ATM S 587, Fundamentals of Climate Change

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Next Topic: Paleoclimate

- Climate of the past
  - Snowball Earth
  - Hot climates
  - Ice ages
  - Last few thousand years
What Sets the Climate Over Earth’s History?

- **The Sun**
  - It’s changed in magnitude over its lifespan
    - Over last billion years, increased 10%
    - Initially 75% as strong as it is now
What Sets the Climate Over Earth’s History?

- The orbit of the Earth around the Sun
  - If the solar system was just the Earth & the Sun, the orbit would be a perfect ellipse that never changed
  - However, there are other planets/moons in the solar system which causes orbits to change with time
    - Ex: the tilt of the Earth changes over a 41,000 year cycle (pretty quickly!)
  - What would a higher tilt mean for the climate?
    - More seasonality (colder winters, warmer summers)
What Sets the Climate Over Earth’s History?

- Location of the continents
  - These have shifted with time
  - Mountain ranges appear, sometimes high latitude ice sheets aren’t possible, etc
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Exact representation of continental drift... → →
What Sets the Climate Over Earth’s History?

- **Volcanoes**
  - On short timescales, cause cooling
  - Over very long timescales, can add significant CO$_2$ to the atmosphere
How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Biological data**
    - Tree rings, pollen, corals, fossils
    - Ex: Alligator skeletons at relatively high latitudes tell us the Eocene winter temperatures must have been very mild then!
How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Ice core data**
    - Ice at the bottom of Greenland/Antarctica is over 100,000 years old
    - Ex: Ice cores have **tiny bubbles of air** trapped inside that reveal past atmospheric composition
How Do We Know About Paleoclimate?

- **Proxy data**: tells us about temperature, precipitation, etc through other indicators
  - **Geological data**:
    - Rocks, sediments, shape of the land, etc
    - Ex: land in the Seattle area is cut out by glacier flows from when ice sheets used to have a much larger extent
How Do We Know About Paleoclimate?

- **Proxy data:** tells us about temperature, precipitation, etc through other indicators
  - **Isotopic data:**
    - Many of the previously mentioned datasets can be dated using carbon dating or other radiometric dating techniques
    - Also isotopes can tell us about precipitation and temperature as we’ll see
We’ll look at this timeline:
- Lifetime of Earth (4.5 billion years)
- Past 250 million years
- Past million years
- Past 20,000 years

Equivalent timeline for 20 yr old student:
- Whole life
- 250 million yrs = last year
- 1 million yrs = last 36 hours
- 20,000 yrs = last 45 minutes
Temperature through Time

Note: time scale is very non-linear

“deep” (distant) past was mostly warmer than today

Kasting et al
“Faint Young Sun” Paradox

- The Sun was initially around 75% as strong as it is now
- “Faint Young Sun” Paradox: raised by Carl Sagan in 1972
  - Earth was **warm** most of this time when the Sun was **weak**
    - We know this from geologic evidence
      - Rounded pebbles, mud cracks, ripple marks, microfossil algae
      - High greenhouse gas concentrations are likely key to keeping it warm
Snowball Earth– occurred several times in the last billion years when ice-albedo feedback spiraled out of control
Temperature through Time

Millions of years ago

EARTH BIRTH

PRESENT DAY

Snowball Earth Events

Kasting et al
An ice-covered Earth would have a very high albedo and an extremely low temperature.

If the Earth ever became ice covered, how could the ice ever melt?
Extremely high greenhouse gas concentrations would be required to deglaciate

Let’s discuss controls on carbon dioxide over very long timescales (this is important not just for the Snowball Earth question)
Controls on Carbon Dioxide Over Time

- **Release by volcanoes** is a relatively efficient way of getting CO$_2$ into the atmosphere
  - Remember this is small as compared to **current** human emissions
  - Volcanoes are very important over **hundred thousand year** timescales
- When we’re considering long timescales, have to think about how CO$_2$ is **removed** as well
Chemical Weathering

- How does CO$_2$ get **removed** from the atmosphere over long times?
  - **Land masses** are key in a process called **chemical weathering**
  - When rain/snow falls on silicate rocks, it reacts and takes CO$_2$ out of the atmosphere
- **Chemical weathering is a negative feedback**
  - When climate is hotter, it’s easier for weathering to take CO$_2$ out of the atmosphere
  - Likely key for **stabilization** of climate over millions of years
During Snowball Earth, volcanic activity injected CO2 into the atmosphere. With the land and oceans covered by ice, there was no chemical weathering to remove CO2 from the atmosphere, so it accumulated.
Eventually the greenhouse effect became so strong that the ice began to melt, despite its high albedo.
Once initiated, melting would proceed very rapidly as the albedo dropped.
Post-Snowball “Hothouse” Climate

- Immediately after Snowball Earth thaws, CO\textsubscript{2} concentrations would have been tremendously high.
- Was likely the **hottest period** in Earth’s history right after the **coldest**!
  - Temperatures jumped from -50\textdegree\ C to 50\textdegree\ C in only 1000 years!
- Massive weathering would gradually bring down CO\textsubscript{2} and temperatures.
How Did Life Survive?

- We know life existed before Snowball events
- How would it have survived the ice-covered surface?

![Diagram showing time in millions of years with labels for life, eukaryote life, Snowball Earth events, and 11 animal phyla emerging.](image)
How did life survive Snowball Earth?

Cracks in the ice?

Hydrothermal vents?

Cracks in dynamic sea-ice, a potential refugium for phototrophs on snowball Earths.
Ice in Snowball Earth

- Steve Warren (UW Atmos Sci/ESS) studies ice types in Antarctica as a way to understand Snowball Earth.

In labs, he also grows other types of ice that don’t currently exist on Earth!

**Blue ice:** what tropical ice was most like on Snowball Earth?
Snowball Earth Timeline

~1 million yrs?

0 ~2000 yrs 1M+1k yrs

Cold jarring

Weathering stops, CO2 builds up, & temp increases slowly

Ice “jumps” to equator. Snowball formed! Temp <-50C

Ice albedo feedback causes ice to advance

Melting starts, ice-albedo feedback causes rapid melt (in ~1k yr)

Super greenhouse effect, very hot ice-free planet

Life survives
Temperature through Time

PRESENT DAY

EARTH BIRTH

Mesozoic/Early Cenozoic Warm Periods

Kasting et al
Previous Warm Climates

- It’s been hotter in the past than we’ll experience with global warming
- The planet and life will survive...
- These warm periods started with a rather massive extinction though
"The Great Dying"

- **Permian-Triassic extinction: 252 million years ago**
  - 90% of marine species went extinct
  - Two-thirds of land species went extinct

- **Happened along with a large warming**
  - Quick onset (one million years)
  - Rising greenhouse gas levels
  - Much warmer oceans inhibited mixing of oxygen into ocean?
Other Possible Causes of Extinctions

- Additional causes may have been important too
  - Maybe a meteorite impact (no clear crater though)

- **Methane hydrates** may have been important in causing warming
  - May have rapidly been released from the bottom of the ocean, increasing greenhouse gas concentrations quickly
Mesozoic (250 - 65 million years)
Triassic, Jurassic, Cretaceous
Dinosaurs - 2-6 deg C warmer globally
Poles were especially warm - mystery

Evidence for polar warmth:
Lush ferns and alligators in Siberia
CO₂ levels were several times higher than present.
- We know this from many lines of evidence: isotopes in rocks/fossils, examination of plant fossils, carbon cycle models.

Increased undersea volcanic activity was likely important for releasing more CO₂.
- Plates were separating more quickly back then, causing more volcanoes.
Cretaceous sea levels were 200 m higher than today!

The entire middle of N. America was a giant seaway

Lots of chalk deposits from shells in the inland seas

(*Cretaceous* = chalky)
Why Were Sea Levels so High?

- No ice sheets at all
- Thermal expansion of seawater
- Ocean was less deep (tectonic activity)

These factors led to 200 meter higher sea levels

Cretaceous chalk deposits
After the Cretaceous

- 65 million years ago dinosaurs went extinct
  - Due to meteorite impact
- Warm climates persisted for a while after though

Note this huge & rapid warming event
“Paleocene-Eocene Thermal Maximum”

- 55 million years ago there was a quick jump in temperature
  - Same time as pockmarks on the ocean floor suggesting methane hydrate release
The Role of Continental Drift in Climate

Continental Drift (Alfred Wegener, 1920s)
Another major factor in the history of climate change
Plate tectonics and climate

- **Movement of Antarctica** over the South Pole
  - Allowed an ice sheet to form – higher planetary albedo
- Decline in atmospheric CO$_2$ starting 60 million years ago
  - Coincides with the rise of the Himalayas and Rockies
    - **More weathering** as fresh rock exposed
  - Also there was a concurrent slowdown in continental drift
    - Less volcanism, less CO$_2$
- Closing of the **isthmus of Panama** was the last major change to the land distribution (about 4 million years ago)
Last 35 million years (since end of early Cenozoic)
• Earth slowly cooling
• Life retreats from poles
• Polar ice caps established
• Most recent ice-ages begin ~3 million years ago

Cause of decline in CO2?
Himalayas form when India collides with Asia and the fresh rock and high precipitation around mountains increased weathering (maybe)
Temperature through Time

- Glacial Conditions (ice-ages)
- Inter-glacial Conditions (e.g. the present)

PRESENT DAY

EARTH BIRTH

Mean Global Temperature
Cold ▼ Warm

Quaternary
Pliocene
Miocene
Oligocene
Eocene
Paleocene

Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian

Proterozoic
Archean
The Ice Ages

- The Ice Ages lasted 2.7 million ybp to about 10,000 yrs ago

- Large ice sheets covered Northwestern Europe and Northern North America
What does an ice age look like?

- Reconstruction of land and sea ice 21,000 years ago
The last glacial maximum (LGM) occurred around 20,000 years ago.

Sea level was lower by ~120 m at the time of the LGM because of the storage of water in the continental ice sheets.

The land bridge
The home ice sheet ~20kbp

Cordilleran Ice Sheet
Lake Missoula
Spokane Floods (from Lake Missoula)
Geology of Seattle and the Seattle area, Washington

Figure 1. Location of Seattle, Puget Lowland, and most recent ice limit (shown by hachure marks) in Washington State (modified from Booth et al., 2004b).

From Troost & Booth 2008
What does an ice age look like?
The Puget Sound Lobe
Figure 8. Three-dimensional (3-D) image of shaded-relief digital elevation model from light detection and ranging (LIDAR) data of north Seattle with 8x vertical exaggeration showing drumlins and scoured topography. View is west-northwest along the ship canal valley (heavy dashed line) from Lake Washington to Puget Sound. Note the north-south glacial striations on the drumlins. UW—University of Washington.

Striations in Seattle (topography has been exaggerated 8x for visibility)
Glacial Striations in Victoria, BC
Ice Core Records

- Present day ice sheets provide excellent records of the past!
- **Ice cores** have been taken from Greenland and Antarctica
  - Up to 800,000 year old ice!!
  - Up to 3700 m deep!
Russian scientists first struck Lake Vostok on Feb 5 2012
Isotopic Evidence

Two immensely valuable consequences:

- Isotopes in ocean sediments records glacial ice volume
- Isotopes in ice-cores indicates local temperature
Huge temperature changes in ice ages: up to $10^\circ C$ in Antarctica, $5^\circ C$ globally. Slow onset of glacial periods and rapid decay. Suggests that ice dynamics may play a role in the decay process (one reason we’re concerned about dynamical loss in Greenland/West Antarctica).
Carbon dioxide concentrations (measured in air bubbles trapped in the ice) show a remarkable correlation with temperature.

Methane concentrations decrease during ice ages as well.
Can extend records back (to 3 million ybp!) with ocean sediment data.
3 Million Year Record of Global Ice Volume

From oxygen isotopes in ocean sediments

More frequent switching between glacial/interglacial before 600,000 years ago

Kasting et al
What Causes Ice Age Cycles?

- Is carbon dioxide the driver of ice ages? **No!**
- In this case, carbon dioxide was acting as a *feedback* not a *forcing*
  - Carbon dioxide changed due to temperature changes, and amplified the changes (positive feedback)
- The driver is changes in **solar radiation** due to changes in **Earth’s orbit** around the Sun
What Drives the Ice Age Cycles?

- Solar radiation in the Northern Hemisphere summer is key for growth/melt of ice sheets
  - It’s always cold enough for snow in the winter at high latitudes, so winter temperatures don’t matter
  - A colder summer means snow doesn’t melt and can accumulate
  - Less sunlight in the summer means colder summers & expansion of high latitude ice sheets
  - And vice versa...
Theory of the Ice Ages:
Orbital induced solar radiation changes and global ice volume

Deglaciation events happen when there’s more summer sunlight.

Onset of ice ages occurs when there’s less summer sun.
Orbital Parameters and Their Changes

- **Eccentricity**: how circular/elliptic the orbit is
  - Matters for whether some times of the year get more radiation than other times
  - Varies from 0 to 0.06 (currently 0.017) (always pretty darn circular) over 100,000 year periods

- **Obliquity**: tilt of the Earth
  - Causes seasonal cycle (summer gets more direct light)
  - Varies from 22 to 24.5 (currently 23.5) over 41,000 year cycle

- **Precession**: what day of the year is closest to Sun
  - Varies on 23,000 and 19,000 year cycles
  - Currently Jan 3 gets the most radiation
  - No effect if eccentricity equals zero!
Efficacy of Forcings

- Eccentricity is tiny on its own
- Obliquity is a strong, direct forcing of high lats → → →
  - Around 10% change in high latitude insolation (40 W/m²)
    Top panel = current insolation
    Bottom panel = insolation at largest - smallest obliquity values (24.5 – 22.5)
- Eccentricity plus precession can be 15% change max
- 30% change from all forcings
Glacial Cycles over Time

- Early on, 40,000 year cycles dominated
  - Obliquity having a direct effect
- More recently, 100,000 year cycles have been most prevalent
Last 20,000 Years

- Ice sheets started shrinking 15,000 yrs ago
- 12,000 yrs ago: ice sheets pouring lots of meltwater out
- Younger Dryas: 12,000 yrs ago
  - Relapse into ice age conditions
  - Lasted 800 yrs
  - Unlikely that this was global in extent
  - Surge of meltwater shutting off thermohaline circulation?
- Mild temperature swings ever since then
  - The stable Holocene period
  - All ice sheets had melted approximately 7000 yrs ago
Very likely that current GHG concentrations are biggest in 650,000 yrs (from ice core data)
- And current rise in GHGs is completely anthropogenic

CO₂ concentration (left)

Rate of change of radiative forcing (right)

From IPCC AR4
Relation of Current Climate to Paleo

• Very likely that CO2 amplified glacial-interglacial cycles
  ○ But rises in CO2 didn’t cause deglaciation! Temperature started rising first, and CO2/water vapor was a feedback

• Climate forcings of LGM:
Relation of Current Climate to Paleo

- Virtually certain that orbitally induced cooling will not be significant any time soon
  - Next natural ice age: 30,000 yrs from now
The Ice Age Cycles: Some big unsolved questions
The Ice Age Cycles:
Some big unsolved questions

Why is CO$_2$ so highly correlated with ice volume?
Why is CO$_2$ even more highly correlated with Antarctic temperature?
A simple but incomplete answer:

Colder oceans can dissolve more atmospheric CO2

Why aren’t we sure?
Possibly more plankton active taking CO2 out of the atmosphere and/or seawater exchange between surface and deep was greater…
Rapid Climate Change, interstadials, or "Dansgaard-Oeschger events"
Retreat of the Laurentide ice sheet

Very fast ice loss
Younger Dryas (YD) - example of Rapid Climate Change

• 14,700 kbp, the warming trend reversed

• relatively cold period lasted about 2,000 years

• warmed very abruptly about 12,000 years ago, and has been relatively stable since then.
YD probably caused by ice sheet breakup and flooding in the northern North Atlantic.

The meltwater pulse could cause the thermohaline circulation to shutdown.

Reducing heat transport into northern North Atlantic.

The YD was probably largest in the North Atlantic, consistent with the thermohaline shutdown mechanism.
The last 160,000 years
(from ice cores) and the
next 100 years
The Holocene:
Time since last ice age
(last 15k yr)
Tree Ring Data to Infer Past Temperatures

- Trees near mountain tree lines can tell how tree lines have moved in the past
  - This tells about temperature variations
- Our dean is an expert in this!

Lisa Graumlich,
Dean of the College of the Environment
looking back at the history of global temperature

Note that there are no numbers on the temperature scales

We have learned much about paleoclimate in the intervening years
Proxy records suggest that the Little Ice Age and Medieval Warm Period were more localized events (i.e., some parts of the world were warmer during the Little Ice Age).