Announcements

- Homework 1 will be posted online today; due in class in 1 week.
- Presentation topics will be posted Friday; please email us (all 3) with your top three picks and the name of your partner (if you know this). We will assign topics Tuesday if we do not hear from you.
- Did you receive my email yesterday? If not, send me your contact information please - thanks.

Radiative Forcing and Global Change

- Earth’s energy budget
- Forcing vs feedback
- Electromagnetic radiation - basics
- Calculating temperature from radiative forcing
- Aerosols
- Greenhouse gases

Image Courtesy of SOHO/EIT.
Earth's energy budget

Feedbacks vs forcings as causes of environmental change

- **Forcing**: a primary cause of change
  - Changing solar radiation or other energy imbalance
- **Feedback**: process triggered by an initial change, which either amplifies or dampens the initial change
  - A positive feedback enhances the initial change:
    - example: warming climate melts ice, which reduces albedo, further warming the planet.
  - A negative feedback dampens the initial change:
    - example: as atmospheric CO$_2$ increases, more plants may grow, taking in CO$_2$ and reducing atmos. levels.

Most predicted climate change is the result of feedbacks, which tend to be positive (for climate)

Electromagnetic radiation

- All objects with temperature > absolute zero (0 Kelvin) emit **electromagnetic radiation**
- Electromagnetic radiation travels at the **speed of light** ($c = 3 \times 10^8$ m/sec) and is characterized by a **wavelength** ($\lambda$) and a **frequency** ($\nu$): $\lambda \nu = c$
- The important wavelengths of radiation, for our purposes, are in the **near-infrared to ultraviolet** range (0.2-100µm).
  - **Shortwave** - UV and visible; the Sun's radiation
  - **Longwave** - near IR to IR; the Earth's radiation

What is radiative forcing?

- Net (down-up) change in radiation, measured at tropopause
- Used to compare different causes of changes in radiative balance
  - E.g. solar intensity, greenhouse gases, aerosols.
- Measured in W/m$^2$ (watts per meter squared)
- Positive = expected warming, negative = expected cooling

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**Simple behavior of radiation**

- **Reflection**
  - No change in wavelength
  - No impact on surface

- **Absorption**
  - Reradiation at new wavelength - depends on temperature
  - Changes temperature of surface

- **Refraction**
  - Change in angle as radiation passes thru material (not wavelength)

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**Blackbody radiation**

a helpful idealization: absorbs all radiation that falls on it and re-emits at wavelength that depends on temperature

- Wavelength of max emission depends on temperature
- Intensity depends on temperature (thus on wavelength)
- Sun: T about 6000K; wavelength about 0.5 µm
- Earth: T about 300 K, wavelength about 10µm

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**Relevant laws and equations**

- Objects radiate at a wavelength that is a function of their temperature, according to Wien’s law:
  \[ \lambda_{(\text{max})} = \frac{2898}{T} \ \mu\text{m K/T} \]  
  (where T is in Kelvin, K)

- The Stefan-Boltzmann law says that the flux of radiation is proportional to temperature:
  \[ F = \sigma T^4 \]  
  (where \( \sigma \) is the S-B constant = 5.67x10^{-8} W/m²K^4)

Reminder: temperature scale in Kelvin has absolute zero as 0, which is -273°C. One degree C is the same as one Kelvin.
Radiation-temperature calculation

Assuming steady state, radiation (in) = radiation (out), we can calculate temperature of Earth from simple radiation parameters.

Incoming from Sun: 1370 W/m² (treating Earth as a flat disk facing Sun, which is how it receives energy).

Area of disk = \( \pi R^2 \)

Outgoing from Stefan-Boltzman law: Flux = \( \sigma T^4 \)

This occurs over full surface area of Earth (surface of a sphere = \( 4\pi R^2 \))

\[
\text{Rad (in)} = \text{Rad (out)} \\
\pi R^2 \times 1370 \text{ W/m}^2 = 4\pi R^2 \times \sigma T^4
\]

Solve for \( T \)... answer is around 5°C. Is this right?

Albedo...

Earth reflects 30% of incoming radiation back to space.

How to account for this?

Use 70% of the solar constant

Does this help or make it even worse?

Radiation scenarios so far...

Incoming

Reradiated

Incoming

Reradiated

Reflect

All absorbed

70% absorbed, 30% reflected

Earth T ~ 5°C

Earth T ~ -18°C

Other complications?

- **Greenhouse gases:** these absorb much of the outgoing longwave radiation and send it back to Earth surface
- **Water vapor** most important; also \( \text{CO}_2, \text{CH}_4, \text{O}_3, \text{N}_2\text{O}, \text{CFC's} \)
- Naturally occurring greenhouse gases cause the Earth’s temperature to be about 33°C warmer than it would otherwise be due to radiation alone.
  - (this number includes the longwave effect of clouds)
Radiative forcing and climate change

- Temperature record reflects result of changes in forcings AND feedbacks
- How has radiative forcing changed?
- How will it change in future?

Surface albedo
- Fresh snow: 75-95%
- Old snow: 40-60%
- Sand: 18-28%
- Grassland, open forests, crops: 15-25%
- Cities: 14-18%
- Dense forest: 5-10%
- Water 2-6%

- Average Earth surface: 15%
- Average top of atmosphere: 30%

Why are last two different?

Cloud radiative forcings

ALBEDO:
- Thin stratus: 30%
- Thick stratus: 60-70%
- Cirrus: 20%
- Nimbostratus: 70%

Clouds also absorb infrared radiation and reradiate to space at colder temperatures (greenhouse)

High clouds: greenhouse >> albedo; net warming
Low clouds: albedo >> greenhouse; net cooling

Effects are large in both directions; total effect of clouds today is a small cooling (but can change)
Radiative forcing: a changing Sun

- Solar radiation varies on all time scales, but particularly on decade-century.
- High sunspot activity: higher radiative output
  - dark spots are surrounded by brighter faculae
- Total amount of radiation variance is small: 0.2-0.4% over centuries
  - Long-term variability is really hard to pin down
- Can a small change in Sun’s output create observable changes in Earth’s climate?

http://www.windows.ucar.edu/tour/link=/sun/activity/solar_variation.html

Solar irradiance changes since 1600

- Sunspot cycles well observed
- Background changes less well known
- Big uncertainty over centuries
- Paleodata suggest a link to climate that is small but visible
- How can small changes (0.2%) influence climate?
  - Stratosphere; circulation; clouds

Has the Sun caused the recent warming of climate?

- NO - if it had, atmosphere would be warming at all levels
  - Cooling stratosphere consistent with radiation trapped in troposphere
- NO - solar radiation has no strong increasing trend, as temperature does.
  - Solar cycles of 11 yrs

Exact value of solar constant varies w/observational datasets

Aerosols

Particles or droplets suspended in atmosphere

- Natural Sources:
  - Desert dust
  - Volcanoes
  - Biogenic emissions
  - Sea spray
  - Meteorite impacts
**Aerosols**

- **Anthropogenic Sources**
  - Land use changes:
    - Deforestation
    - Desertification; other activities in semiarid regions
  - Biomass burning
- **Pollution**
  - Industry
  - Transportation

**Sink:** gravity or rainout

**Residence time:** days to weeks in troposphere; 1-2 years in stratosphere

**Vertical Distribution:** mostly troposphere, near region of production
  - Our focus is on tropospheric aerosols
  - Volcanic aerosols have strong global climate impacts if they reach stratosphere (cooling of 0.5-1°C that persists a few yrs)
- **Horizontal distribution:** (tropospheric) depends heavily on local weather/climate; moved by wind

**Localized source example - fires in Mexico**

**Global Distribution**

- Mostly over regions of production
- Satellite sensing has difficulty over bright surfaces or with low solar angle (highest lats)

Kaufman et al. 2002
**Sources and sizes**

- **Fine:**
  - Often anthropogenic
  - Pollution (Europe, N America, Asia)
  - Fires (Africa, S America)

- **Coarse:**
  - Often natural
  - Dust from African and Asia
  - Sea salts from ocean (most turbulent = Southern Ocean)

Kaufman et al. 2002

**Compositional breakdown**

- **Sulfate:** small, reflective droplets/particles
  - Pollutant; ocean; volcanic

- **Black carbon:** dark, absorptive particles
  - Pollutant; biomass burning

- **Organic carbon:** non-absorbing carbonaceous particles
  - Biomass burning

- **Mineral dust:** reflective, range of sizes
  - Land surface

- **Sea salt:** coarse particles, absorb very little
  - Ocean spray

**Direct radiative effects**

- Depend on size, shape, composition, distribution

  - **Scattering (reflection):** shortwave radiation strikes and bounces off in all directions. Usually COOLING.
    - Reflects radiation back to space; cooling
    - Typically smaller particles, droplets
    - Impact depends partly on albedo of surface below

**Indirect radiative effects: Clouds & precipitation**

Clouds are made of droplets that have coalesced around a particle:

- **CCN = cloud condensation nuclei**

More particles = more droplets, but with same amount of water vapor, the droplets are smaller.

- **Smaller droplets = clouds become more reflective (add to cooling)**
- **Reduced precipitation due to smaller droplets**
- **Longer cloud lifetimes and larger areal coverage because less rainout (albedo changes add to cooling)**
The “semi-direct” effect

Absorbing aerosols warm the air around them, usually at heights of several km in the troposphere, with several results:

• Reduces cloud formation as droplets do not condense as easily in warm air
• Reduces precipitation
• Cools the surface as radiation is intercepted

These are dark colored “black carbon,” organic carbon, or “brown cloud” aerosols.

Presence of such aerosols can change the net influence on clouds from a stimulant to a suppressor.

How do clouds form? (an aside)

• Clouds form when vapor condenses into small droplets on particles (CCN’s)
• This occurs as air cools and can no longer hold water in vapor form (warm air holds more vapor)
• Cooling occurs as air rises: it is warmed by radiation from the Earth’s surface and thus becomes less dense than the overlying cool air, so it rises and cools and vapor condenses
• If the upper air is warmed by aerosol absorption, then the rising is suppressed (the atmosphere is said to be more stable) and no clouds form.

Issues

• Basic lack of knowledge about many relevant processes
• Observations have uncertainties
• Prediction extremely difficult (local sources, control by local circulation)
• Transboundary air pollution
• Health and air quality
• Scale is regional

Aerosol summary

• Direct effects cool the planet by reflection
• Indirect effects cool the planet by increasing clouds and their lifetime, area, and reflectivity
• Effects on hydrology include burning off clouds (semidirect) and making clouds less likely to rainout
• Remain a major uncertainty in projections and physical understanding of climate

http://science.nasa.gov/headlines/y2001/ast17may_1.htm
"Global dimming" - aerosols reduce radiation reaching the Earth's surface

- Sun's radiation striking surface has decreased by 9-30% in recent decades (depending on region and interval)
- Masks full extent of global warming! (how much? Up to 1.5°C?) “aerosol climate protection”
- Likely to weaken as pollution controls expand

Aerosol climate protection?

Strong present-day aerosol cooling implies a hot future

- CO2 accumulates; aerosols wash out
- As aerosols reduced, warming will accelerate
- Extent of additional warming depends on radiative impact of aerosols

Aerosols as disease agents

- Smoke from Indonesian fires, 1998
  - Human instigated; drought exacerbated
- Deposition of particulates on Sumatran reefs (iron)
- Red tide develops
- Coral mortality high

Abram et al. 2003, Science

Regional aerosols and snowmelt

NSIDC
Do aerosol particles in smoke inhibit clouds over the Amazon?

- Semi-direct effect: warming air at upper levels of atmosphere
- Clouds “burn off”
- Less rainfall

Images: http://earthobservatory.nasa.gov/Features/SmokeClouds/
From Koren et al. 2004

Greenhouse gases

- Water vapor, CO₂, CH₄, N₂O, O₃, CFCs
  - In dry air, these are less than 0.04% of atmosphere (water: 0-4%)
  - GH - Any molecule with >2 atoms; also asymmetric molecules
- Trap radiation at specific wavelengths
  - Most effective in atmospheric "window region"
  - Bands do saturate

From Turco, 1997
Effectiveness

- The effectiveness of a greenhouse gas depends on several factors
  - **Wavelength**: where absorbing (bands can saturate)
  - **Lifetime**: if stays in atmosphere long, very effective!
  - **Molecule**: some are just more efficient (CFCs and relatives)

- **Global Warming Potential** - relates each gas to CO$_2$ in terms of effectiveness, for a specified time horizon
  - A way to compare different gases at different time horizons
  - For 100yr horizon, GWP’s can reach 10,000+ for CFC’s and related compounds! (AR4 Chapter 2)
  - “Doubling CO2” includes all GHGs converted to CO2 equivalent
  - We account for GHGs in CO2-equivalent units