Climate Dynamics (PCC 587): Paleoclimate/Cryosphere II

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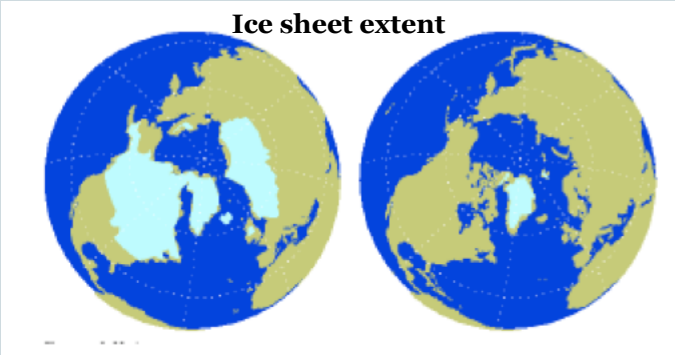
History of the World, Part II

- We'll look at this timeline:
  - Lifetime of Earth (4.5 billion years)
  - Past 100 million years
  - **Past million years**
  - **Past 20,000 years**
- Equivalent timeline for 25 yr old student:
  - Whole life
  - 100 million yrs = last 6 months
  - **1 million yrs = last 2 days**
  - **20,000 yrs = last hour**
- Also we'll study the current state of the cryosphere

Past Million Years

- Past coupled million years dominated by **glacial** vs **interglacial** climates



The Cryosphere in Present Day

- Cryosphere: frozen water in the climate
  - **Mountain glaciers**: permanent ice on top of mountains
  - **Ice sheets**: glaciers that cover a large amount of land
    - Currently only Greenland and Antarctica
  - **Seasonal snow cover**
  - **Sea ice**: frozen ocean water floating
  - **Permafrost**: frozen soil

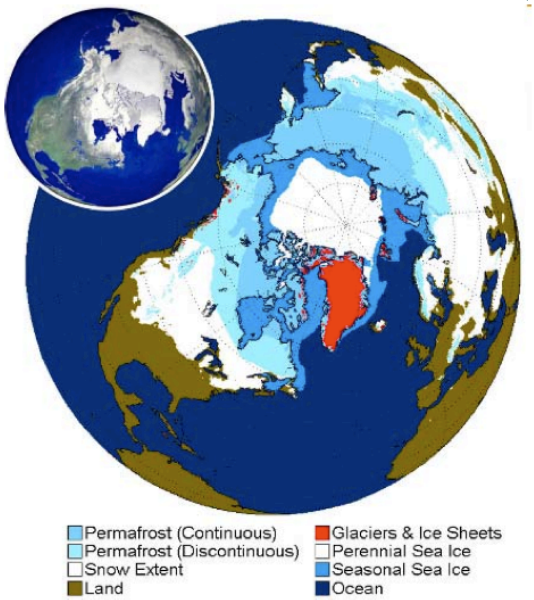
Relative Sizes of Cryosphere

- Cryospheric components:
  - In terms of **coverage area** (percent of Earth surface area) and **volume** (how much sea level rise (SLR) would result from melting it all)
  - Antarctic ice sheet: 2.7% of Earth surface area, **61.1 meters** of sea level rise (SLR) if melted
  - Greenland ice sheet: 0.35% of area, **7.2 meters** of SLR
  - Alpine glaciers: 0.01% of area, 0.2 m of SLR
  - Seasonal snow cover: 9% of area (maximum), <0.01 m of SLR
  - Permafrost: 5% of area, 1 m of SLR
  - Sea ice: 7% of area (in season of maximum extent), 0.01 m of equivalent mass, (no sea level rise when sea ice melts)

Northern Hemisphere Cryosphere

- Maximum extent of ice types in NH:

(snow extent here is where snow coverage is > 50% during month with max coverage)



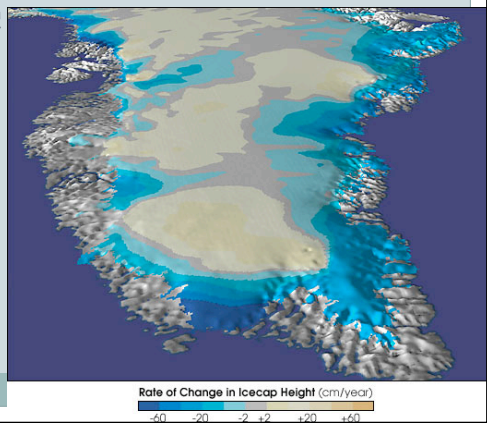
Greenland Ice Sheet

- Greenland: ice is ~100,000 yrs old
  - Surface is depressed to approximately sea level in the middle, mountains on the perimeter
  - Loses mass from sublimation, calving of icebergs away from edges, & running off of meltwater
  - Gains mass by snowfall
  - Large temperature rise in Arctic means melting has outweighed increased snowfall recently

Greenland summit is approximately height of Mount Baker

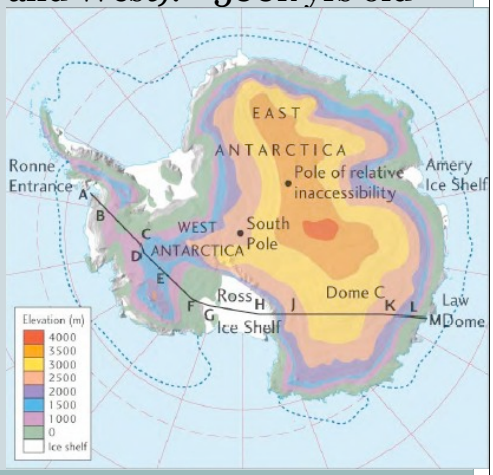
Future of Greenland Ice Sheet

- Arctic is ground zero for global warming – what will happen to Greenland ice sheet?
  - Melt area has been expanding in recent years
  - Ice sheet models indicate 3 C warming would lead to 1 m sea level rise over 1000 yrs
  - Possible positive feedback that could speed this up: meltwater leaks through the bottom, lubricates surface, leads to slipping of ice



Antarctic Ice Sheet

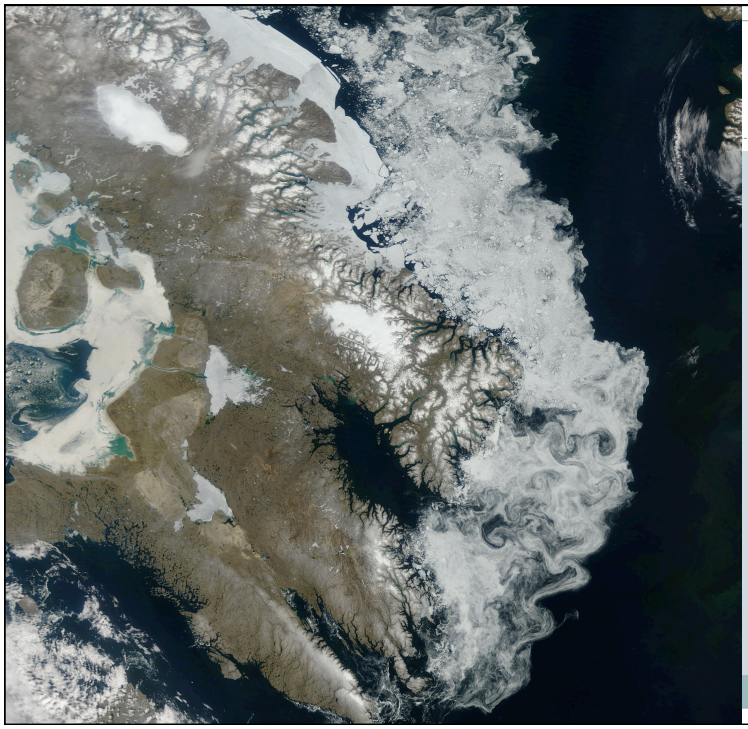
- Antarctic ice sheets (East and West): ~500k yrs old
  - East sheet: 90% of mass
  - West sheet: 10% of mass
  - Ice shelves (Ross, Amory): when ice flows from sheet onto the ocean



Max thickness is ~300 m taller than Mt Rainier

Future of Antarctic Ice Sheet

- Antarctic ice sheets (East and West)
  - East sheet: appears to be in balance (not gaining or losing mass) and not warming much
    - Due to increases in snow, and less warming due to ocean heat uptake and ozone depletion strengthening circumpolar jet
  - West sheet: losing mass
    - Also potentially rather unstable due to geometry (much is under sea level)



Sea ice
off Baffin
Island, Canada

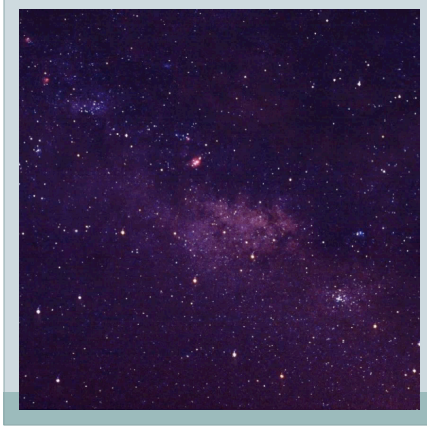
Sea Ice

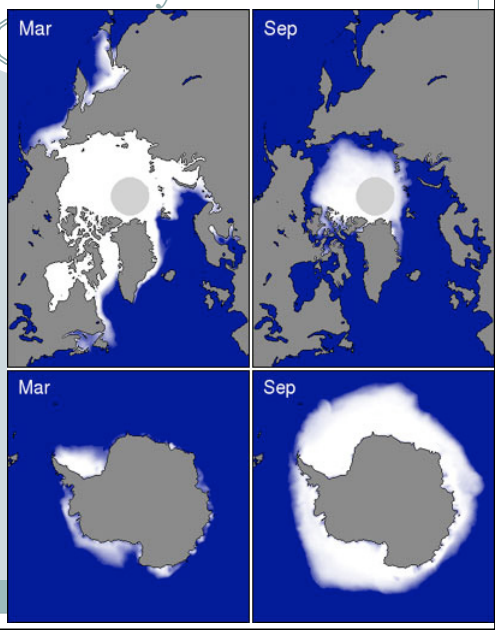
- Covers large area of Earth (up to 9%), but relatively thin (1-3 meters)
- Very seasonal in its coverage
- *Floes* separated by *leads* of open water
- Freezes from the bottom, melts on the top
- Transported around by wind stresses

Pressure ridges on sea ice

Sea Ice Seasonal Cycle

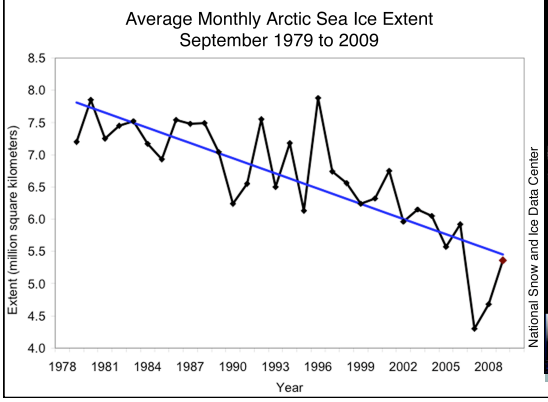
- NH and SH seasonal cycles

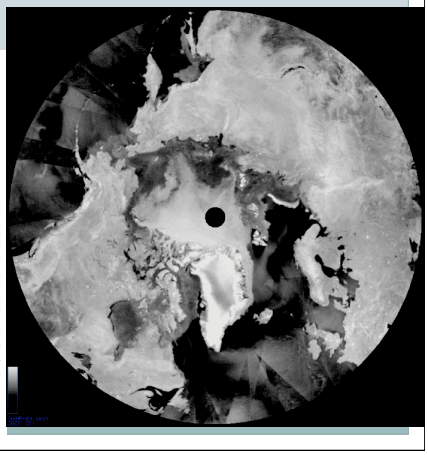




Arctic Sea Ice Decline

- Record minimum in Sept. 2007 was 23% lower than any previous minimum





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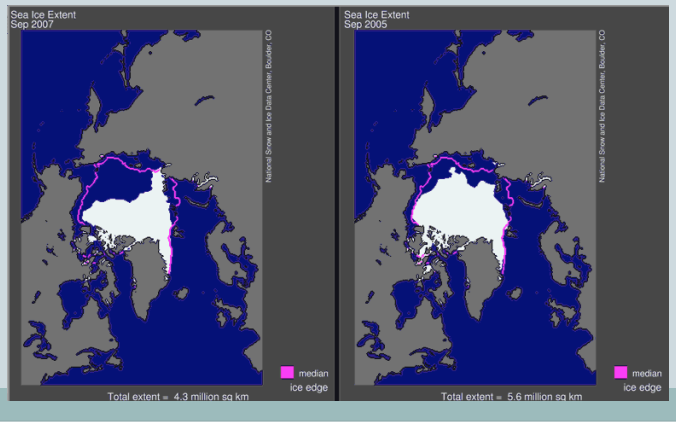
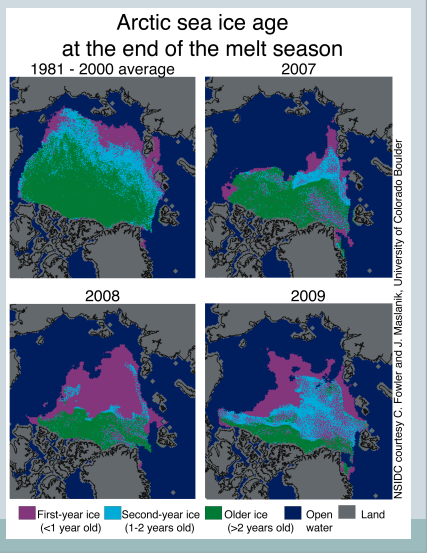


Arctic Sea Ice Decline

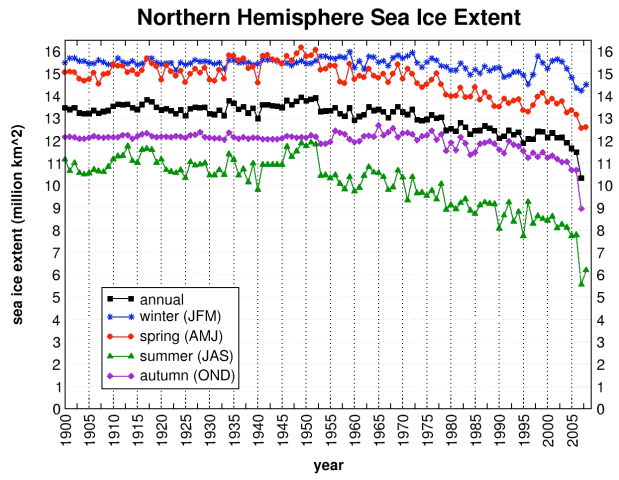
- First year vs multi-year ice
  - Multi-year ice is likely harder to melt than first-year
  - Thickness is important, not just extent!



NH Sea Ice Trends

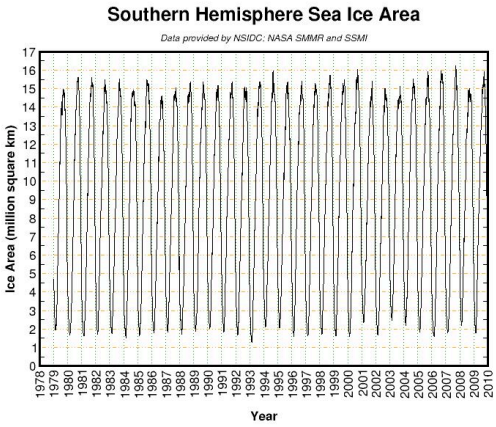
- NH extent (seasonal averages)

Little decrease in winter (ice always refreezes during polar night



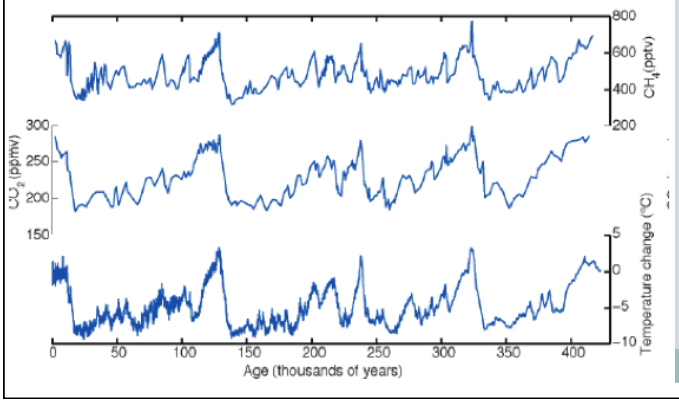
Antarctic Sea Ice Trends

- Not much trend in S. Hem. (slight increase actually)
  - Related to ozone depletion? (Turner et al 2009)



Back to Glacial Cycles

- Last 2.5 million years characterized by glacial vs interglacial periods
  - Ice core data of temperature, CO2, methane from Antarctica:



Methane

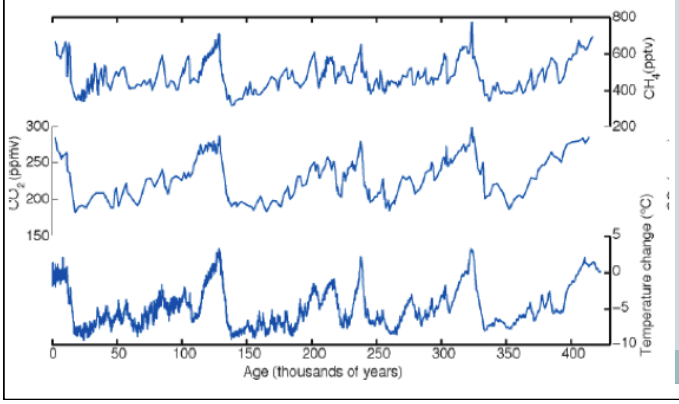
CO2

Temperature

(Note time runs forward to the left)

Glacial Cycles

- Roughly 100,000 year cycles
  - Much more rapid warming, slow & steady cooling
  - Most recent: "Last Glacial Maximum" (LGM), 20k yrs ago



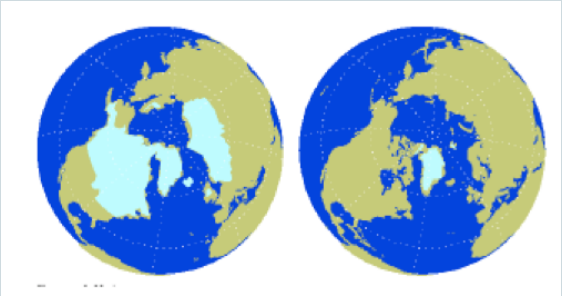
Higher temperature periods also associated with higher CO2 and methane

(LGM CO2 = 180 ppm, preindustrial CO2 = 280 ppm current CO2 = 384 ppm)

Changes in temperature/ice extent lead CO2 changes slightly

Last Glacial Maximum Conditions

- Ice sheet extent:
  - Over Canada, this ice sheet was up to 3 km thick
  - Global sea level was **125 meters lower** than today!
  - Greenland 10 C colder, tropics 4 C colder



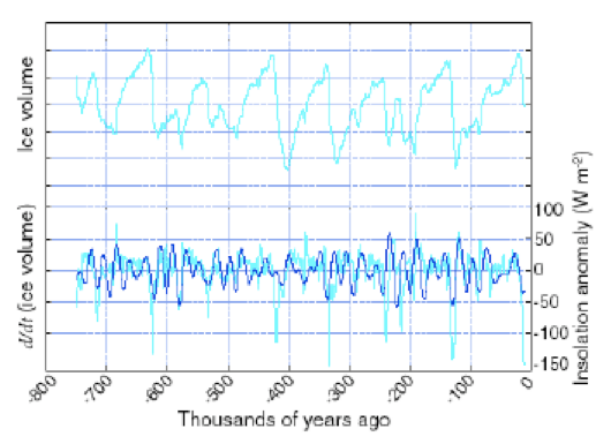
Last Glacial Maximum **Present**

Reasons for Glacial Cycling

- Changes in solar input in the NH summer are thought to drive the cycles
  - Reduced summer insolation would mean less winter snow melts → would eventually grow ice sheets
  - Increased summer insolation → more snow melts → easier to shrink ice sheets
  - N. Hem. matters more b/c there's more land there
- Albedo and CO2/methane are positive feedbacks
  - Play important role in setting amplitude of changes

Ice Sheet Growth versus High Latitude Solar

- Total ice volume change is well-correlated with solar radiation at 65 N:



Wallace & Hobbs

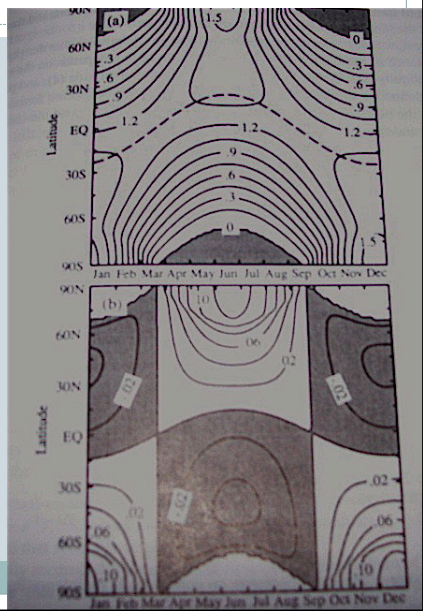
Orbital Parameters and Their Changes

- 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

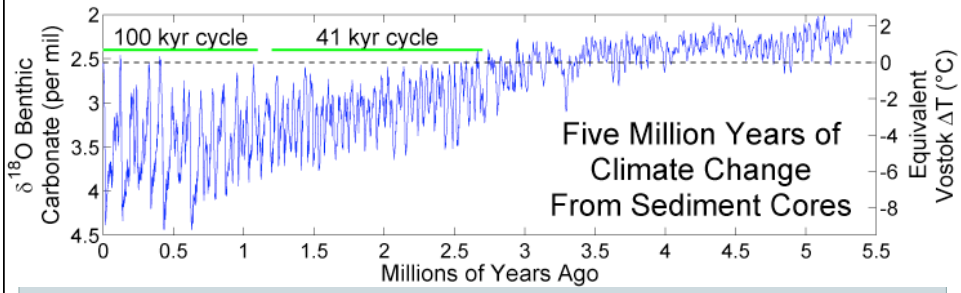
- Eccentricity is tiny on its own
- Obliquity is a strong, direct forcing of high lats → → →
  - Around 10% change in high latitude insolation (40 W/m2)

  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

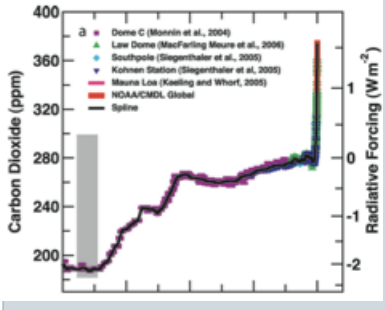


Last 20,000 Years

- 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

Relation of Current Climate to Paleo

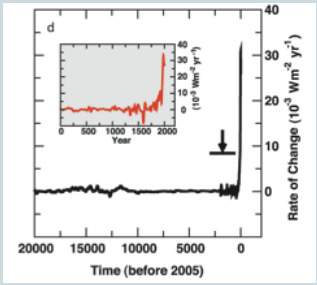
- Very likely that current GHG concentrations are biggest in 650,000 yrs (from ice core data)
  - And current rise in GHGs is completely anthropogenic



CO2 concentration (left)

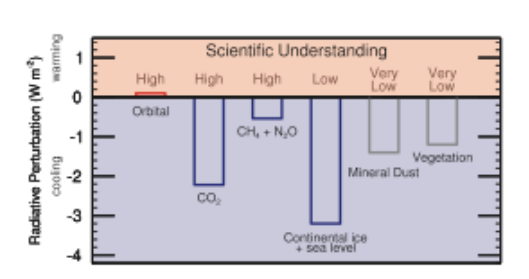
Rate of change of radiative forcing (right)

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 be significant any time soon
  - Next natural ice age: 30,000 yrs from now