
  - Reflection changes from this is too small to explain the full effect though
- Cloud changes are important too: thicker and longer lived clouds
- Trend has reversed since 1990s (likely due to Clean Air Acts)
NH vs SH Temperature Changes

- NH vs SH warming difference due to aerosols/global dimming?

![Hemispheric Temperature Change Graph](image-url)
Aerosols Impact on Climate

- Aerosols are **biggest uncertainty** in radiative forcing of climate change:

Radiative forcing of present climate, with uncertainties

IPCC AR4 SPM
In equilibrium, energy in = energy out
- This is the “energy balance” equation

The Earth loses energy only through longwave radiation
- The Earth’s surface radiates away lots of longwave radiation
- Is this able to make it out to space easily?

Infrared satellite image ➔
Greenhouse Effect

- The surface emits $390 \text{ W/m}^2$ of longwave radiation, but only $40 \text{ W/m}^2$ makes it directly out to space.

- The rest is trapped by greenhouse gases and clouds!
The Greenhouse Effect

- Greenhouse effect is intuitive if you pay attention to the weather!
  - Cloudy nights cool less quickly
  - In the desert, temperatures plunge at night!
    - No clouds & little water vapor in the desert: little greenhouse effect
The Greenhouse Effect

- Without the greenhouse effect, surface temperatures would be $-18^\circ C$
- Book also has example of atmosphere that’s purely opaque to longwave and transmitting to shortwave

- Result: surface temperature $= 303$ K
  - Too hot, but closer to this limit than no greenhouse effect...
Atmospheric Energy Budget

- Surface is heated more by **longwave** than shortwave!

Source: Global Warming Art
Greenhouse Gas Absorption

- For a gas to absorb a particular wavelength (and energy), there must be an allowed transition with the same energy
  - Rotational modes
  - Vibrational modes
  - Photodissociation (e.g., ozone breaking down into oxygen)
- No transitions => radiation makes it through air without being absorbed
Greenhouse Gases

- Diatomic molecules (N$_2$, O$_2$, etc) and monatomic molecules don’t interact with longwave.
- Greenhouse gases are all polyatomic: H$_2$O, CO$_2$, CH$_4$, O$_3$, N$_2$O.
  - Vibration mode is the transition that absorbs the infrared.
- Absorption tends to be at a single wavelength ("line").
  - Lines are then broadened by various processes.

![Infrared absorption spectra for various atmospheric gases.](image-url)
Absorption of Longwave Radiation

- LW absorption on the right
- Note CO2 band is **saturated** in the middle
  - Myth: saturation means CO2 can’t cause global warming
  - Lines still can get broader

Source: Global Warming Art
Absorption of Longwave Radiation

- **Water vapor** does most of the absorption of shortwave radiation.

- Also the most important greenhouse gas!

Source: Global Warming Art
Another Way to Think about Greenhouse Effect

- The atmosphere gets thinner as you go up
- So eventually greenhouse gases become less prevalent and radiation can escape more easily
- But it’s colder up there too! So emission is less

- Thinking about the vertical temperature profile is important for the greenhouse effect – next topic!
Radiation Summary

- Solar variability is small (< 0.1%)
- 30% of solar radiation is reflected back to space
  - 20% by clouds, 5% by atmosphere, 5% by surface
- Greenhouse effect is big on Earth!
  - Very hard for radiation to escape from space
  - “Back radiation” (longwave down at the surface from the greenhouse effect) is almost twice as big as solar!
  - Greenhouse effect causes planet to be around 33° C warmer