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DAY 13: 11/6/12
The Instrumental Temperature Record

- Global temperature since 1880

Stevenson screens to measure temps on land, ocean temps from buckets or intake.

Groups attempt to remove inhomogeneity in the datasets.
Other signs of (global) warming

- melting mountain glaciers
- decrease in winter snow cover
- increasing atmospheric water vapor
- warming of global oceans
- warming of upper atmosphere
- rising sea level (due to warming and ice-melt)
- timing of seasonal events
  e.g. earlier thaws, later frosts
- thinning and disappearing Arctic sea ice

Every one of these data sets can be questioned to some extent.
Taken together, the totality of evidence of global warming is quite convincing.
Solar vs Terrestrial Radiation

- Solar (blue) vs terrestrial (red) radiation:

  Very little overlap: solar (“shortwave”) and Earth (“longwave”)
Solar Radiation and Earth

• 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
- **Albedo**: reflectivity of surface (0 = black, 1 = white)

(Remember poles are exaggerated in Mercator projections like this)
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
“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)
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
Shortwave Climate Forcings

- **Radiative forcings** for shortwave agents in current climate vs preindustrial (best estimates)
  - Remember CO$_2$ radiative forcing is currently: 1.66 W/m$^2$
  - **Solar** radiation changes (low certainty): 0.12 W/m$^2$
  - **Land** cover changes (low): -0.20 W/m$^2$
  - **Soot** on snow (low): 0.10 W/m$^2$
  - **Aerosol direct** effect (medium/low): -0.50 W/m$^2$
  - **Aerosol indirect** effect from clouds (low): -0.70 W/m$^2$
Earth Radiation

- 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 ➔
Atmospheric Energy Budget

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

Source: Global Warming Art

**The Greenhouse Effect**
- Solar radiation absorbed by Earth: 235 W/m²
- Directly radiated from surface: 40
- Thermal radiation into space: 195
- Heat and energy in the atmosphere: 168
- Greenhouse gas absorption: 350
- Earth's land and ocean surface warmed to an average of 14°C

Very hard for radiation to escape straight out to space
Greenhouse Gases

- Diatomic molecules ($N_2$, $O_2$, etc) and monatomic molecules don’t interact with longwave.

- Greenhouse gases are all polyatomic: $H_2O$, $CO_2$, $CH_4$, $O_3$, $N_2O$
  - 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.
These are all current values vs preindustrial values

- Carbon dioxide: $1.66 \text{ W/m}^2$
- Methane: $0.48 \text{ W/m}^2$
- Nitrous oxide: $0.16 \text{ W/m}^2$
- CFCs: $0.32 \text{ W/m}^2$

- But CFCs are decreasing now (everything else is increasing)
Moisture in the Atmosphere

- **Saturation vapor pressure:**
  - Tells how much water vapor can exist in air before condensation occurs

- **Exponential function of temperature**
  - Warmer air can hold much more moisture
Water Vapor Content and Global Warming

- Constant relative humidity $\rightarrow$ warmer climates have much more moisture!
  - 7% increase per degree of warming
- More water vapor $\rightarrow$ more water vapor greenhouse effect
  - Primary positive feedback to global warming
- Water vapor is a *feedback* to climate change, not a *forcing* of climate change
  - Can’t change water vapor content directly: it responds to the global mean temperature
Ice-Albedo Feedback

- Warming → ice melting → dark open ocean visible → more warming
- Similar feedback is present for snow (revealing darker land surfaces below)

Very important for local Arctic temperatures

Not nearly as strong as water vapor feedback in global importance
Cloud Feedbacks

- Two opposite effects:
  - Reflecting solar radiation (cooling)
    - Based on their **thickness**
  - Greenhouse effect (warming)

- Can either have warming or cooling effect depending on type!
  - High, thin cirrus have a warming effect
  - Low, thick clouds have a cooling effect
Feedback Factors for Global Warming

Colman (2003):
- Clouds have largest uncertainty by far (when water vapor and lapse rate are combined)
- Cloud LW forcing is expected to be slightly positive (depth of high clouds to increase)

Soden & Held (2006):
- \( \bar{f} = 0.62; \sigma_f = 0.13 \)

Colman (2003):
- \( \bar{f} = 0.70; \sigma_f = 0.14 \)

Individual feedbacks uncorrelated among models, so can be simply combined:
Distributions of Sensitivity

\[ \Delta T = \frac{\Delta T_0}{1 - f} \]

\( f = 0.65 \)
\( \sigma_f = 0.14 \)

- Skewed tail of high climate sensitivity is inevitable!
- Note the expected value has slightly less warming though
Condensation and Latent Heating

- We’re all familiar with the idea that evaporation causes cooling
  - Evaporation of sweat cools you off
  - Getting out of a pool on a windy day → cold!
- Similarly, **condensation** -> **heating** of the atmosphere
  - Condensation of water vapor is associated with a release of latent heat
  - Huge heat source:
    - Average tropical lower tropospheric moisture values: 45°C of heating potential!
A Dry Atmosphere

- In a dry atmosphere forced from below, convection (vertical overturning) occurs, and temperatures decrease as air goes to lower pressure.
- Lapse rate $\frac{dT}{dz}$ is constant in this atmosphere,

$$\frac{dT}{dz} = -\frac{g}{c_p} = -9.8^\circ C/km$$

“dry adiabatic lapse rate”

Note this is much larger than the observed lapse rate of 6.5$^\circ$ C/km.
Missing Ingredient from our Model: Moisture

- Observed lapse rate of 6.5° C/km is due to moisture condensation
  - Moisture condenses as it rises, releasing heat

Solid: dry
Dashed: with moisture

Dashed curve is just a schematic: Moisture make the lapse rate not constant with height (*moist adiabatic profile*).
Lapse Rate Feedback

- Due to the greenhouse effect, outgoing longwave radiation on Earth comes from high levels in the troposphere.
- Moisture causes the highest levels to warm the fastest.
  - This means OLR can increase faster: negative feedback to warming!
  - Primary negative feedback to global warming.
Tropopause Height

- Good approximation of lower stratospheric temperature: constant temperature
  - Determined by ozone content, solar forcing, CO2 content, etc
- Stratosphere puts a lid on convection
  - Connect the dots: Surface temp + lapse rate + stratospheric temp => tropopause height!
Three reasons the tropopause rises with global warming (listed in order of importance, most to least):

- Changes in lapse rate
- Tropospheric warming
- Stratospheric cooling
What’s Required for Rain?

- To get rain, you need **water vapor** and **rising motion**
  - **Condensation** (water vapor turning to liquid water) happens when **moist air cools**
    - And this cooling almost always happens with rising motion

- **Tropics:**
  - Rising motion & rain over **warmest temperatures**
    - The **Hadley circulation** moistens the tropics & dries the subtropics

- **Midlatitudes**
  - Rising associated with high/low pressure systems
  - Storm track location/intensity is key
What Causes Primary Precipitation Features?

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Moisture Flux as an Energy Flux

- Poleward moisture flux acts to flatten temperature gradients just like heat fluxes
  - Comparable to dry energy fluxes in midlatitudes
  - Increased moisture flux leads to more high latitude warming
Why Wet Get Wetter

- More moisture in the atmosphere → more moisture convergence → wet get wetter
- This explains tendency for **high latitudes** and **tropics** to moisten

*Figure SPM.7. Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. (Figure 10.9)*
Global Average Precipitation Changes

- As it turns out, global mean precip can’t rise very fast (only 1-2%/K or so)

- Why?
  - Evaporation **cools the surface** so requires energy
  - Condensation **releases heat** into the atmosphere, so requires the atmosphere to be able to shed that heat
Some Places Must Dry...

- Subtropics is where much of the predicted drying is
  - More moisture taken out of there
- Also poleward shifts of midlatitude circulations help with subtropical drying
- **Potential evaporation** (how much water *could* be taken out of land if it was wet) is highly expected to increase
  - Mostly due to temperature increases
  - Leads to drying over land unless precip goes up...
However, Some Shifts are Hard to Predict...

- **Shifts** in rising motion could happen **due to**:
  - Differences in **forcings/feedbacks**
    - E.g., aerosols cooling the oceans in places
  - Changes in **ocean currents**
    - A natural example that messes with rain patterns is **El Niño**
- Lots of uncertainty in tropical precip responses...
Geostrophic Balance in the Atmosphere

- Jet streams
- High is on your right (when following the flow) in NH
Geostrophic Balance in the Ocean

- Sea surface height isn’t flat! It’s maintained by geostrophic balance
The “Thermal wind”

- **Temperature gradients** determine how winds change with height
- This is why winds get more **westerly** with height over most of the globe!
Where do eddies grow?

- Eddies grow due to **baroclinic instability**
- Faster eddy growth where there’s...
  - Large **temperature gradient**, or equivalently, large **wind shear**
  - Also **small stratification** helps and **higher latitudes** are better due to Coriolis

**Potential temperature**

**Zonal wind**
What Causes Surface Westerlies?

- Eddies also flux momentum flux into the jet

From Vallis textbook
Natural Variability of Storm Tracks

- Wobbling of jet stream is most common variability
- S. Hem. has even simpler wobbling N & S
Carbon Cycle: Reservoirs

- **Atmosphere:** 700 Gton
- **Land:** 500 Gton living, 1500 Gton dead in soils
- **Ocean:** 38,000 Gton dissolved inorganic C, 600 Gton of dead organic material
- **Solid earth:** 1.2 million Gton in rocks
  - Chemical weathering is the process that creates the sedimentary rocks (takes 100,000s of years)
    - Thought to be primary stabilizer of climate over millions of years
Anthropogenic Emissions

- Of CO2 emissions, around 25% goes into the ocean immediately
  - Not necessarily a good thing -- causes ocean acidification
- 25% goes into the land currently
  - This fraction could change...
- 50% stays in the atmosphere
  - This is called the “airborne fraction”
What if we immediately stopped emitting?

- Some carbon would likely stay in the atmosphere for **thousands** of years!
- Ocean uptake happens “quickly” (300 yrs)
  - A few years for surface ocean to 300 yrs for deep ocean
- Carbonate weathering:
  - As ocean pH recovers, more carbonate is formed & buried in deep ocean
  - Takes 5000 yrs
- Silicate weathering takes 100,000 yrs
Ocean Acidification

- When carbon dioxide is dissolved in water, some **carbonic acid** is formed (\( \text{H}_2\text{CO}_3 \))
- Water becomes **more acidic**
  - And the pH of the ocean has been decreasing as CO₂ levels have risen
  - From 8.2 to 8.1 already, & predicted to go to 7.8 by 2100

pH has been dropping at this Hawaii station (and globally as well)