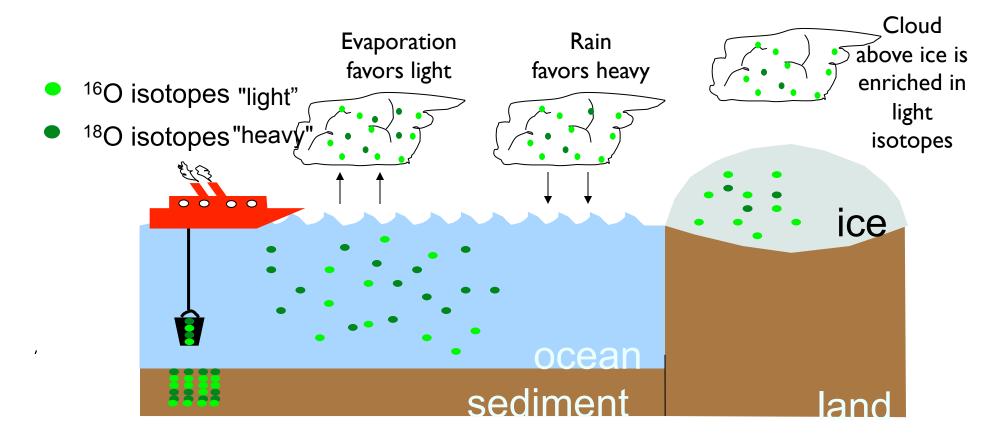
#### **Welcome to ATMS 111 Global Warming**

#### http://www.atmos.washington.edu/2010Q1/111



"This is it, Jenkins ... indisputable proof that the Ice Age caught these people completely off guard."

## Isotopic Evidence

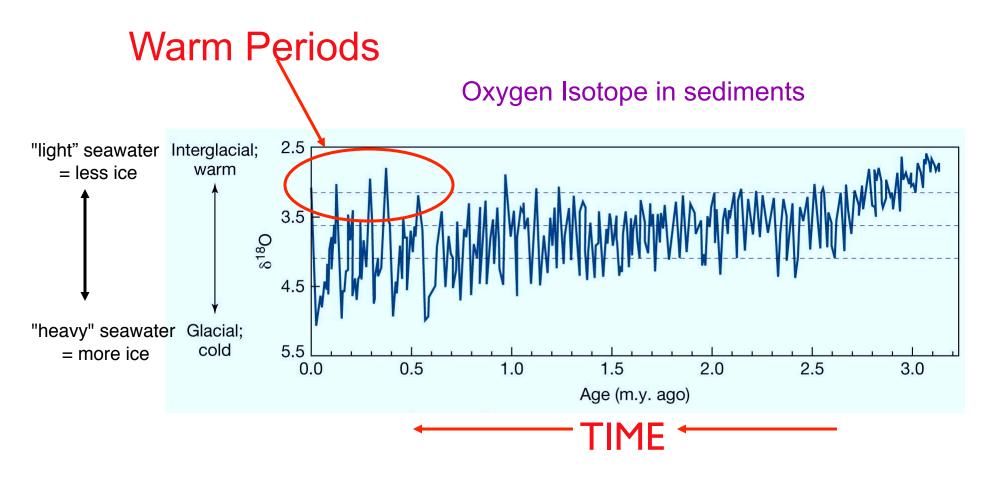


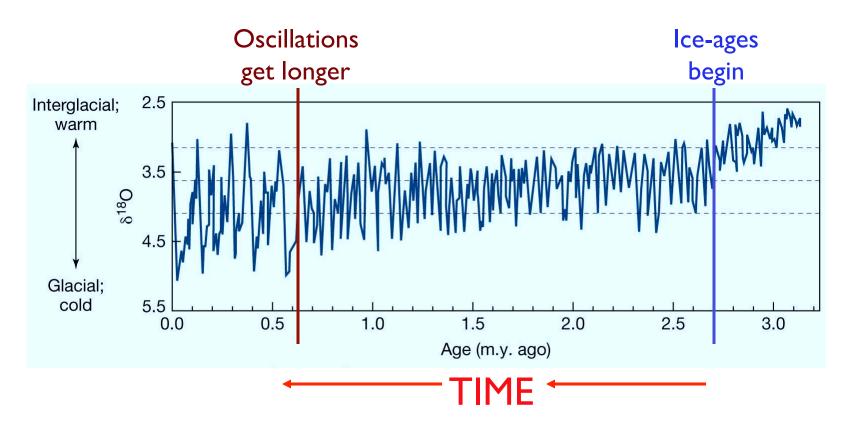
#### Two immensely valuable consequences:

Isotopes in ocean sediments records glacial ice volume

Isotopes in ice-cores indicates local temperature

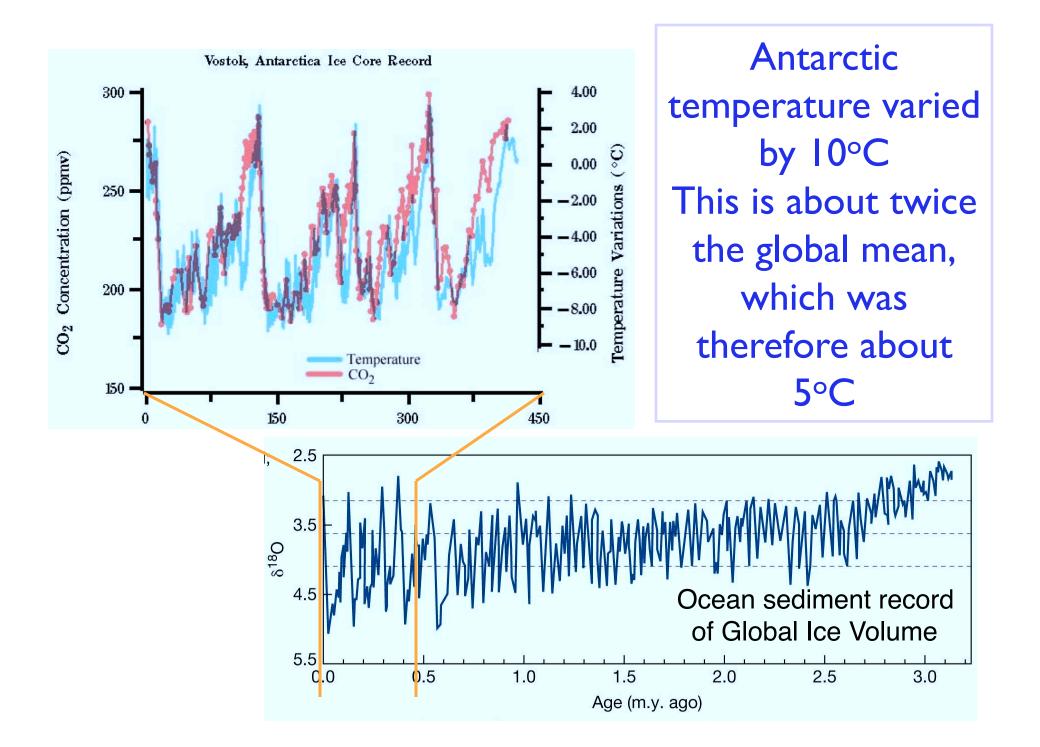
#### 3 Million Year Record of Global Ice Volume





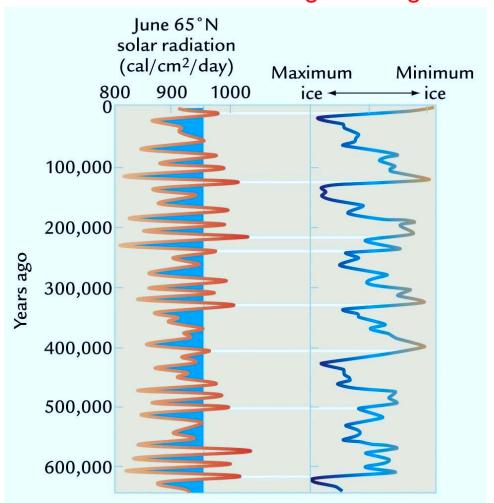
Question:

Was sea-level lower or higher than today during the three most prominent previous interglacial periods?



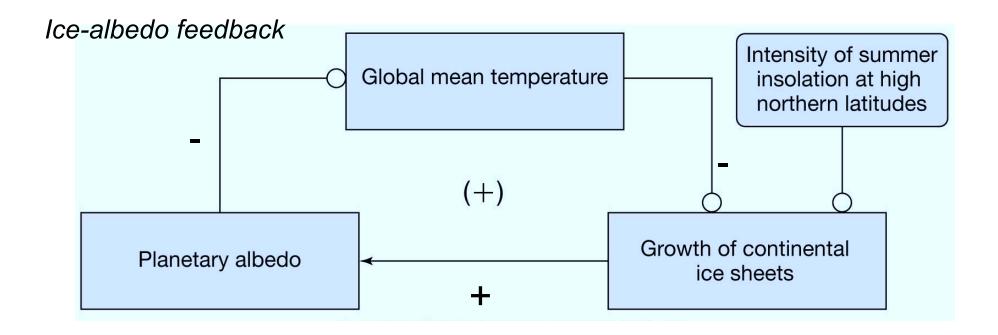
## Theory of the Ice Ages:

Orbital induced insolation changes and global ice volume



Strong summer insolation peaks pace rapid deglaciation. Low insolation in summer is key to onset of ice age.

#### Orbital Theory: Trigger and Feedback Mechanism



Trigger with feedback causes ice-sheets...
to grow and keep growing

C

to melt and keep melting

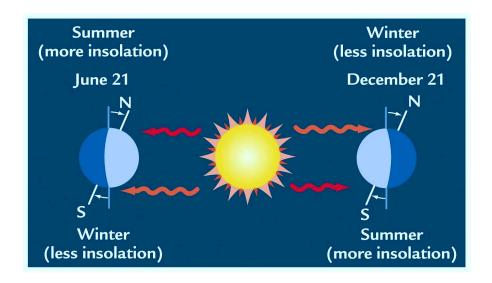
Greenhouse gases (e.g. CO<sub>2</sub> and CH<sub>4</sub>) are involved too.

# Orbital Variations and Insolation Obliquity or Tilt

- Tilt angle is presently 23.44°
- Tilt is the main reason why we have seasons

If tilt increases would our summers be warmer or cooler?

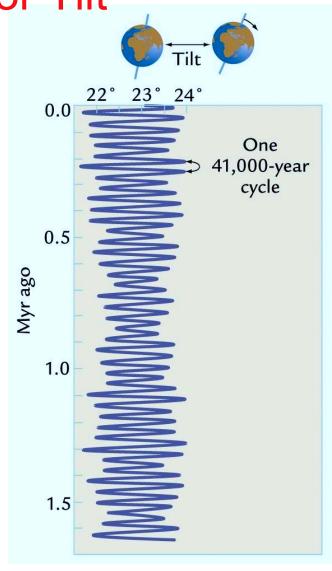




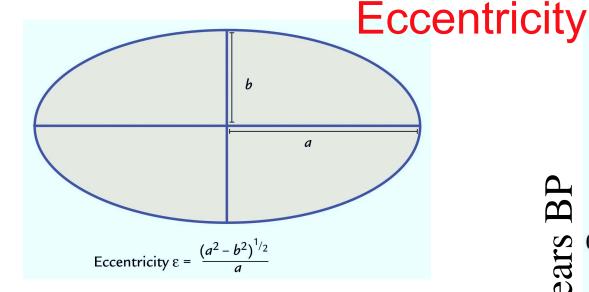
**Orbital Variations and Insolation** 

**Obliquity or Tilt** 

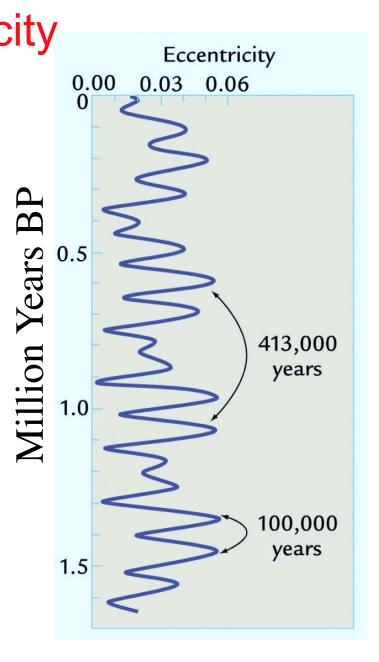
- Tilt of axis of rotation varies from 22.5 ° and 24.5 °.
  - Dominant period of 41 kyr
- Higher tilt makes summers hotter and winters colder, especially in high latitudes
- We are currently in the middle at the road, but tilt is decreasing and will reach its minimum in ~8,000 yrs



### **Orbital Variations and Insolation**



- Eccentricity: Lower is more circular and higher is a more elongated ellipse
- Varies on long timescales, primarily 100k and 413k years

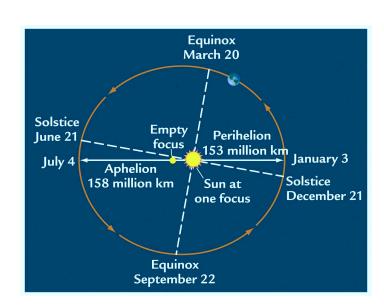


### **Orbital Variations and Insolation:**

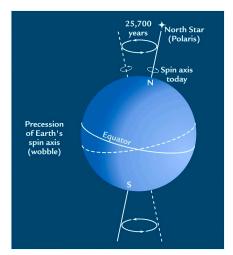
Precession

Presently Earth is closest to the sun during NH winter, which makes the NH seasons slightly less extreme.

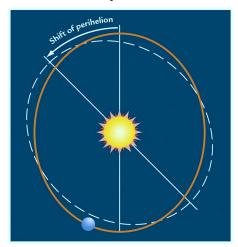
Is Earth's current precession state favorable for glaciation?

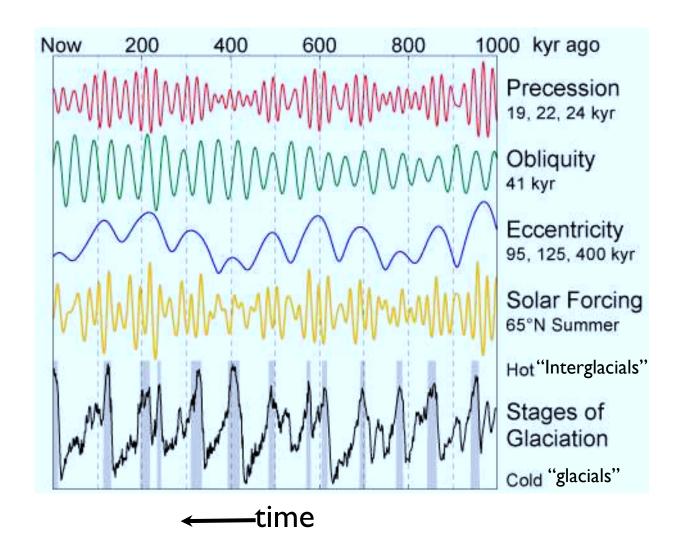


Wobble



Precession of Ellipse



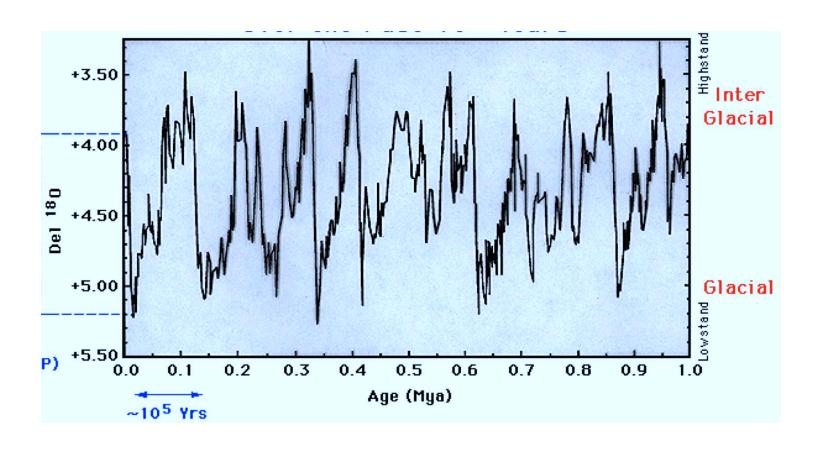


The colored curves represent the strength of the radiation incident on high latitudes of the NH during summer due to each of the three kinds of orbital variations. When the combined effect is such that the radiation is weak, winter snow can remain unmelted through the summer, building a continental ice sheet.

## Summary: orbital changes on insolation

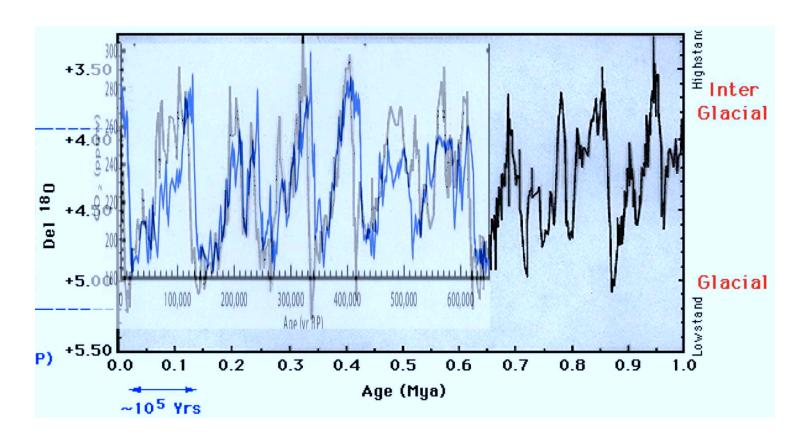
- Tilt and precession can act together to make conditions favorable for glaciation (double whammy on ice volume).
- For example, right now the precession cycle makes cool summers in the NH, which favors glaciation. Tilt is in between extremes but it is declining, but will eventually favor glaciation in ~8,000 yrs.
- Only eccentricity can change the global, annual average insolation by about .18%, or 5 Wm <sup>-2</sup>.
- Compare this to ~2.5 Wm <sup>-2</sup> for the radiative punch from anthropogenic GHG to date.
- By the end of this century, will humans totally dominate the signal from orbital changes?

# The Ice Age Cycles: Some big unsolved questions

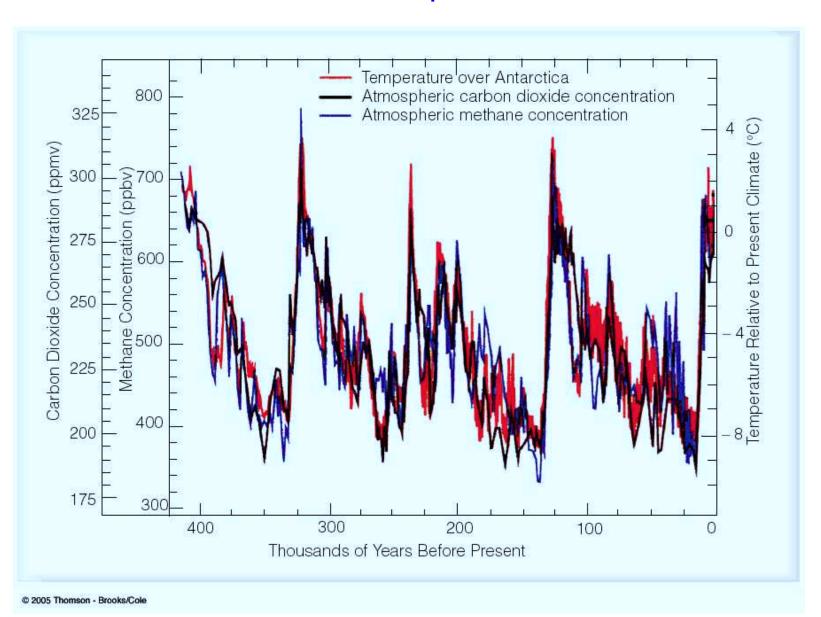


# The Ice Age Cycles: Some big unsolved questions

Why is CO<sub>2</sub> so highly correlated with ice volume?



## Why is CO<sub>2</sub> even more highly correlated with Antarctic temperature?



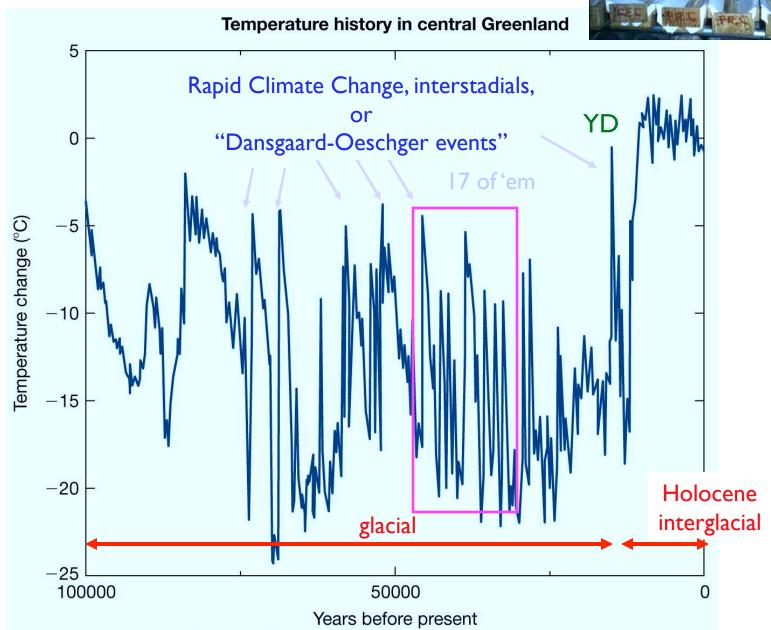
#### A simple but incomplete answer:

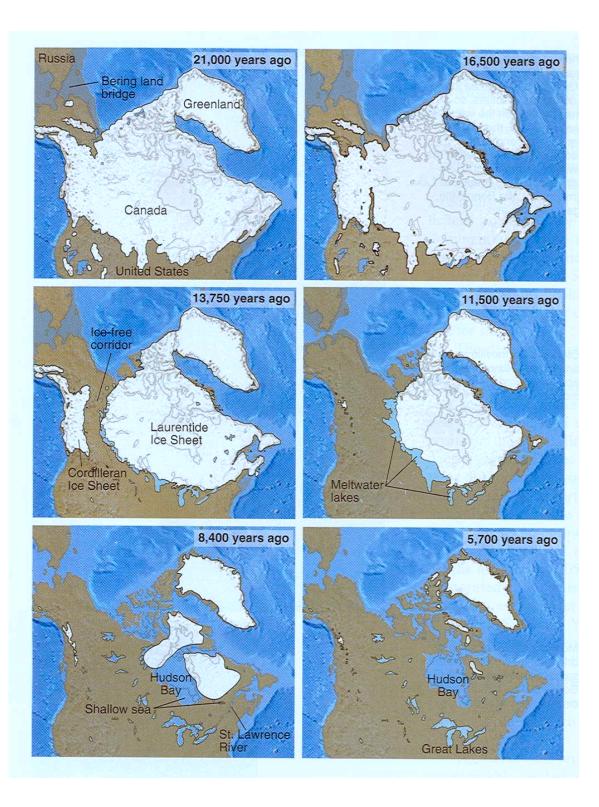
# Colder oceans can dissolve more atmospheric CO2

Why aren't we sure?

Possibly the biological pump was more active and/or seawater exchange between surface and deep was greater...





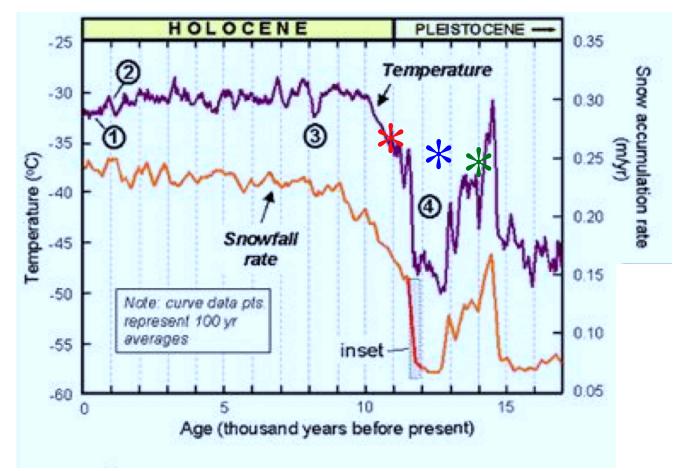


## Retreat of the Laurentide ice sheet

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.



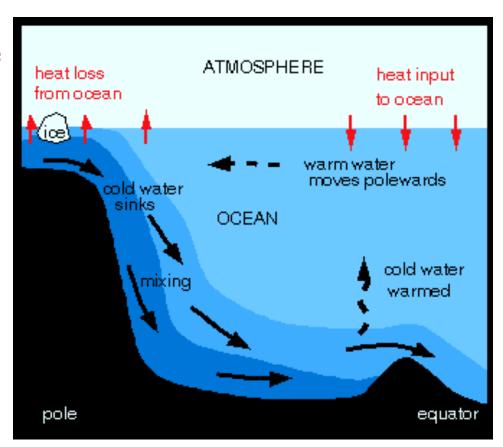
Time

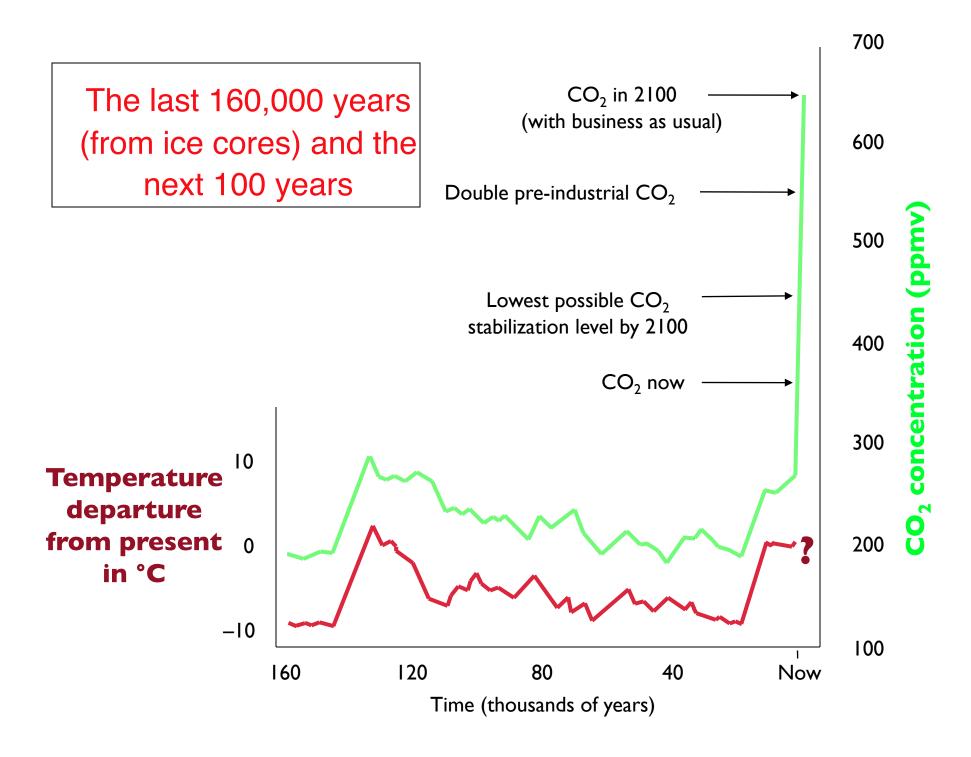
YD probably caused by ice sheet breakup and flooding in the northern North Atlantic

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.





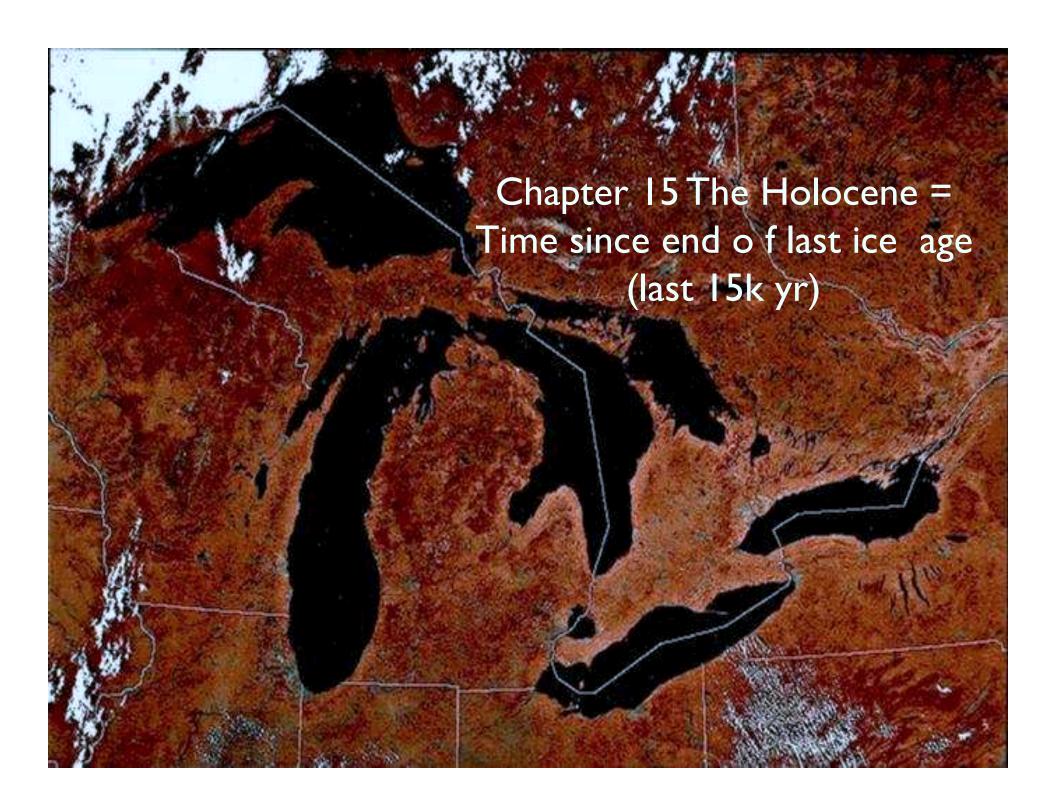
# The Ice Age Cycles: Some big unsolved questions

- Why is CO<sub>2</sub> so highly correlated with ice volume and Antarctic temperature?
  - Simple but incomplete answer: colder ocean can uptake more CO<sub>2</sub>
- Are changes in CO<sub>2</sub> fundamental for ice ages, or do they provide a weak positive feedback?
- Why did the period of glacial-interglacial cycles grow from ~40,000 yrs to ~100,000 yrs about 500,000 ypb?

# The Ice Age Cycles: Some big unsolved questions

- What causes the major deglaciations? Why are they so fast?
- What caused the abrupt climate change and what do they mean for future climate change?





#### The Holocene Epoch

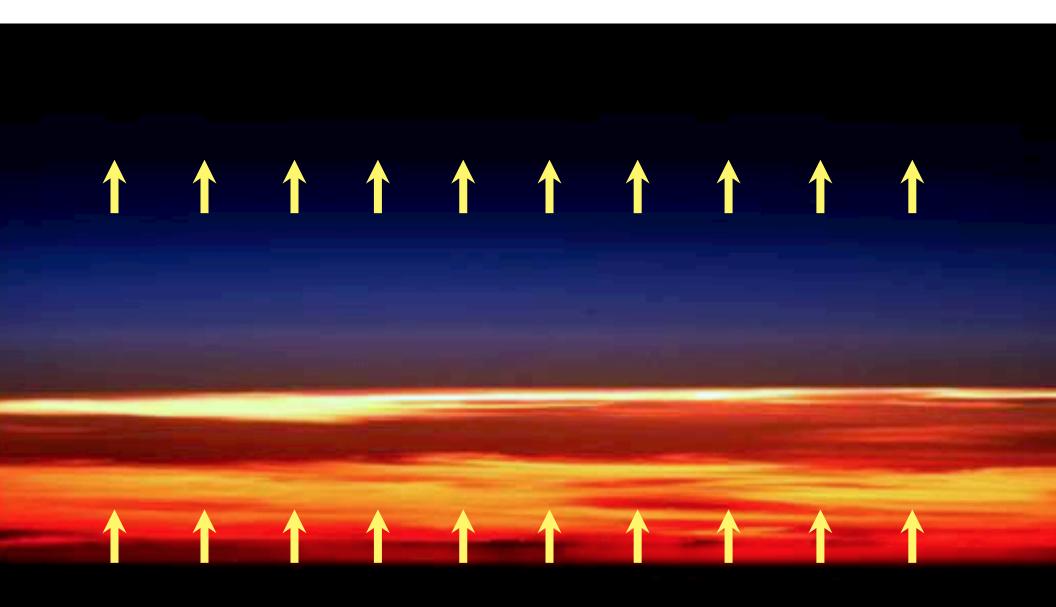
About 15,000 years ago, the earth began to warm\* and the huge ice sheets began to melt. This had a number of impacts:

- (I) lake formation in regions left behind by glaciers
- (2) sea level rise
- (3) Vegetation expanded

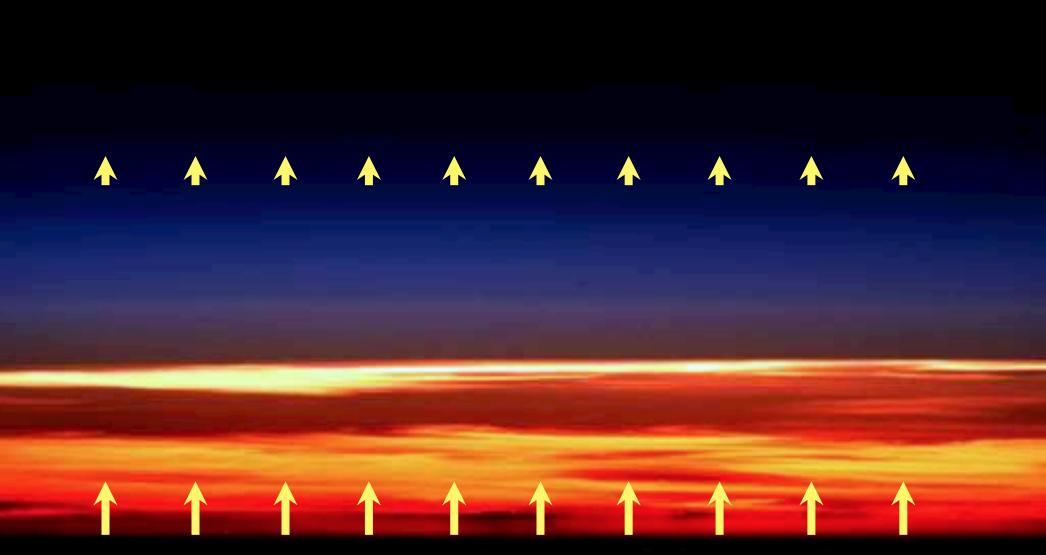
\*warming leads CO2 rise



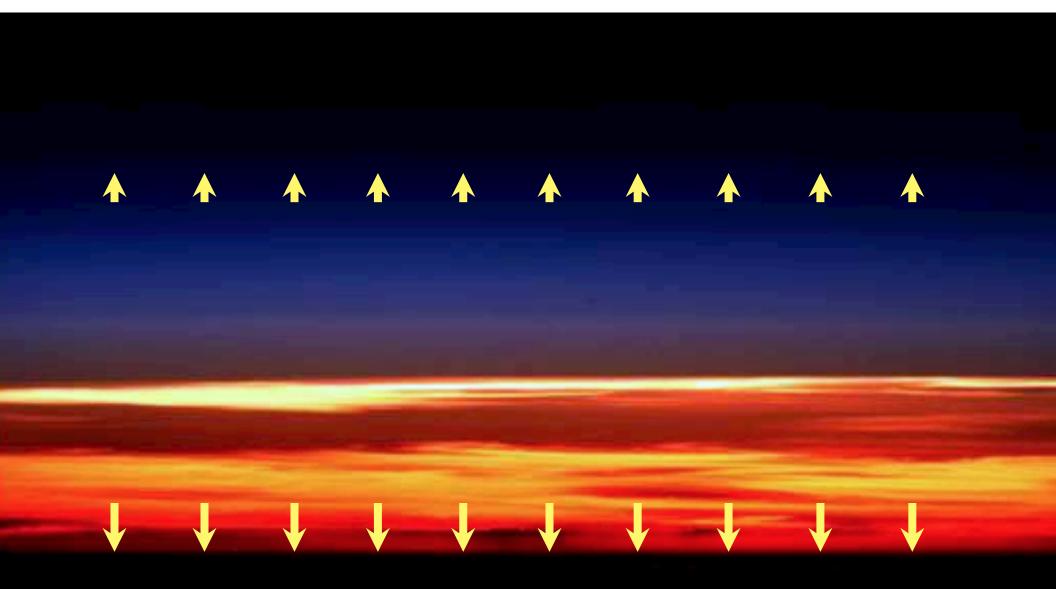
First a review of the GHE



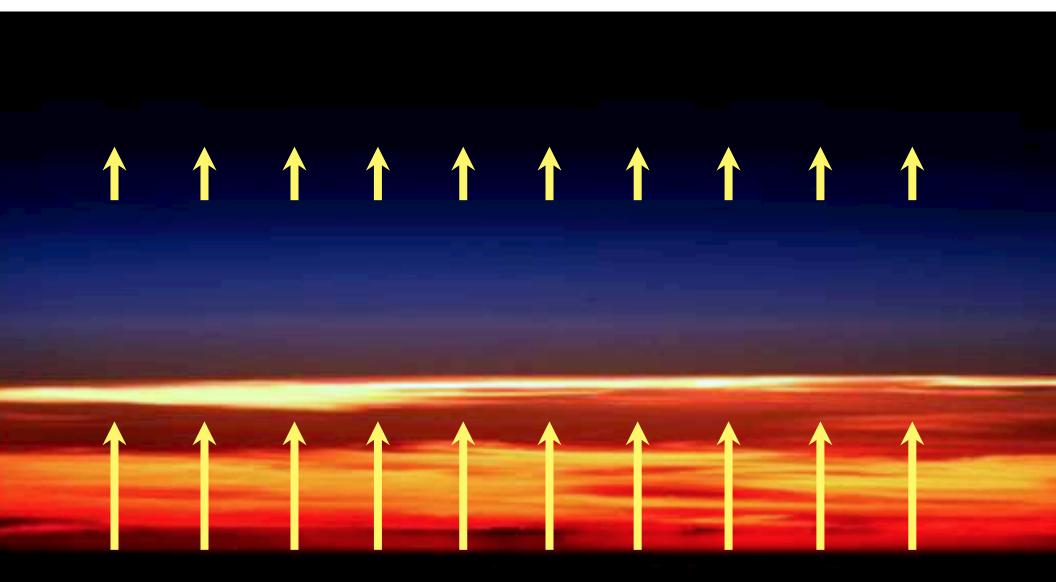
If the atmosphere had no GHG and clouds, infrared radiation would pass through it without being absorbed.



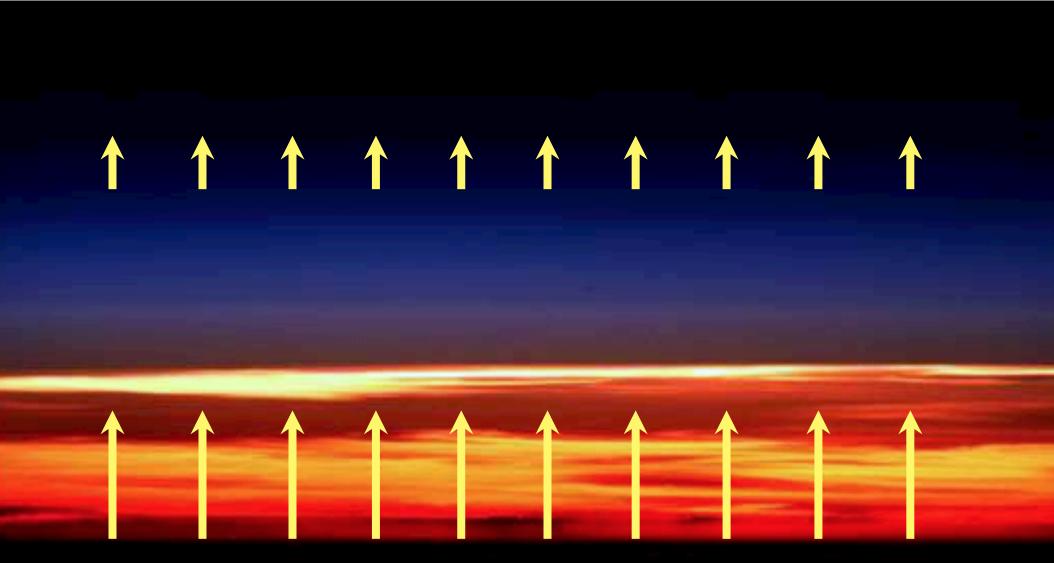
But if we suddenly add GHGs and clouds, most of the radiation emitted by the Earth's surface would be absorbed, and only a small fraction passes through.



The GHG and clouds emit radiation too. More of it is emitted downward near the Earth's surface. The outgoing radiation is much less because the upper atmosphere is cold.



The downward flux of infrared radiation from the atmosphere makes the Earth's surface warm up, and as it gets warmer it emits more radiation



Eventually the system (Earth + atmosphere) comes into equilibrium. The Earth's surface has been warmed by the GHGs and clouds. This is the essence of the greenhouse effect.

#### **Estimating "Radiative Forcing"**

Perturb the system AND BEFORE the surface and atmosphere warm up, see how much the top of the atmosphere fluxes change

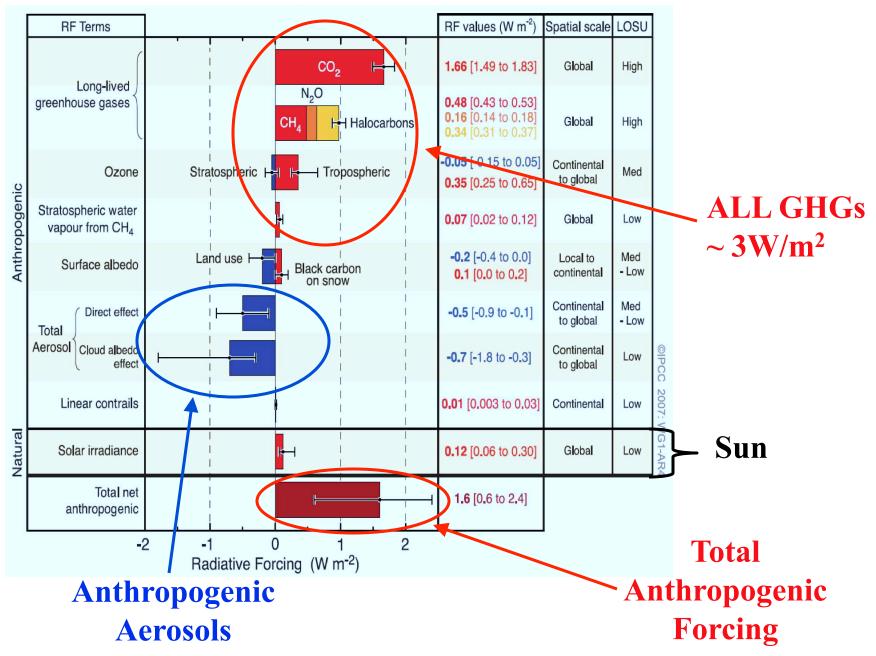
For example, double CO2 in the atmosphere and what happens?

The outgoing flux F<sub>OUT</sub> decreases

Recall that  $F_{OUT}$  needs to balance the net solar radiation  $F_{IN}$ 

When double CO2,  $\Delta F = F_{IN} - F_{OUT} = 3.7 \text{ W/m}^2$ 

#### Forcing In 2005 relative to preindustrial



## Sunspots and Climate Change

Sunspots are dark
but they are
surrounded by
brighter areas known
as Faculae

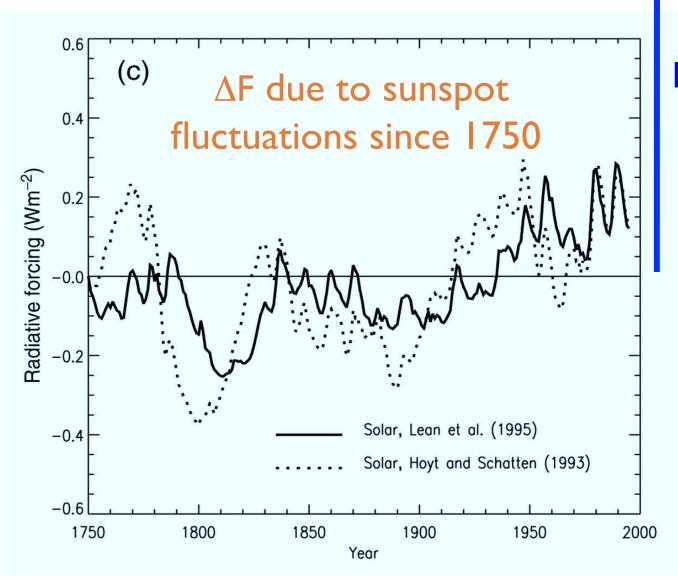
#### Sunspot number vary causing solar intensity S to vary

S is measured with satellites for past 27 yrs

 $S = 1366 \text{ W/m}^2$ , varies by about 0.1% so  $\Delta S \sim 1.3 \text{ W/m}^2$ 

Recall S is "shared by whole sphere" so divide it by 4, and some of it is reflected back to space so multiply by (I-planetary albedo)

giving ~0.2 W/m<sup>2</sup> change in radiative forcing for satellite era

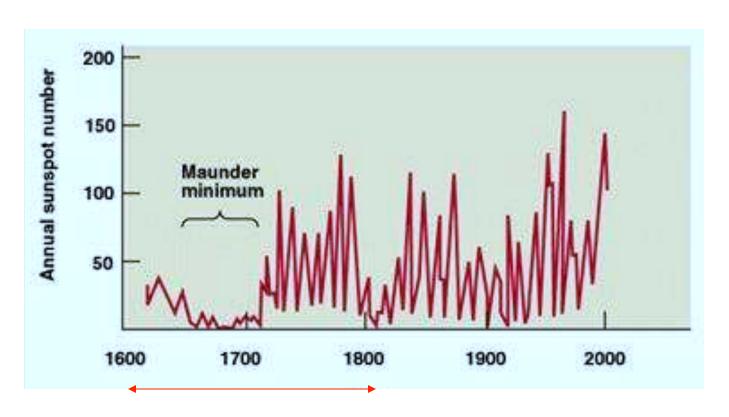


ΔF ~ 3 W/m<sup>2</sup>
From ALL GHG
ALREADY
X10 greater

#### What other data tell us about sunspot activity?

- •Telescopes since Galileo 1610
- Naked eye
- Aurora frequency historical literature
- •Cosmic Rays create <sup>14</sup>C and <sup>10</sup>Be isotopes then measured in tree rings and ice cores
  - variations like those during the Little Ice Age are common
  - no smoking gun for ice ages

#### Prior to satellite era, we rely on sunspot number to infer S



Little Ice Age?

But their number is related to S in an uncertain way => controversy