Earth Week Climate School
Caltech, April 16-17

Jess Adkins - General, Paleoclimate, Carbon Cycle
Joern Callies - The Atmosphere
Andy Thompson - The Ocean
Austin Minnich - Climate Outreach
Mean Annual Northern Hemisphere Temperature

Temperature Difference from Average

Year

1860 1880 1900 1920 1940 1960 1980 2000

Hadley Centre for Climate Prediction and Research
Based on Jones et al. (1999) and Parker et al. (1995)
Temperature Anomaly Data from NASA/GISS

annual zonal mean anomalies vs 1951–1980

12-month zonal mean anomalies vs 1951-1980

Year in the Past
The Earth is Differentially Heated

Equal Input

Unequal Distribution over the earth’s area
A Quick Lesson in Energy Balance

Input = Output

Solar short wave = Terrestrial long wave

\[ S(1-a) \propto \sigma T^4 \]

\( a = \) albedo

\( \sigma = \) Stephan-Boltzmann constant

\( S = \) Solar constant

But...

The earth receives radiation as a disk and radiates energy back to space over the whole sphere

\[ \pi r^2 S(1-a) = 4\pi r^2 \sigma T^4 \]
The ‘Faint Young Sun’ Paradox

Known Snowballs

![Graph showing the relationship between solar luminosity, temperature, and the freezing point of water over billions of years ago.](image)
The time where we have shelly fossils to record climate change.
Geologists go outside and walk around...
How do we collect past climate information from our archives?

Some of the more important archives are sediments, ice cores, corals and stalagmites (newcomer on the scene...)

Proxy Value
(Color, isotope ratio, elemental ratio, species concentration, faunal abundance, etc...)

Depth (cm)
(This axis must be turned into time, thus creating the all important “Depth vs. Age” plot)
Two Important Archives for Paleoclimate

Globigerinoides ruber (white)
So why is this $^{18}\text{O}/^{16}\text{O}$ ratio helpful?

$$
\text{H}_2^{18}\text{O} + \text{CO}_3^- \leftrightarrow \text{H}_2\text{O} + \text{CO}_2^{18}\text{O}^-
$$
And
$$
\text{Ca}^{++} + \text{CO}_3^- \Rightarrow \text{CaCO}_3
$$

Then Overall...

$$
\text{CaCO}_3 + \text{H}_2^{18}\text{O} \leftrightarrow \text{CaCO}_2^{18}\text{O} + \text{H}_2\text{O}
$$
And...

$$
\frac{{(^{18}\text{O}/^{16}\text{O})}_{\text{solid}}}{{(^{18}\text{O}/^{16}\text{O})}_{\text{water}}} \propto K_{eq}, \text{ So the isotopic ratio of the solid is a function of temperature and the }^{18}\text{O}/^{16}\text{O} \text{ ratio of the water.}
$$
Glacial-Interglacial changes in $\delta^{18}O$

$\Delta \delta^{18}O$

$\delta^{18}O_M = 0 \%^o$

$\delta^{18}O_G \sim 0.9 - 1.3 \%^o$

$\delta^{18}O_{Ice} \sim -30 - -45 \%^o$

Mean Ocean Mass Balance:

$$(\delta^{18}O_M) \ (Vol_M) = (\delta^{18}O_G) \ (Vol_G) + (\delta^{18}O_{Ice}) \ (Vol_{Ice})$$
The time where we have shelly fossils to record climate
There are 3 Ways to Change the Average Temperature of Earth

1. Change the Sun (or the orbit)
Regular changes in the earth’s orbit change how the sun hits the surface.
Regular changes in the earth’s orbit change how the sun hits the surface.

Viewed in the present, the tilted Earth revolves around the Sun on an elliptical path. The orientation of the axis remains fixed in space, producing changes in the distribution of solar radiation over the course of the year. These changes in the pattern of radiation reaching Earth’s surface cause the succession of the seasons. The Earth's orbital geometry, however, is not fixed over time. Indeed, long-term variations in the Earth's orbit help explain the waxing and waning of global climate in the last several million years.
Gravity Coring
Glacial and Deglacial Sequence from the Cariaco Basin in the Caribbean
The marine record of the last 5 Million Years follows the changes in earth’s orbit around the sun.

Lisiecki and Raymo, 2006
There are 3 Ways to Change the Average Temperature of Earth

1. Change the Sun (or the orbit)

2. Change the albedo
Removing the lid from the top of the planet
Loss of reflective ice cooling ‘albedo’
Replaced by dark ocean warming
At the Last Glacial Maximum there was a lot more ice in the northern hemisphere
There are 3 Ways to Change the Average Temperature of Earth

1. Change the Sun (or the orbit)

2. Change the albedo

3. Change the Greenhouse Effect
CO₂ and H₂O trap the heat radiated from the earth, warming the surface.
The famous ‘Keeling Curve’

Atmospheric CO$_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
We are conducting an experiment that is global in scale…

CO₂ levels over the last 10,000 years

- Taylor Dome Ice Core
- Law Dome Ice Core
- Mauna Loa, Hawaii

First human agriculture
Miami Dolphins last win Super Bowl
Magna Carta
Pericles’s Athens
The past atmosphere preserved for our use
The long record of CO$_2$ and Temperature from Antarctic Ice Cores
A Polar and Deep Ocean View of Climate

- **Atmosphere pCO$_2$**
- **Antarctic Temperature**
- **Deep Ocean Temp/Ice Volume**
- **Solar Forcing**

**Axes:**
- **pCO$_2$ (ppm)**
- **dD (permil)**
- **Benthic $d^{18}O$ Stack (permil)**
- **Insolation 65°N Summer (W/m$^2$)**

**Calendar Age (years):**
- 0 to 800

**Temperature and pCO$_2$ fluctuations** are observed, with significant variation over time.

**Deep Ocean Temp/Ice Volume** and **Benthic $d^{18}O$ Stack** show consistent trends, indicating correlations between marine and atmospheric conditions.

**Insolation 65°N Summer** varies, affecting the climate system as a whole.
In the early 1990’s our view of past climate changed:

- Dryas
- Heinrich Event 1
- Younger Dryas
Ice Core from the Summit of Greenland
Warm and Stable

Cold and Variable

Dansgaard/Oeschger Event
And then around 2000 our view changed again…

Blunier and Brook, 2000
For D/O Events Antarctica lags Greenland by 200 years

Greenland $\delta^{18}$O and Antarctica $\delta^{18}$O/dt

- Greenland Warming
- Greenland Cooling

Buizert et al., 2015
The long record of CO$_2$ and Temperature from Antarctic Ice Cores

Calendar Age (years)

pCO$_2$ (ppmV)

Temperature Change (°C)

Atmosphere pCO$_2$

Temperature
The Global Carbon Cycle, with timescales

Atmosphere: $\text{CO}_2 = 600 \text{Pg C}$
$\tau_{(\text{atm.-surf.})} = 10 \text{ yr}; \tau_{(\text{atm.-terr.})} = 6 \text{ yr}$

Terrestrial: $C_{\text{org}} = 2,100 \text{Pg C}$
$\tau_{(\text{atm.-terr.})} = 18 \text{ yr}$

Surface ocean: $\text{DIC} = 700 \text{Pg C}$
$\tau_{(\text{surf.-deep})} = 25 \text{ yr}$

Export: $C_{\text{org}} = 4 \text{Pg C yr}^{-1}; C_{\text{CaCO}_3} = 1 \text{Pg C yr}^{-1}$

River input of dissolved $\text{CaCO}_3$: $0.2 \text{Pg C yr}^{-1}$

Sediments and crust:
$C_{\text{org}} = 15,000,000 \text{Pg C}$
$\tau_{(\text{weathering})} = 240 \text{ Myr}$
$\tau_{(\text{weathering})} = 300 \text{ Myr}$

The deep sea is large and turns over

Deep ocean: $\text{DIC} = 38,000 \text{Pg C}$
$\tau_{(\text{surf.-deep})} = 1,250 \text{ yr}$

CaCO$_3$ burial: $0.2 \text{Pg C yr}^{-1}$

Fossil Fuels are Old
The Global Carbon Cycle

Legend

Units: Petagrams (Pg) = 10^15 gC
- Pools: Pg
- Fluxes: Pg/year

© 2007 GLOBE Carbon Cycle
Combined $O_2$ and $CO_2$ measurements are very powerful.
We are conducting an experiment at the global scale with uncertain outcomes...
Some Approaches to Carbon Sequestration

Trees die, and give back the CO$_2$. Trees need lots of fresh water.


The planet will do it this way...

CaCO$_3$ + CO$_2$ = 2HCO$_3^-$ + Ca$^{2+}$

But... It will take tens of thousands of years.
We know how the planet will do CO\textsubscript{2} Sequestration

The ocean and atmosphere will react to excess CO\textsubscript{2} emissions by reacting it with CaCO\textsubscript{3} sediments in the deep ocean. That is, the shells of dead plankton will buffer the CO\textsubscript{2} addition.

\[
\text{Ocean Sediment} \quad + \text{CO}_2 = 2\text{HCO}_3^- + \text{Ca}^{2+}
\]

Archer et al., 1997