

Climate (and the Geologic Record)

T. Perron – 12.001

Anthropogenic climate change is probably the largest experiment humanity has ever conducted. One of the major goals of climate science is to understand the system so we can predict how it will respond. But we are also interested in understanding and reconstructing past climate so we can study the geologic past. Our discussion in one lecture will only scratch the surface, and will be focused on the geologic controls on, and record of, past climates. If you want to learn more, take the EAPS Global Warming Science course.

Definitions:

- Weather: instantaneous conditions at a point on Earth's surface (T, P, precip, wind, humidity, etc)
- Climate: Average conditions at a point on Earth's surface, and how it varies with the seasons and with longer-term changes in forcing.

I. Radiative balance and the greenhouse effect

- What controls a planet's surface T? Internal + external energy sources
 - Heat flux from Earth's interior: $\sim 50\text{-}100 \text{ mW/m}^2$
 - Solar flux: 340 W/m^2 (remind them of def of Watt)
 - Clearly, solar flux dominates
- How does solar flux determine temp?
 - Simplest case: "black body" [PPT: black body curve]
 - Rocky planet with negligible internal heat flux and no atmosphere that absorbs and re-radiates all incident radiation
 - The more radiation absorbed, the warmer the planet gets, the more energy it re-radiates (and it does so at shorter, higher-energy wavelengths).
 - Stefan-Boltzmann Law: $F = \sigma T^4$, where F is in W m^{-2} and σ has units of $\text{W m}^{-2} \text{K}^{-4}$. Note the T^4 !
 - More realistic is a "gray" body: $F = \epsilon \sigma T^4$, where ϵ is the emissivity, the fraction of incident radiation that is re-radiated
 - Black body will heat up until it radiates as much energy as it absorbs \rightarrow equilibrium T_s

- For Earth, T_s would be 254K. Actual is 287K.
- Earth, Mars, and Venus have similar distances from the Sun, and so receive comparable amounts of solar radiation, but have dramatically different T_s (Venus=730K, Earth=287K, Mars=210K)
- Clearly this model is missing something
- Next level of complexity: add an atmosphere [PPT: Greenhouse schematic]
 - Basic principle: Some of the re-radiated energy (which is mostly infrared at terrestrial planet temps) is absorbed by molecules in the atmosphere and re-radiated again, warming the atmosphere and surface.
 - This is the main reason for differences among Venus (90 bars of CO_2 ; intense greenhouse), Earth (CO_2 , CH_4 , H_2O , O_3 ; moderate greenhouse), and Mars (thin CO_2 atmosphere; small greenhouse)
- So why can't we predict climate easily just by knowing atmospheric composition? There are more complicated mechanisms and feedbacks.

II. Major geologic climate mechanisms and feedbacks

- Many of these have to do with:
 - The amount or distribution of incident radiation
 - How the incident radiation is absorbed, reflected and re-radiated
 - Reservoirs that store and move heat

We will now discuss examples of each of these.

- Amount/distribution of incident radiation: Milankovitch cycles [PPT]
 - Why are there seasons? (incidence angle of sun and hours above horizon varies, so fewer W/m^2)
 - Earth's orbital geometry varies over time, which changes the amount of radiation (though only a little), the timing of the seasons, and the intensity of the seasons
 - Quasiperiodic variations in:
 - Eccentricity (95, 125, 400 kyr): Distance to sun affects seasonality
 - Obliquity (aka tilt) (41 kyr): Amplitude of sun angle changes affects intensity of seasons
 - Precession of the equinoxes (aka wobble) (19, 22, 24 kyr): Affects geographic trend of seasonal extremes

- Fractions of incident radiation absorbed, reflected & re-radiated
 - Ice albedo feedback: More ice cover raises albedo, which lowers T. Less ice lowers albedo, raising T. (+ feedback)
 - Plant growth feedback: more CO₂ --> more plant growth --> more CO₂ absorbed and stored (- feedback)
 - Water vapor feedback: warmer --> more water vapor in atm --> H₂O is greenhouse gas --> warming (+ feedback)
 - Cloud feedback: Clouds reflect more radiation back into space, but also absorb and re-radiate heat reflected by surface. (+ or - ?)
- Reservoirs that store and move heat
 - Ocean
 - Surface currents: largely driven by wind
 - Thermohaline circulation [PPT]
 - Convection driven by density contrasts due to T and salinity
 - Keeps Europe (Gulf Stream), S. Pacific warm. Cool periods in N. Hemisphere may be associated with disruption of THC
 - Atmosphere
 - Heat storage and fluxes small relative to ocean, but fast mixing
 - Controls precipitation and weather patterns
- Other geologic feedbacks
 - Silicate weathering feedback
 - CO₂ dissolves in surface water to make carbonic acid
 - Weathering of silicates (esp. plagioclase feldspar) by carbonic acid forms calcium carbonate, which is then buried in ocean
 - Removal of CO₂ (greenhouse gas) from atmosphere leads to cooling, which slows weathering reactions → neg feedback
 - Proposed that uplift of Himalayas increased WX rates, leading to cooling over past 20 Myr. (controversial)
- What has the climate been like over the past few tens of Myr?

III. Geologic record of climate variability

- How do we get climate records?
 - Direct samples of atmosphere in air bubbles in ice (CO₂ before Keeling measured it on Mauna Loa)
 - Biological indicators (fossil species composition, leaf crenulations, tree rings, pollen)
 - Isotopic proxies
 - Stable isotopes of H and O to get T and precip. Most commonly used: $\delta^{18}\text{O}$
 - Measures difference in relative abundance of ¹⁸O and ¹⁶O relative to a standard. Usually measured in ice or carbonates.
 - Influenced by temperature via distillation of atmospheric water vapor, formation of continental ice, and biological precipitation of CaCO₃
 - Higher $\delta^{18}\text{O}$ = colder
 - Stable isotopes of C as indirect climate proxy: $\delta^{13}\text{C}$
 - Primary productivity: organisms preferentially take up ¹²C, so higher $\delta^{13}\text{C}$ in carbonates means more productivity. (And large negative excursions accompany mass extinctions.)
 - Carbon burial: organic carbon is light, so higher $\delta^{13}\text{C}$ in carbonates also means more carbon burial. (Example: elevated $\delta^{13}\text{C}$ accompanied rise of land plants in Devonian.)
- What do we see in past 65 Myr of climate records?
 - [PPT: Zachos 2001] Overall cooling. Start of various glaciations: Antarctic glaciation began 25 Ma, Greenland 20Ma, Alaska 7Ma. Global Northern hemisphere glaciations began ~4Ma.
 - [PPT: Lisiecki & Raymo] The past 5 Ma are dominated by quasi-periodic cycles. Change in cycles ~ 700 ka from ~41.7 kyr (obliquity?) to ~100 kyr (eccentricity?)
 - Last ~700 kyr dominated by these 100 kyr cycles: gradual coolings into glacials, then abrupt warmings (remember this!)
- What is responsible for the observed variations?

- Milankovitch cycles play a significant role, but can explain only ~25% of variance in Pleistocene temp (Wunsch)
- The rest is feedbacks, not all of which are understood, all of which are difficult to measure in the geologic past
- Longer-term mechanisms
 - Plate tectonics
 - Arrangement of continents
 - Land at poles promotes ice accumulation
 - Supercontinents may promote ice accumulation
 - Ocean circulation: Opening and closing of passages can change warm/cold currents and inhibit or enhance T difference btw equator and poles (J. Marshall)
 - Past cycles may have been even more extreme: recall Snowball Earth

IV. Anthropogenic climate change (time permitting – we will cover this more in the day on Earth Science & Society)

- Perhaps the most common statement that accompanies denials of anthropogenic climate change: “Earth’s climate has always been changing. This is just part of a natural cycle.”
 - As we have seen, the first part of this statement is correct
 - Why is the second part likely to be wrong?
- Evidence that the anthropogenic component is significant:
 - It is true that the previous interglacial was even warmer. But the recent warming trend, which correlates with elevated GHG, has different trend and rate than in the past (rapid rise vs. slow cooling with little variation) [PPT: Textbook figs]
 - Patterns (fingerprints) of GHG-induced warming are predicted by climate models
 - Geographic pattern of T changes [PPT: models that don’t include human effects get the 20th century wrong]
 - Increases in nighttime low T > increases in daytime high T
 - Shrinking mountain glaciers at low latitude [PPT]
- What are the major anthropogenic forcings, and which are the most important? [PPT: IPCC figure]

- Note that these are forcings, not feedbacks (that's why, for example, increased tropospheric water vapor due to warmer temperatures is not here)
- Note the large uncertainty on the cloud albedo effect
- Note the magnitude of the change in solar irradiance (another common argument of those who deny anthropogenic climate change)

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