a) textbook does indeed state 15°C
b) STP (standard temperature and pressure) is actually 0°C (273.15 K)
c) definition that 1 DU is 0.01 millimeter thickness of a gas is based upon evaluation at 1 atmosphere and 0°C
Overview:

1) Techniques for quantifying past climate

2) Remarkable changes in past climate

3) Challenge in applying past climate sensitivity to future climate

The details of this “challenge” are quantitative and come at end of lecture. I generally do not like to place quantitative material at the end of lecture; please bear with me today as this arrangement seems best way to organize material.

Legend for slides to follow →

The climate of the Cambrian is not well known. It was probably not very hot, nor very cold. There is no evidence of ice at the poles. Source: http://www.scotese.com/ecambcli.htm

Berner et al., Science, 1997

Mild climates probably covered most of the globe. The continents were flooded by the oceans creating warm, broad tropical seaways.

Source: http://www.scotese.com/cordclim.htm

Berner et al., Science, 1997
Silurian Climate (420 million years ago)

Coral reefs thrived in the clear sunny skies of the southern Arid Belt. Lingering glacial conditions prevailed near the South Pole.

Source: http://www.scotese.com/silclim.htm

Berner et al., Science, 1997

Middle Devonian Climate (380 million years ago)

The Equator ran through today’s Arctic Canada. Coal began to accumulate as land plants flourished in the equatorial rainy belt. Warm shallow seas covered much of today’s North America & Siberia.

Source: http://www.scotese.com/mdevclim.htm

Berner et al., Science, 1997
Carboniferous Climate
(350 million years ago)

Rainforests covered the tropical regions of Pangea, which was bounded to the north and south by deserts. An ice cap began to form on the South Pole.

Source: http://www.scotese.com/serpukcl.htm

Berner et al., Science, 1997

Early Permian Climate
(280 million years ago)

Much of the SH was covered by ice as glaciers pushed equatorward. Coal was produced in Equatorial & Temperate rainforests during warmer "Interglacial" periods.

Source: http://www.scotese.com/epermcli.htm

Berner et al., Science, 1997
Late Jurassic Climate
(150 million years ago)

Global climate began to change due to breakup of Pangea. The interior of Pangea became moister and seasonal snow & ice frosted the polar regions.

Source: http://www.scotese.com/ljurclim.htm

Early Cretaceous Climate
(120 million years ago)

Climate was a mild "Ice House" world. Snow and ice were present during winter and cool temperate forests covered polar regions.

Source: http://www.scotese.com/ecretcli.htm
Late Cretaceous Climate
(70 million years ago)

Global climate was much warmer than today. No ice existed at the Poles. Dinosaurs migrated between Temperate Zones as the seasons changed.

Source: http://www.scotese.com/cretcli.htm

Lecture #3, Last Slide
Earth’s Climate History

Oxygen Isotopes and the Quaternary Climate Record

Oxygen has three stable isotopes $^{16}$O, $^{17}$O, and $^{18}$O

<table>
<thead>
<tr>
<th>Electrons</th>
<th>Protons</th>
<th>Neutrons</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$^{17}$O</td>
<td>8</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

$^{17}$O has such a low abundance that we shall focus on $^{16}$O and $^{18}$O

Chemical and biological reactions involving $^{18}$O require more energy than reactions involving $^{16}$O due to increased atomic mass

This “isotope effect” can be used as a proxy to infer past temperature!
Oxygen Isotopes and the Quaternary Climate Record

Scientists measured the ratio of $^{18}\text{O}$ to $^{16}\text{O}$ in a sample (sea water, shells, etc.) and compare to a “standard value”

$$\delta^{18}\text{O} \text{(per mil)} = \left( \frac{\frac{^{18}\text{O}}{^{16}\text{O}}}{\frac{^{18}\text{O}}{^{16}\text{O}} \text{Sample}} - \frac{^{18}\text{O}}{^{16}\text{O}} \text{Standard} \right) \times 10^3$$

Standard often referred to as SMOW: Standard Mean Ocean Water

If $\delta^{18}\text{O}$ is negative, the sample is “depleted” with respect to current conditions.

If positive, the sample is “enriched”.

**How might $\delta^{18}\text{O}$ become enriched or depleted?**

As temperatures drops, the $\delta^{18}\text{O}$ of precipitation decreases.

Why does this occur?
As an air mass travels poleward, $H_2^{18}O$ rains out more readily than $H_2^{16}O$

When the air mass reaches the pole, its water can have up to ~5% less $^{18}O$ than SMOW.

Deuterium (heavy hydrogen) behaves in a way quite similar to $^{18}O$ (heavy oxygen)!

http://earthobservatory.nasa.gov/Study/Paleoclimatology_OxygenBalance/oxygen_balance.html

Isotopes in Ice Cores: Late Quaternary

- As the air reaches the pole, ambient water precipitate (i.e., it snows!)
- Over many years, layers of snow accumulate, forming an ice sheet. The water in this ice sheet contains a record of climate **at the time the snow was deposited**
- By drilling, extracting, and measuring the $\delta^{18}O$ & $\delta D$ (deuterium/hydrogen ratio) of ice, scientists are able to estimate past **global temperature & ice volume**
- In reconstructing climate during the quaternary (last 1.6 million years), scientists also look at:
  - $CO_2$, $CH_4$, and $N_2O$ of trapped air
  - $\delta^{18}O$ of trapped $O_2$ in trapped air
  - $\delta^{13}C$ of $CO_2$ in trapped air
  - Particulate matter and a wide range of ions
Vostok Ice Core

- January 1998: ice core with depth of 3.6 km extracted at Russian Vostok Station, Antarctica
- Vostok ice-core record extends back 400,000 years in time (Petit et al., Nature, 1999)
- Reconstructed temperature based on measurement of the deuterium content of ice
- $\delta^{18}O$ shows tremendous variations in global ice volume (not shown)
- Ice core data show last four ice ages, punctuated by relatively brief interglacials

![Vostok Ice Core](https://cdiac.ess-dive.lbl.gov/trends/co2/ice_core_co2.html)

- CO$_2$ (air trapped in ice bubbles) and inferred temperature very highly correlated
- Variations in $\Delta T$ & CO$_2$ synchronous upon correction of movement of air bubbles (CO$_2$) relative to ice ($\Delta T$) (Parrenin et al., Science, 2013: http://science.sciencemag.org/content/339/6123/1060)
Figure 6.3, IPCC 2007

See [https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf](https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf) for description of EPICA, European Project for Ice Coring in Antarctica

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Fairly Late Appreciation that Earth Undergoes Ice Ages

On 24 July 1837, at the annual meeting of the Swiss Society of Natural Sciences, Louis Agassiz (1807–1873) startled his learned associates by presenting a paper dealing not, as expected, with the fossil fishes found in far-off Brazil, but with the scratched and faceted boulders that dotted the Jura mountains around Neuchâtel itself. Agassiz argues that these erratic boulders ... chunks of rock appearing in locations far removed from their areas of origin ... could only be interpreted as evidence of past glaciation.

This began a dispute – one of the most violent in the history of geology – that was to rage for more than a quarter century and would end with the universal acceptance of the ice-age theory.

Although this concept did not begin with Agassiz, he served to bring the glacial theory out of scientific obscurity and into the public eye.


Fourier analysis reveals Earth’s climate is changing in a periodic fashion

100,000 year cycle due to changes in the eccentricity of Earth’s orbit, mainly due to gravitational pull of Jupiter and Saturn.

*Ice Ages*, Imbrie and Imbrie, Harvard Univ Press, 1979
Fourier analysis reveals Earth’s climate is changing in a periodic fashion

**43,000 year cycle** due to changes in tilt of Earth’s axis (obliquity).

![Diagram showing Earth's wobbling on its axis](image)

24,000 and 19,000 year cycles due to Earth “wobbling” on its axis.

![Diagram showing Earth's wobbling on its axis](image)

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Glacial Periods MUCH Dustier than Interglacials

Figure 3. Temporal evolution of $\delta$D representing changes in the average local condensation temperature during snow formation, the particulate dust, and the sea-salt component Na$^+$ over the last four glacial cycles as recorded in the East Antarctic Vostok ice core [Petit et al., 1999]. Dashed-dotted lines indicate the mean Holocene level from 0 to 10,000 years B.P.

Fischer et al., Reviews of Geophysics, 2007

Biology in Today’s Ocean

Figure 1. Results of a global model of small phytoplankton growth limitation by Moore et al. 2004 (Global Biogeochemical Cycles). Blue shaded areas denote regions that are potentially limited by iron availability. Iron is supplied by dust from continents and by upwelling of deep water. However, high iron demand in the euphotic zone quickly drives iron concentrations to nano- and picomolar levels that can be limiting to many phyto- and bacterioplankton.

http://www.whoi.edu/page.do?pid=130796
Time to get quantitative: 
how do changes in radiative forcing affect temperature?

Let’s relate a change in temperature to a change in radiative forcing:

\[ \Delta T = \lambda \Delta F \]

\( \lambda \) is the climate sensitivity factor in units of \( \frac{K}{W/m^2} \)

For an ideal blackbody: 
\[ F = \sigma T^4 \]
\[ \frac{dF}{dT} = 4 \sigma T^3 \]

Above equation can be re-arranged to yield:

\[ \Delta T \approx \frac{1}{4 \sigma T^3} \Delta F \]

So: \[ \lambda = \frac{1}{4 \sigma T^3} \]

If we plug in value of Boltzmann’s constant and global mean T at which Earth radiates to space, we find \( \lambda_{BB} \approx 0.3 \text{ K} / (W \text{ m}^{-2}) \)

Here: BB refers to Black Body
Time to get quantitative: how do changes in radiative forcing affect temperature?

Let’s relate a change in temperature to a change in radiative forcing:

\[ \Delta T = \lambda \Delta F \]

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\[ \Delta T \approx \frac{1}{4 \sigma T^3} \Delta F \]

So:

\[ \lambda = \frac{1}{4 \sigma T^3} \]

Another estimate of the response of \( T \) to \( \Delta F \) can be found using a climate model representing that as the atmosphere warms, it can hold more \( \text{H}_2\text{O} \):

\[ \lambda_{\text{ACTUAL}} = \lambda_{\text{BB}} (1 + f_{\text{H}_2\text{O}}) \]

where \( f_{\text{H}_2\text{O}} \) is the \( \text{H}_2\text{O} \) feedback

Here, \( f_{\text{H}_2\text{O}} \approx 1.08 \)

Hence:

\[ \Delta T \approx 0.63 \frac{\text{K}}{\text{W/m}^2} \Delta F \]

How much does \( \Delta F \) change when \( \text{CO}_2 \) changes?

As we will explore in more detail later in class (16 Feb 2017):

\[ \Delta F \approx 5.35 \text{ W/m}^2 \ln \left( \frac{\text{CO}_2^{\text{Final}}}{\text{CO}_2^{\text{Initial}}} \right) \]

Changes in \( \Delta F \) can be caused by changes in chemical composition (GHGs), albedo, aerosol loading, as well as solar output.
Glacial to interglacial changes in T, CO₂ and dust

Chylek and Lohmann (2008) assume:

a) **global** avg ΔT, glacial to interglacial, was 4.65 K

b) ΔF\textsubscript{CO₂} = 2.4 W m\textsuperscript{-2}, ΔF\textsubscript{CH₄+N₂O} = 0.27 W m\textsuperscript{-2}, ΔF\textsubscript{ALBEDO} = 3.5 W m\textsuperscript{-2}, & ΔF\textsubscript{AEROSOLS} = 3.3 W m\textsuperscript{-2}

From this they deduce \( λ_{\text{actual}} = 0.49 \text{ K/W m}^2 \)

Since 0.49 K/W m\(^2\) < 0.63 K/W m\(^2\), one would conclude that either the H₂O feedback is smaller than found in IPCC climate models and/or changes in clouds serve as a negative feedback

* Global ΔT is about half that recorded at Vostok, as stated in the caption of Fig 4.9a of Houghton

**Delta** ΔT = \( λ_{\text{considering aerosols}} \left( ΔF\textsubscript{CO₂} + ΔF\textsubscript{CH₄+N₂O} + ΔF\textsubscript{ALBEDO} + ΔF\textsubscript{AEROSOLS} \right) \)

\( λ_{\text{considering aerosols}} = \frac{ΔT}{ΔF\textsubscript{CO₂} + ΔF\textsubscript{CH₄+N₂O} + ΔF\textsubscript{ALBEDO} + ΔF\textsubscript{AEROSOLS}} = \frac{4.65 \text{ K}}{9.47 \text{ W m}^2} = 0.49 \text{ K/W m}^2 \)

If \( λ_{\text{considering aerosols}} = λ_{\text{BB}} (1 + f) \) and \( λ_{\text{BB}} = 0.3 \text{ K/W m}^2 \),

then \( f = 0.63 \)
Glacial to interglacial changes in T, CO₂ and dust

Chylek and Lohmann (2008) are trying to calculate the sensitivity of climate to various forcings, with and without the consideration of aerosols.

<table>
<thead>
<tr>
<th></th>
<th>ΔF with aerosols (W/m²)</th>
<th>ΔF without aerosols (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>CH₄+N₂O</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>Albedo</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td>Aerosols</td>
<td>3.30</td>
<td>0.0</td>
</tr>
</tbody>
</table>

\[ \Delta T = \lambda_{\text{No Aerosols}} (\Delta F_{\text{CO₂}} + \Delta F_{\text{CH₄+N₂O}} + \Delta F_{\text{ALBEDO}}) \]

\[ \lambda_{\text{No Aerosols}} = \frac{\Delta T}{\Delta F_{\text{CO₂}} + \Delta F_{\text{CH₄+N₂O}} + \Delta F_{\text{ALBEDO}}} = \frac{4.65 \text{ K}}{6.17 \text{ W m}^{-2}} = 0.75 \text{ K W m}^{-2} \]

If \( \lambda_{\text{No Aerosols}} = \lambda_{\text{BB}} (1 + f) \) and \( \lambda_{\text{BB}} = 0.3 \text{ K W m}^{-2} \),

then \( f = 1.5 \)

Let’s apply these two climate sensitivities to future temperature

Both future scenarios assume:

a) CO₂ doubles: i.e., \( \Delta F_{\text{CO₂}} = 5.35 \ln(2) \text{ W/m}² \) or = 3.7 W/m²

b) surface radiative forcing of CH₄ + N₂O will be 40% of CO₂ (future mimics past)

Scenario #1: Weak Feedback found considering aerosol radiative forcing in paleo data & no future change in Earth’s albedo

Scenario #2: Strong Feedback found assuming no aerosol radiative forcing in paleo data & additional surface radiative forcing of 3.4 W/m² due to decline in Earth’s albedo (i.e., the positive ice-albedo feedback will occur)

<table>
<thead>
<tr>
<th></th>
<th>Scenario #1</th>
<th>Scenario #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>ΔF (W m⁻²)</td>
<td>3.7</td>
</tr>
<tr>
<td>CH₄+N₂O</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Total ΔF</td>
<td></td>
<td>5.2</td>
</tr>
</tbody>
</table>

\[ \Delta T \Rightarrow \] or

Take away messages:

1. Climate sensitivity inferred from ice core record depends on how aerosols are handled
2. Future climate will be quite sensitive to:
   - the efficacy of atmospheric feedbacks (H₂O, clouds)
   - the radiative forcing of aerosols (not considered in our simple future scenario)
   - how surface albedo changes
There is much more “recent climate history”, such as:

a) Younger Dryas cooling event at end of last ice age
b) Medieval climate maximum
c) the Little Ice Age (1650 to 1850)

that is deserving of our attention. A few slides on these topics are included in the Extra Material that follows (you will not be tested on the material in these 3 slides)

*Problem Set #1* is due at start of class on **Tuesday**, February 19 (one week from today) and covers material presented in Lectures 1 to 5

If you have questions, please stop by our offices (Ross: Atlantic 2403; Walt: Atlantic 4100) during either our office hours or normal working hours.

You’re also welcome to email us to set up a time to meet

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**Final Thought**

**Extra Slide 1**

**Younger Dryas (about 12,000 years ago)**

Around 12,000 years ago, mean annual temperatures abruptly dropped to levels similar to those during the last glacial maximum

Most scientists believe the cool conditions of the Younger Dryas resulted from a flood of fresh water into the North Atlantic that shut down ocean’s thermohaline circulation.

The flood of fresh water was due to discharge from glacial lakes, formed by the melt water of retreating glaciers.

Some geologists (Firestone *et al.*, *PNAS*, 2007) believe that the Younger Dryas was compounded by a terrestrial impact.

Medieval Warm Period (MWP) ~800 to 1300 AD

δ¹⁴C (radiocarbon) is a proxy that can be used to estimate past solar activity.

Carbon-14 is produced when cosmic rays hit nitrogen (¹⁴N), inducing a decay that transforms this molecule to Carbon-14 (half life of ~5,730 yrs).

Increased solar activity results in a reduction of cosmic rays reaching Earth's atmosphere, reducing production of carbon-14, because cosmic rays are blocked by the outward sweep of magnetic fields of the solar wind.

Measurements of ¹⁴C suggest primary cause of warm conditions during MWP was rise in solar activity

http://en.wikipedia.org/wiki/Medieval_Warm_Period

Little Ice Age (~1350 to 1900)

Major rivers (Thames) & waterways (NY harbor) frequently froze.
Crops and livestock failed.
Cities flooded.
Glaciers expanded.
Why did this happen?

1. Little ice age was an extended period of quiet solar activity: coldest time period is associated with the Maunder Minimum (time of very low sunspot activity ⇒ reduced solar irradiance).
2. Several large volcanic eruptions during this period; resulting aerosol loading led to a reduction in amount solar radiation reaching the surface.
3. Increase in albedo associated with the colder temperatures (colder T results in more ice) led to even more cooling.