

AV Relationships between CO₂ and Temperature in Glacial-Interglacial Transitions of the Past 800,000 Years*

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Abstract

Past changes in CO₂ and temperature can illuminate the potential future effect of continuing CO₂ rise on global mean temperatures. Data from Antarctic ice cores have provided records of surface air temperature and inferred global CO₂ concentrations back to about 740,000 years ago. Surface air temperatures based on the H and O isotopic composition of ice have varied by about 8-12°C on orbital timescales (10,000 to 100,000 years); the longest current records indicate eight glacial-interglacial cycles back to about 740 ka (kiloyears B.P.). Associated with these cycles are ~80-120 ppmv changes in CO₂ concentrations based on measurements of trapped air bubbles. The most rapid changes occurred in less than 10,000 years at glacial terminations, termed Terminations 1-8 at ca. 15, 130, 240, 325, 420, 515, 625, and 730 ka, respectively. These sharp Terminations provide an important test of potential relationships between Antarctic air temperature and global CO₂ concentrations. However, determination of lead-lag relationships is complicated by the fact that air diffuses in compacting snow long after the snow is deposited, leading to significant age differences between air and ice at a given level in an ice core. The so-called “gas age - ice age difference” ranges from about 500 to 6000 years, depending on snow accumulation and compaction rates, with uncertainty on the order of 1000 years. Specifically, this complicates determining the timing of air temperature increase and CO₂ rise because the former is derived from measurements on ice and the latter from trapped air. After constraining the “gas age - ice age difference” several studies have determined that initial Antarctic air temperature increase preceded CO₂ rise on glacial terminations, typically by about 600 to 3000 years. One study used the δ⁴⁰Ar isotopic temperature proxy, measured on the same air samples as CO₂, and found a lead of 800+200 years at Termination 3. These observations suggest that CO₂ rise did not trigger temperature increase. However, these same studies show that approximately 80% of deglacial warming was synchronous with CO₂ rise. Furthermore, sensitivity studies indicate that the magnitude of deglacial warming in response to orbital insolation changes requires substantial feedback from greenhouse gases. Scaling these results to make predictions about the next century is difficult, but past climate change is consistent with CO₂ exerting a strong positive feedback on surface temperature.

References

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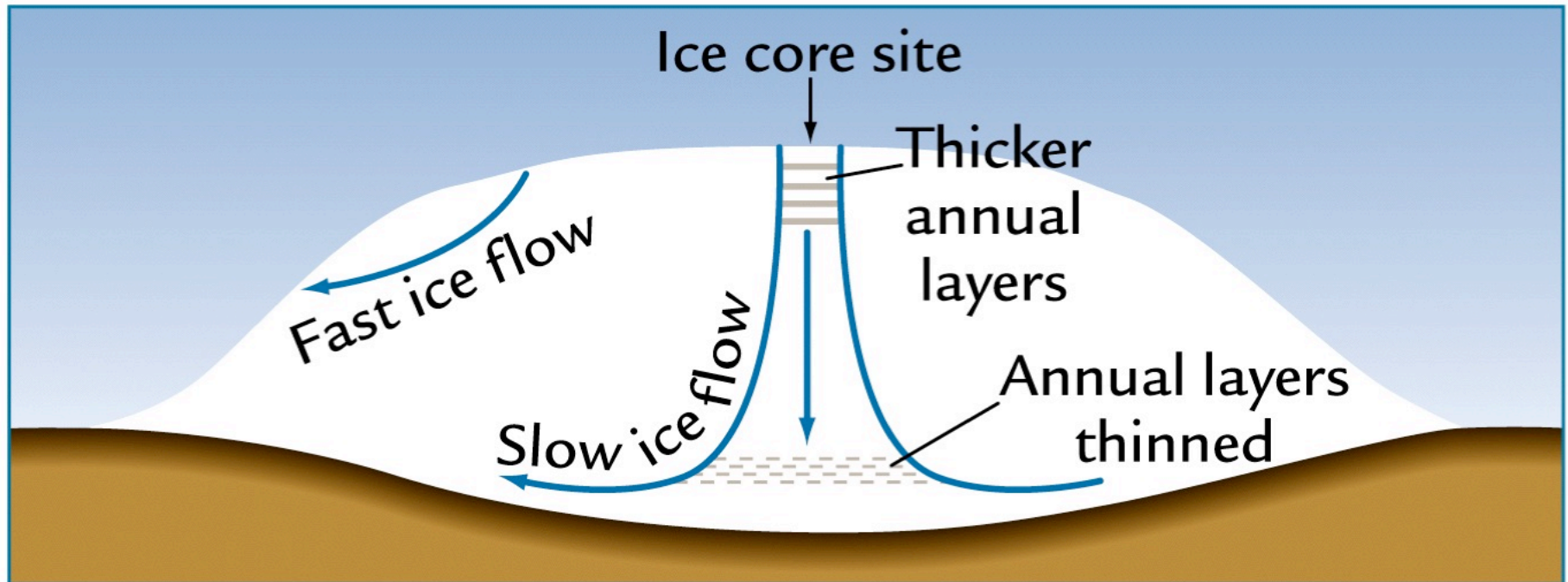
Outline

- **Antarctic ice coring**
- **Glacial-interglacial Antarctic ice core records**
- **CO₂ and temperature phase relations during glacial terminations**

1) Antarctic ice coring



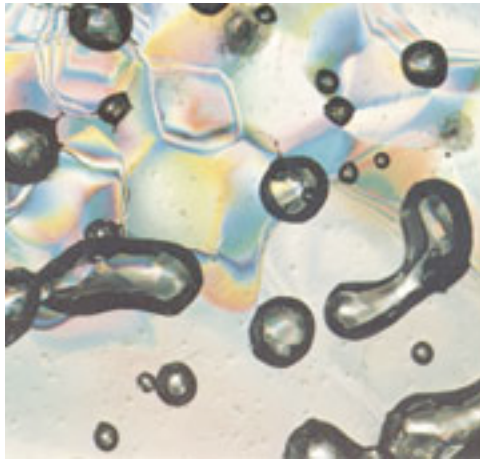
Ice sheet flow



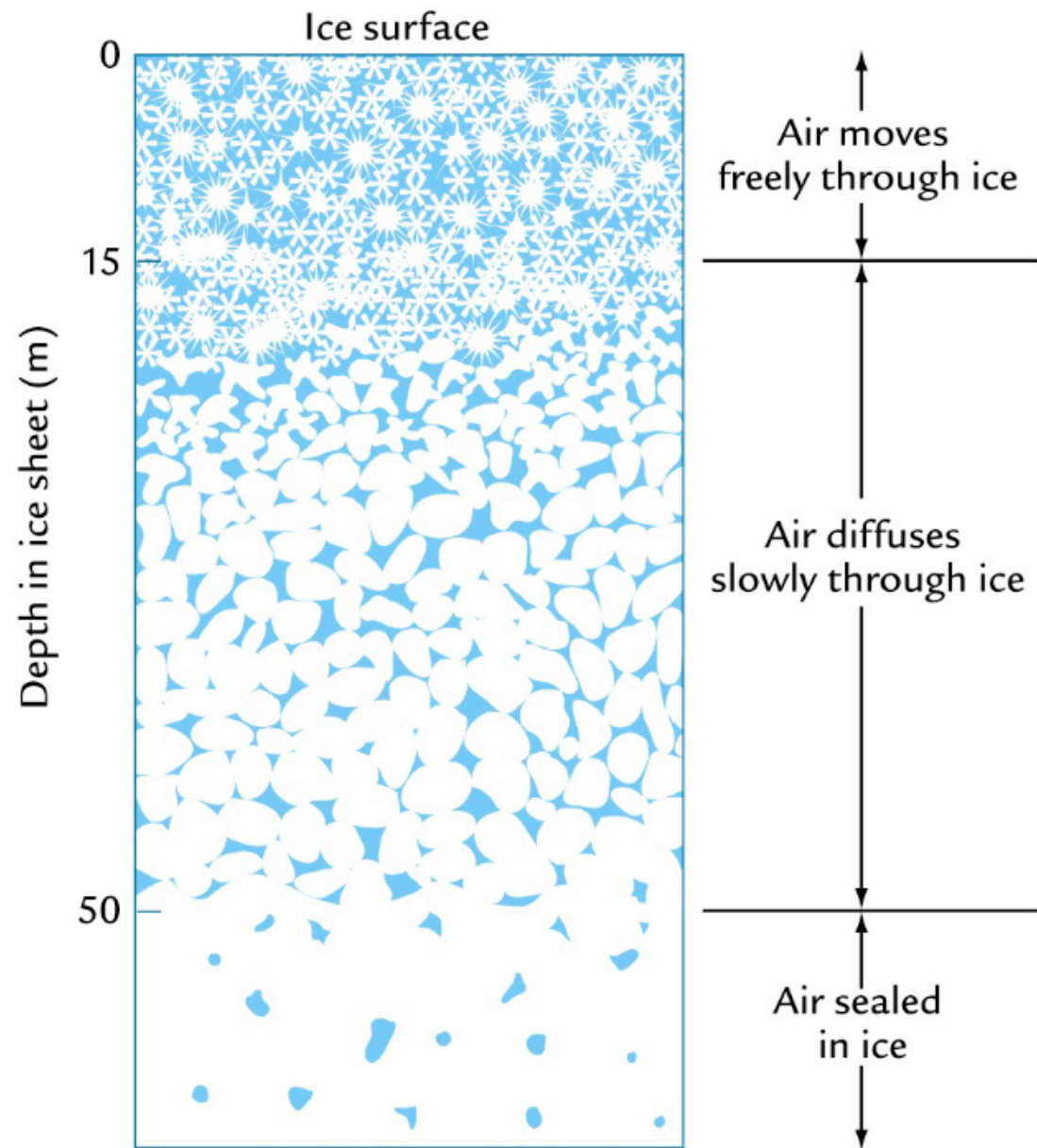
- Age at depth is based on glaciological flow model

Ruddiman 2001

Sealing Air Bubbles in Ice

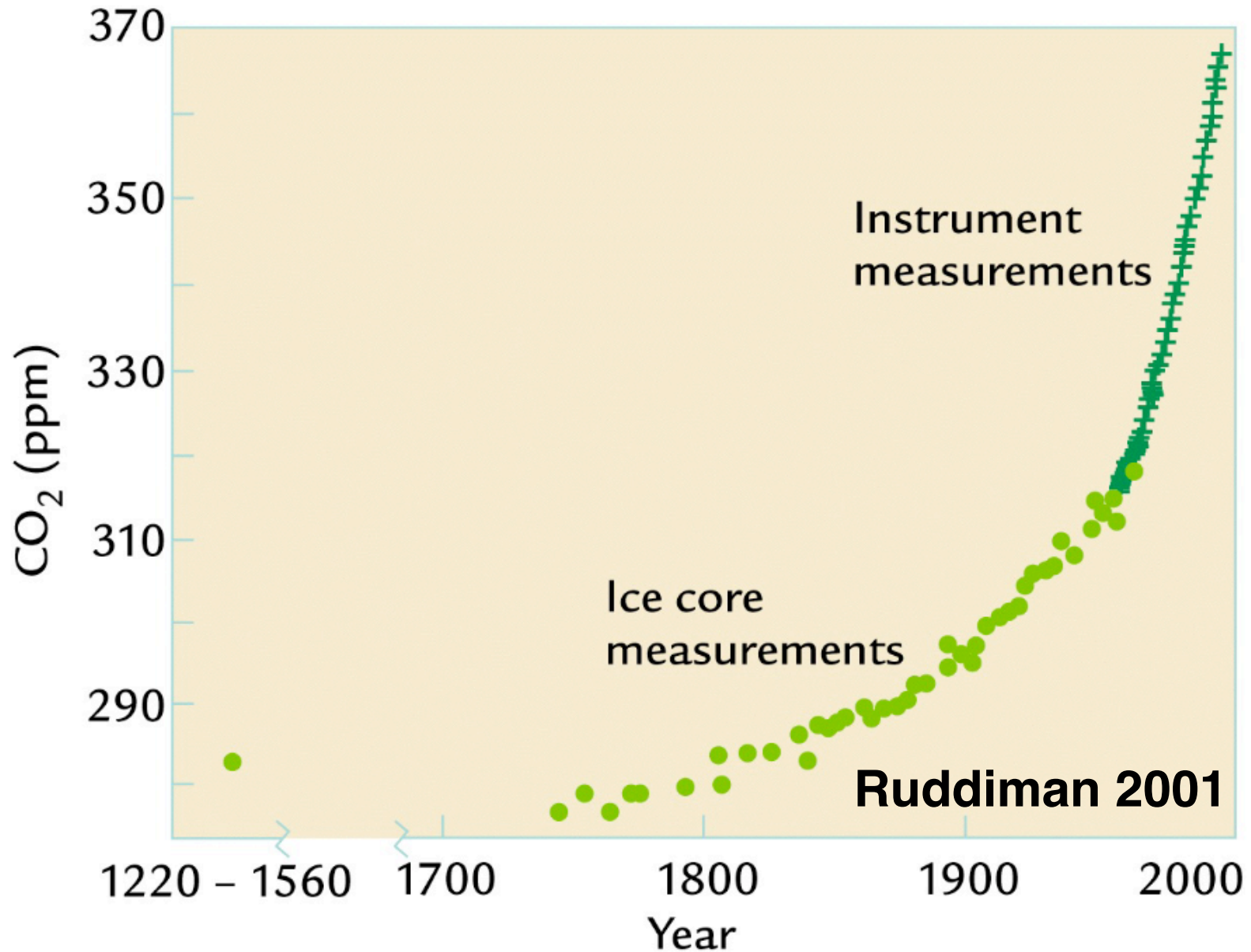


- Firn depth >50 m
- Ice-gas age (Δt) by densification model

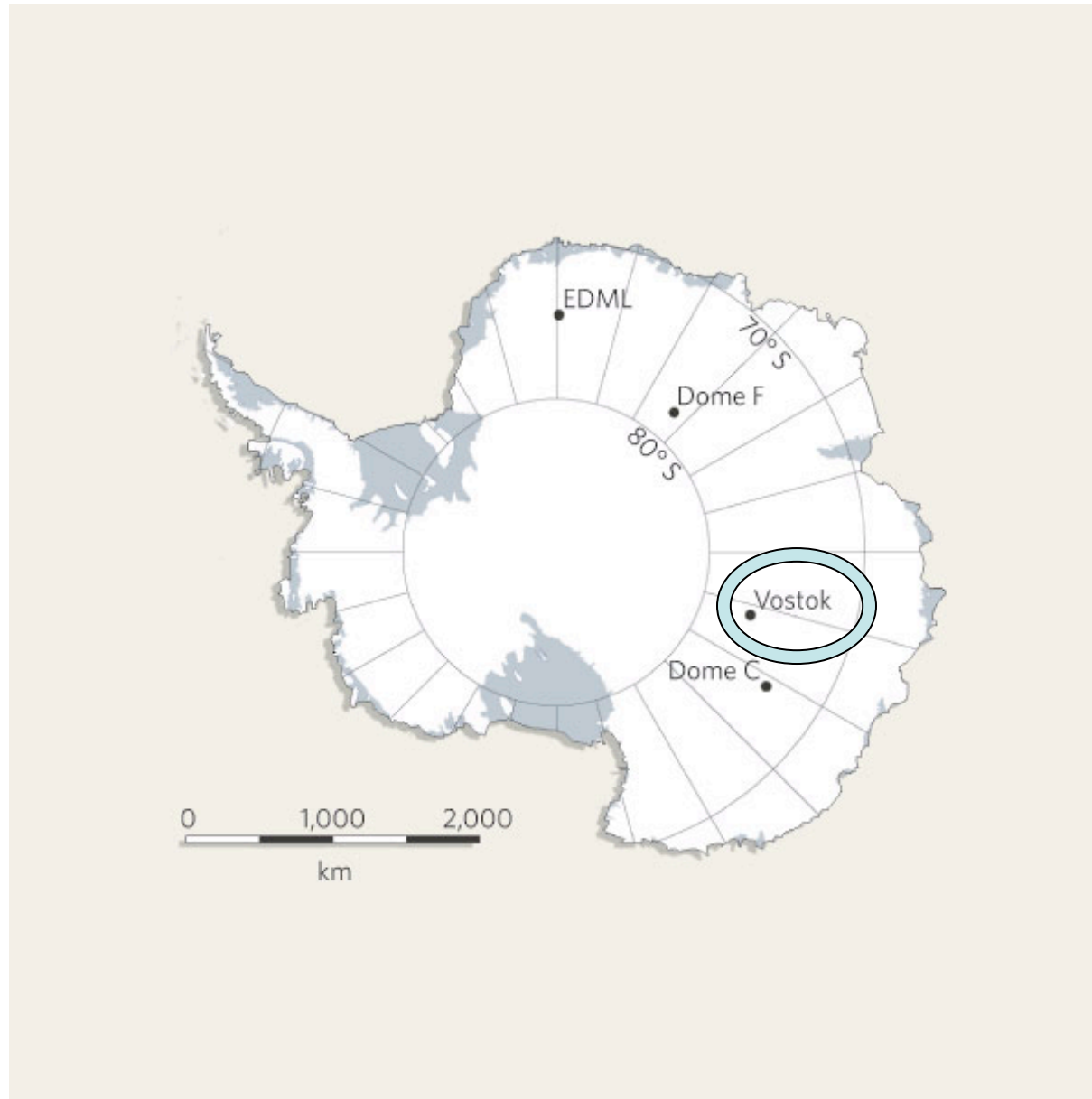


Ruddiman 2001

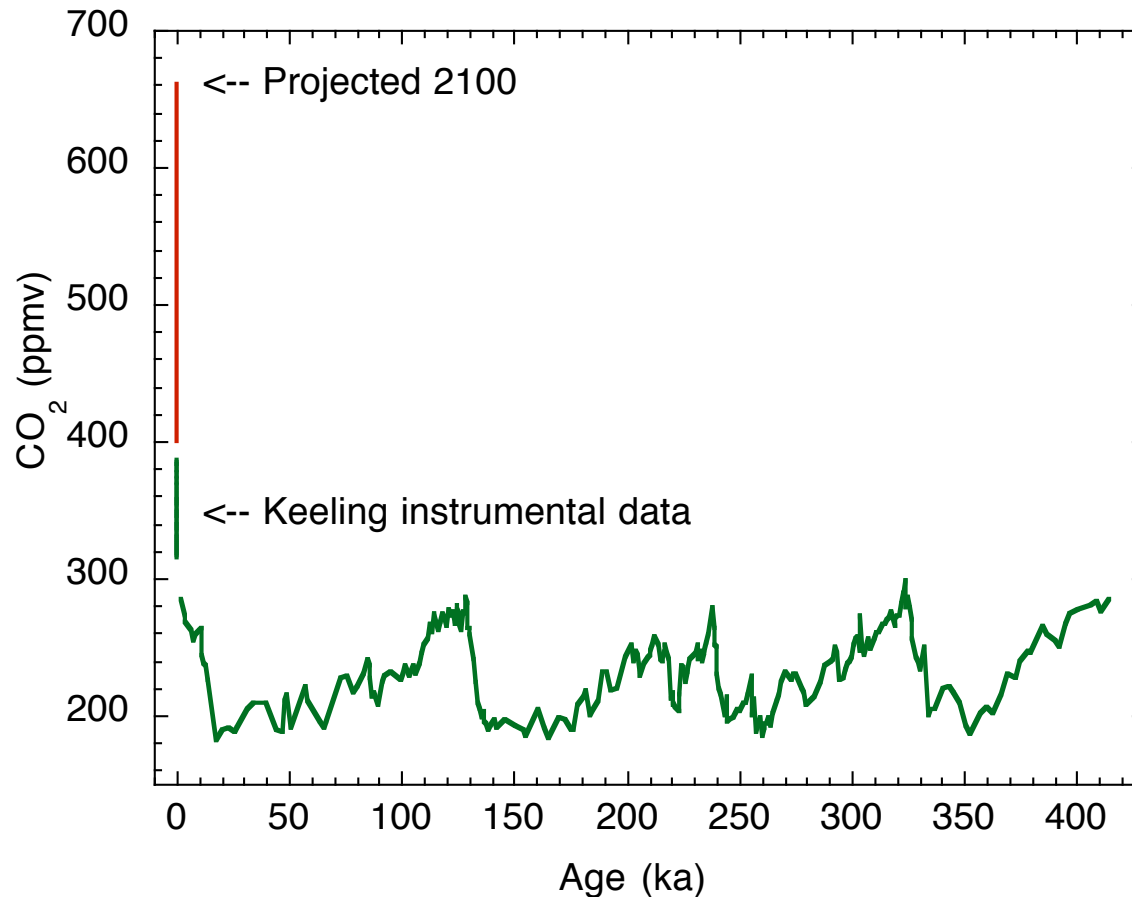
Extending instrumental records of CO₂



2) Glacial-interglacial Antarctic ice core records



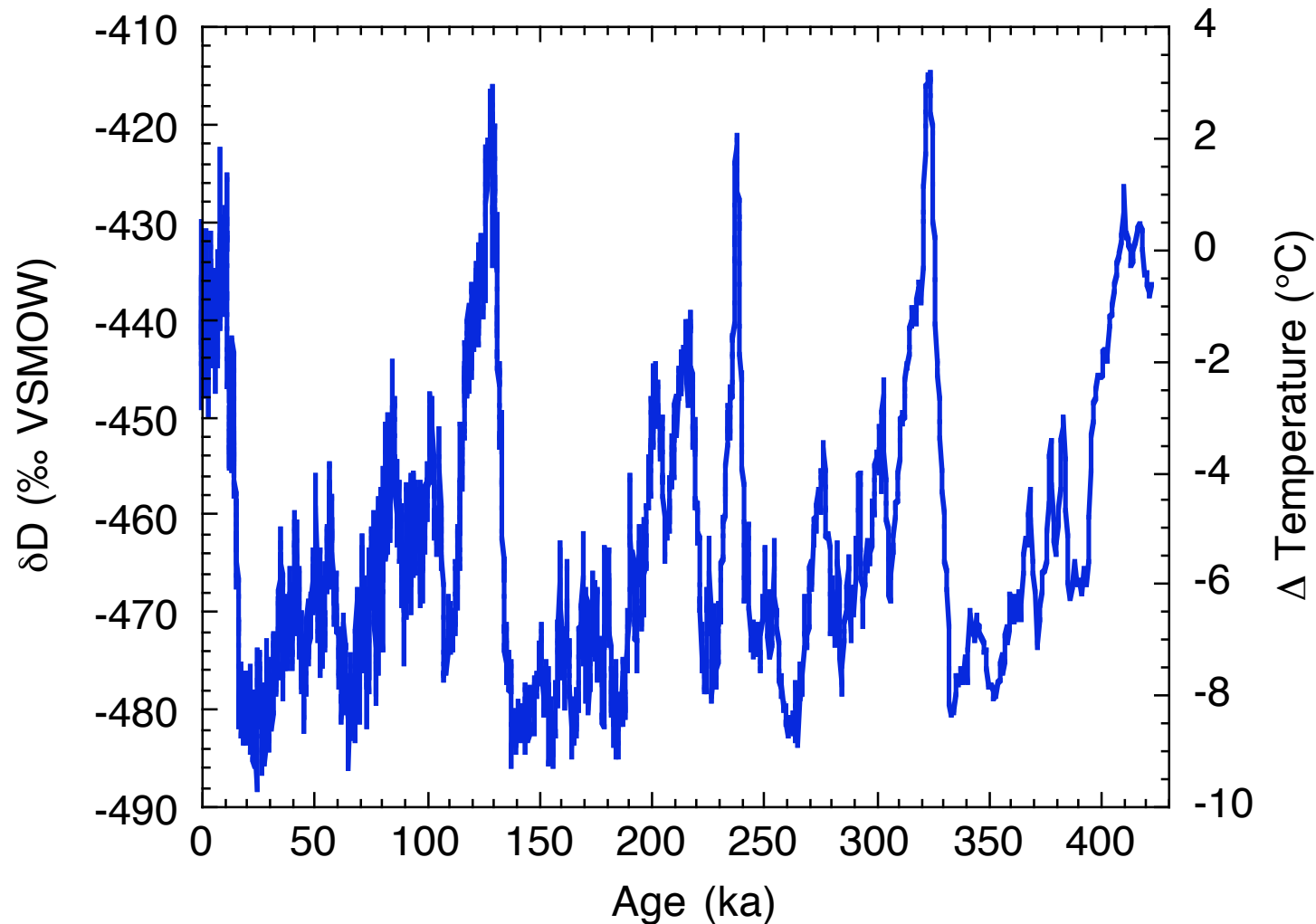
Vostok CO₂ record



- **glacial-interglacial range ~190-280 ppmv (Petit et al., 1999)**
- **May 2009: ~390 ppmv**

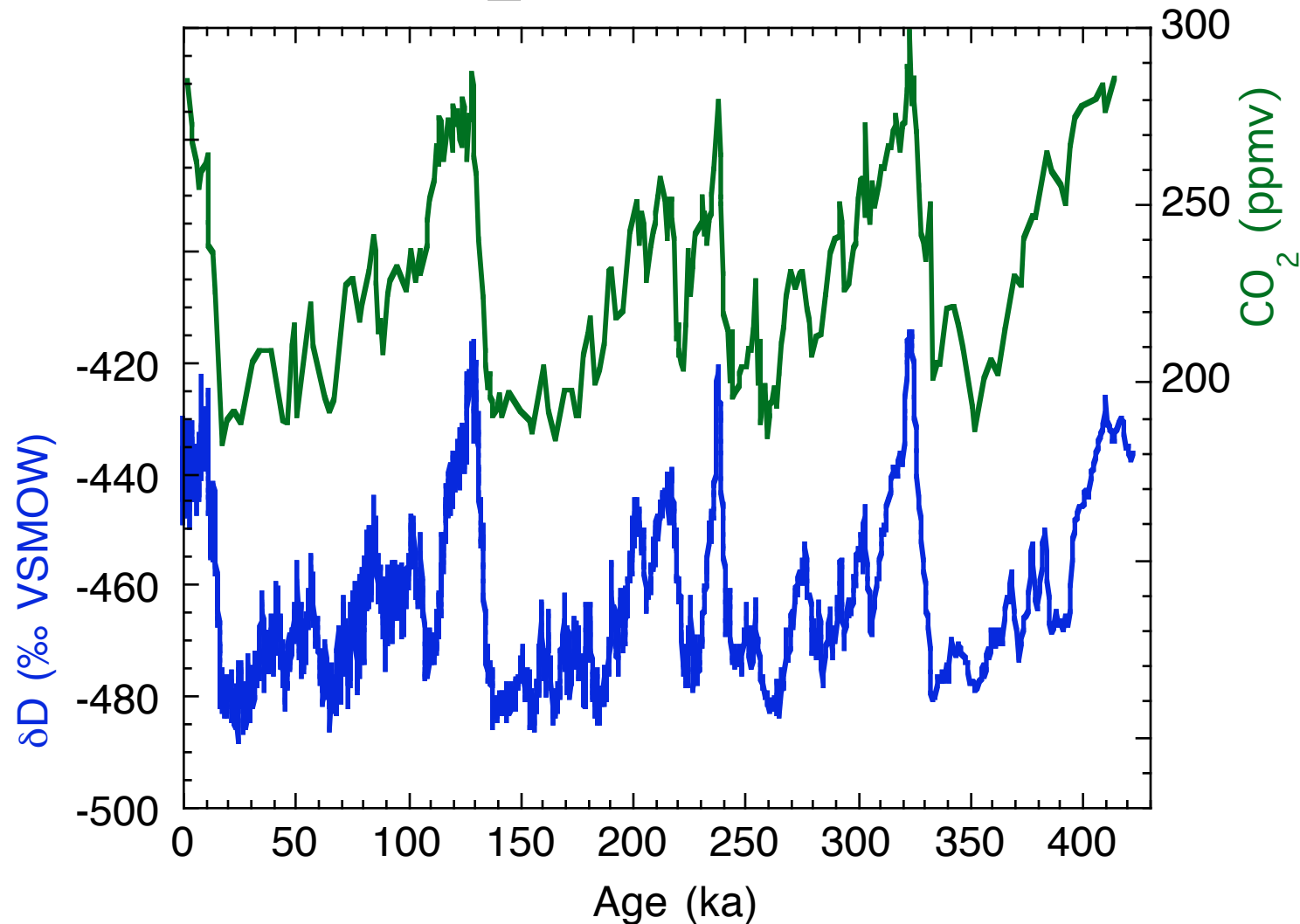
http://www.ncdc.noaa.gov/paleo/icecore/antarctica/vostok/vostok_isotope.html

Vostok δD and Δ Temperature



- Δ Temperature is estimated based on a spatial calibration

Vostok CO₂ and temperature



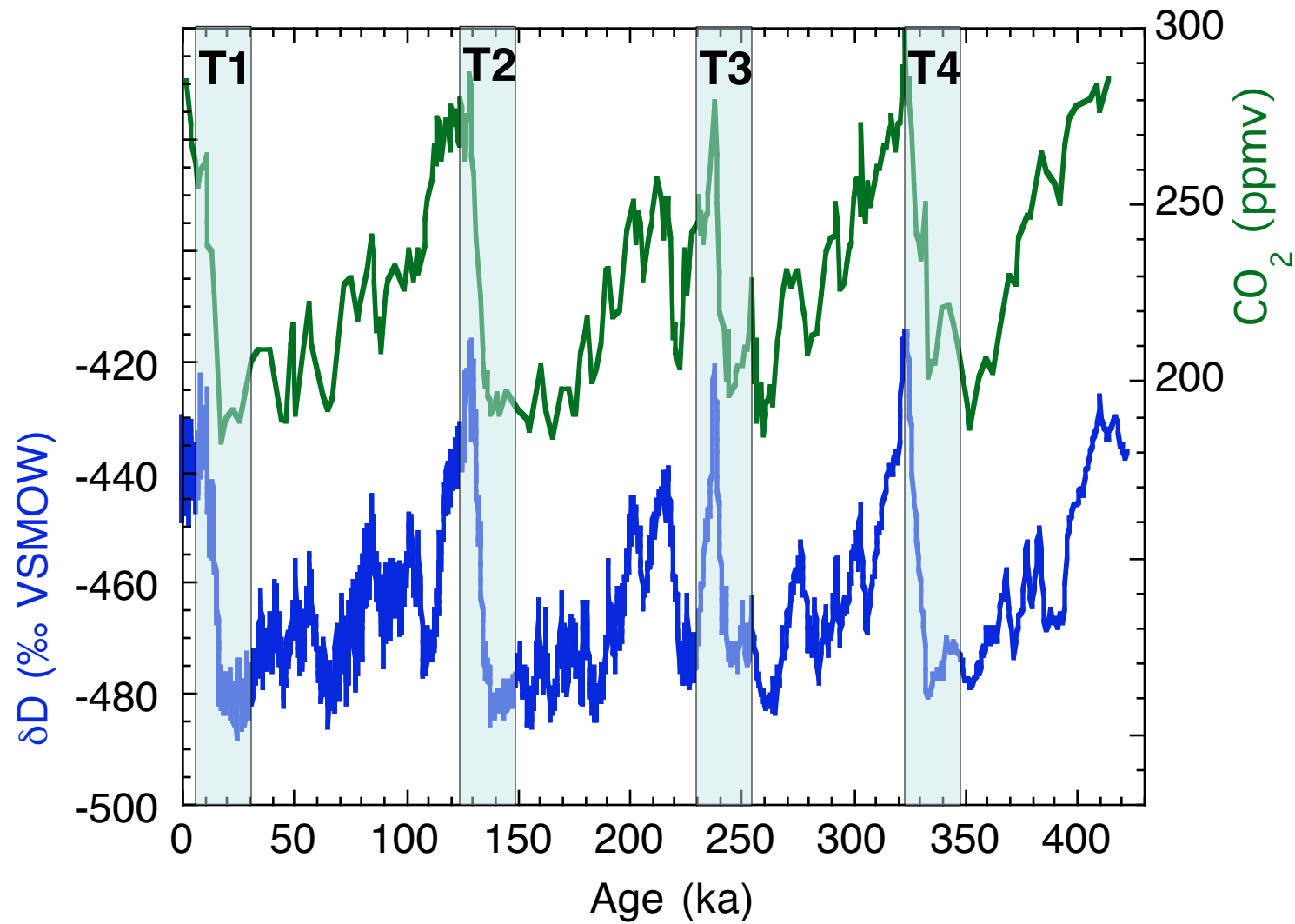
- δD represents regional Antarctic air temperature
- CO_2 represents global atmospheric concentrations

Phasing of CO₂ and temperature

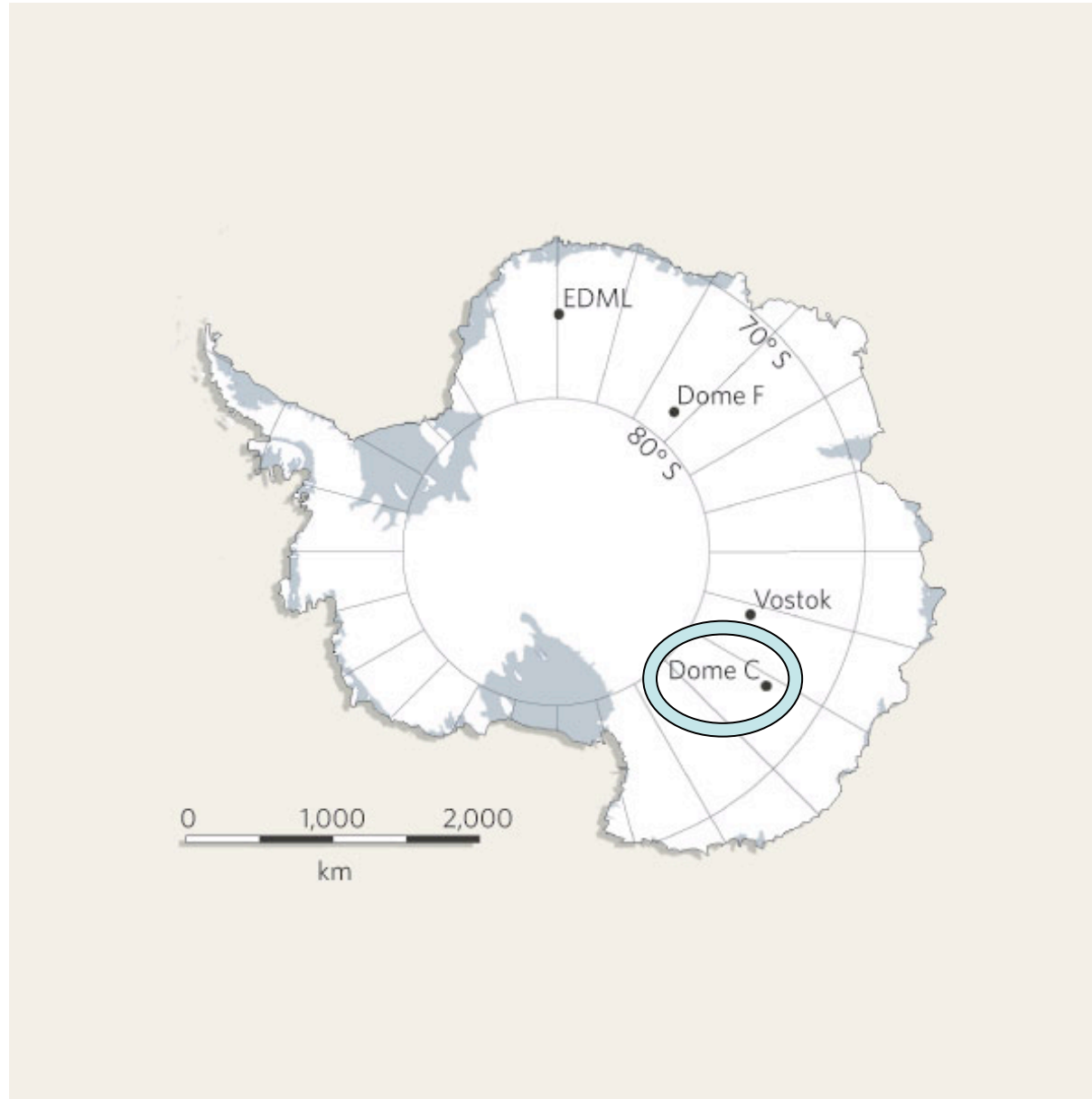
“Considering the large gas-age/ice-age uncertainty..., we feel that it is premature to infer the sign of the phase relationship between CO₂ and temperature at the start of terminations.”

(Petit et al., 1999, *Nature* 399: 429)

3) CO₂ and temperature phase relations during glacial terminations



Dome C



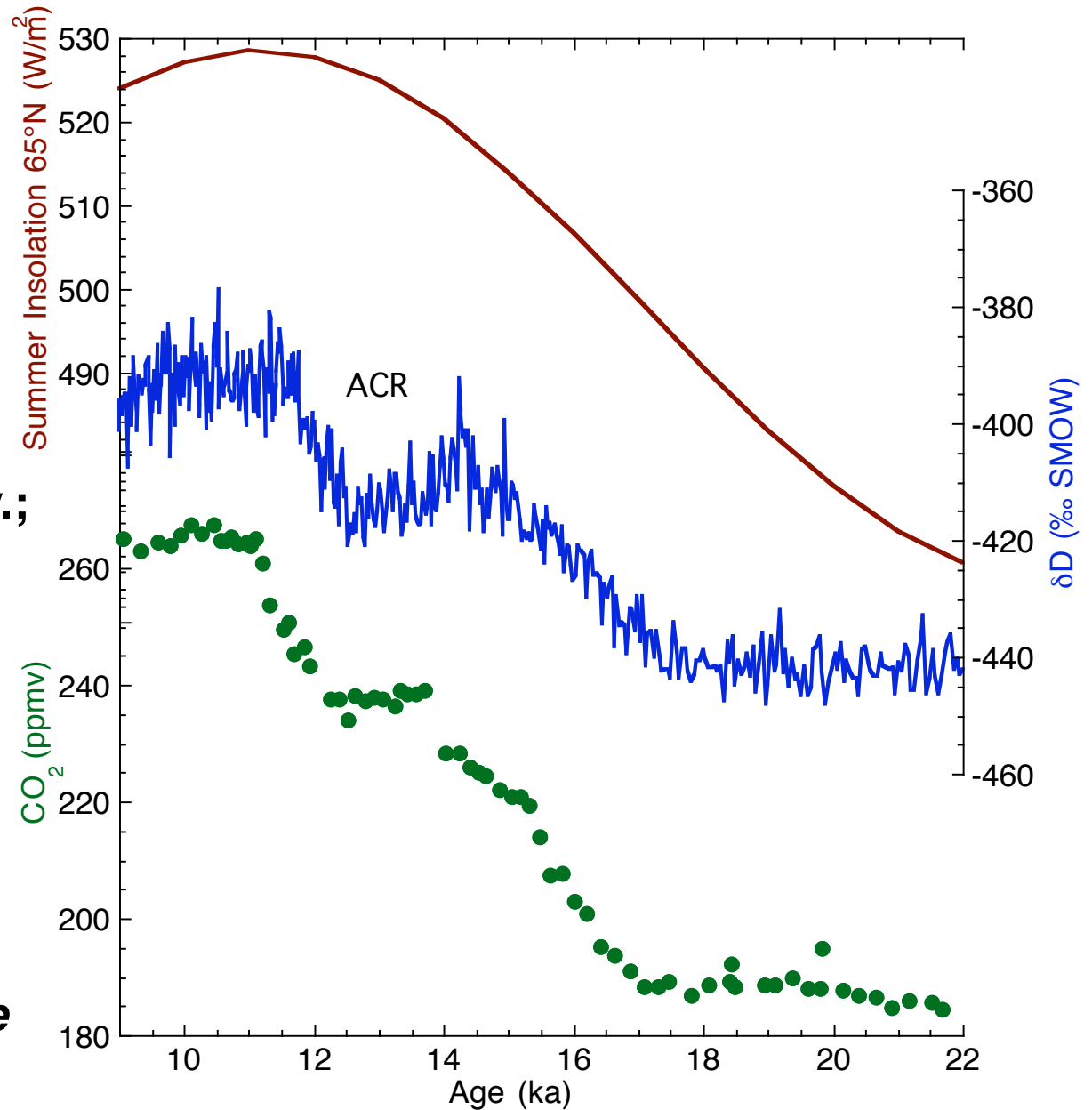
Termination 1

- CO₂ rises from 189 to 265 ppmv (76 ± 1 ppmv)

- average rate: 20 ppmv/k.y.;
max. rate: 30 ppmv/k.y.
($<25\times$ 20th century rate)

- CO₂ tracks temperature
($r = 0.85$)

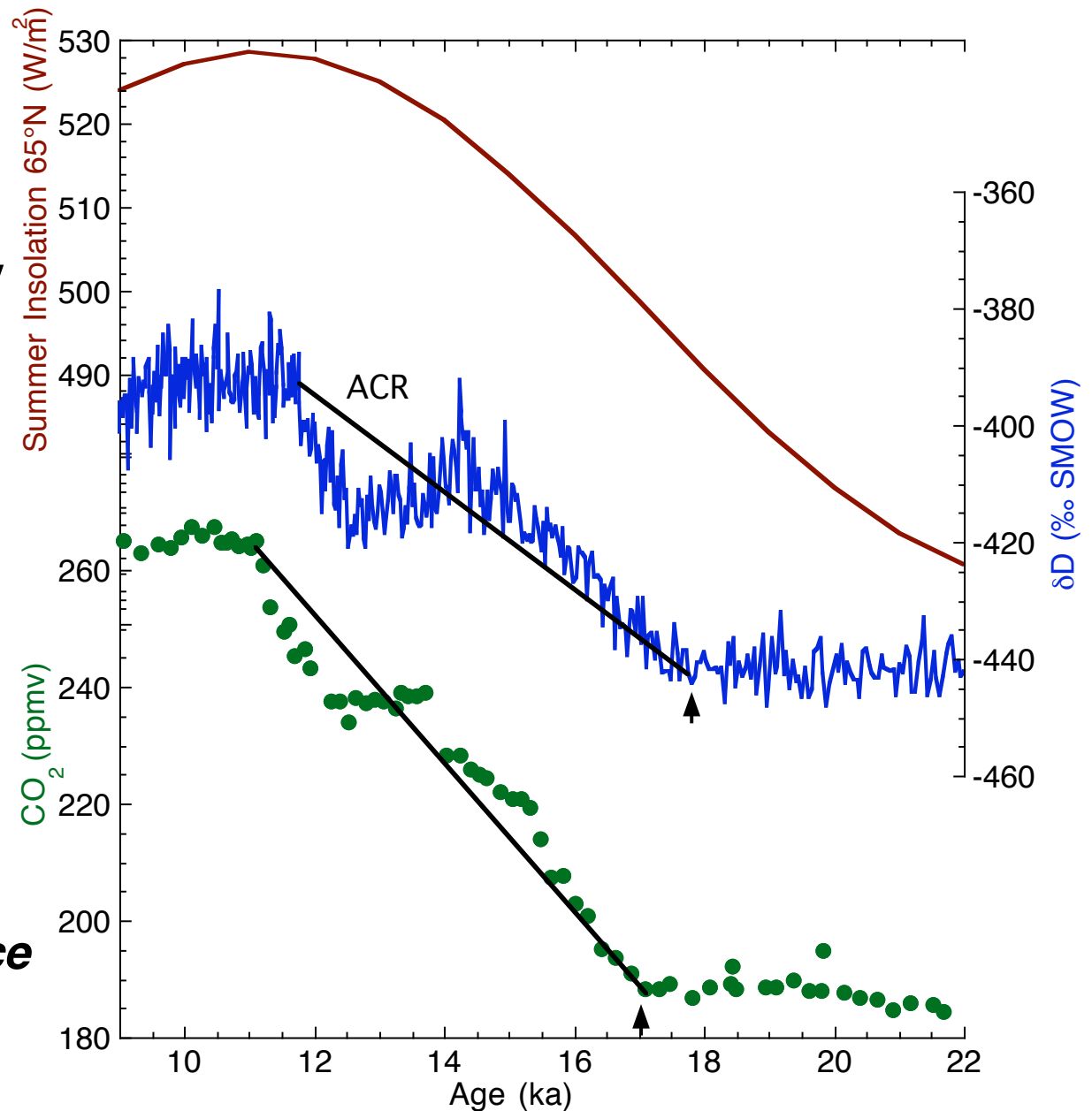
Monnin et al., 2001 *Science*
291: 112 (Dome C)



Termination 1

- ice-gas age (Δt) is 5500 y during LGM ($\pm 10\%$)
- CO_2 rise lags onset of Antarctic warming by 800 ± 600 y
- lag/common duration = $800/6000$ y (13%)

Monnin et al., 2001 *Science*
291: 112 (Dome C)

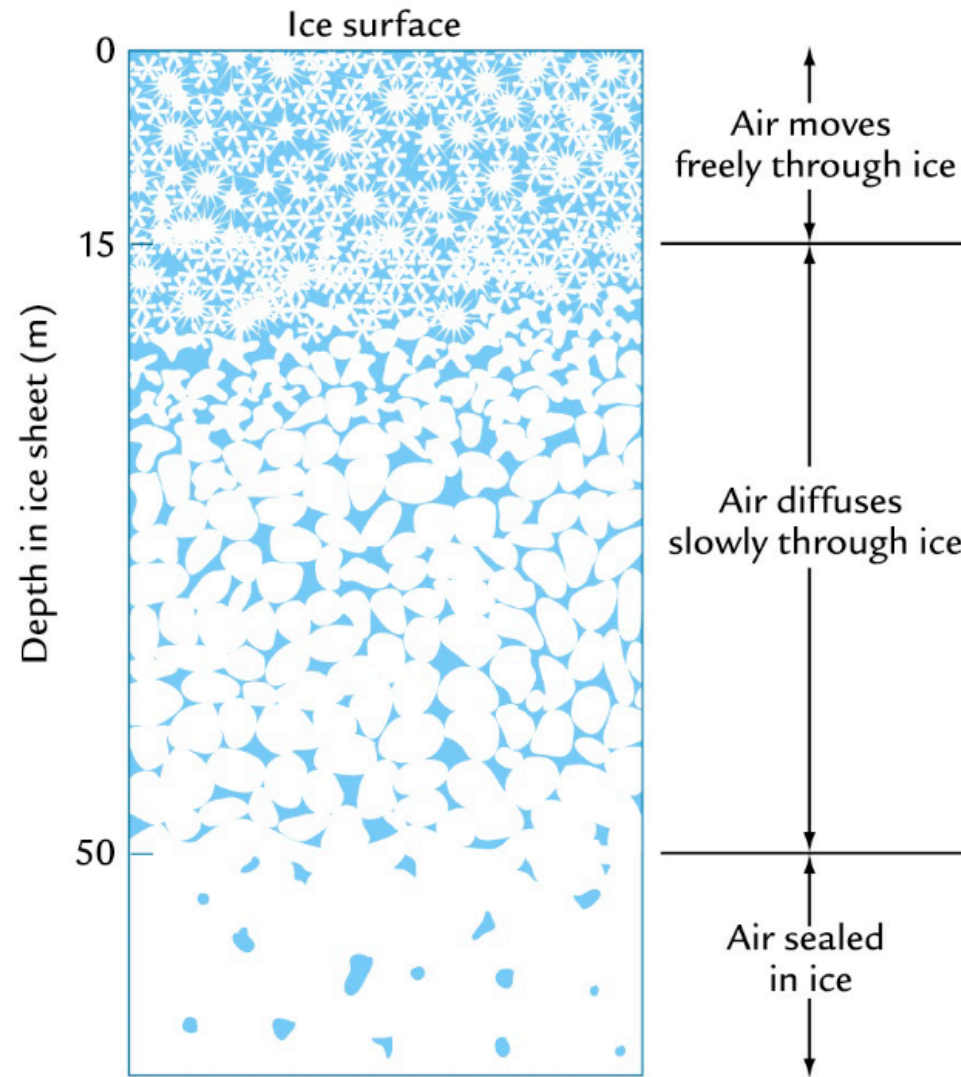


Relevance to greenhouse warming

“The estimated time lag... does not cast doubt on the importance of CO₂ as an amplification factor of the temperature increase.”

Monnin et al., 2001 *Science* 291: 112 (Dome C)

Circumventing the ice age – gas age difference

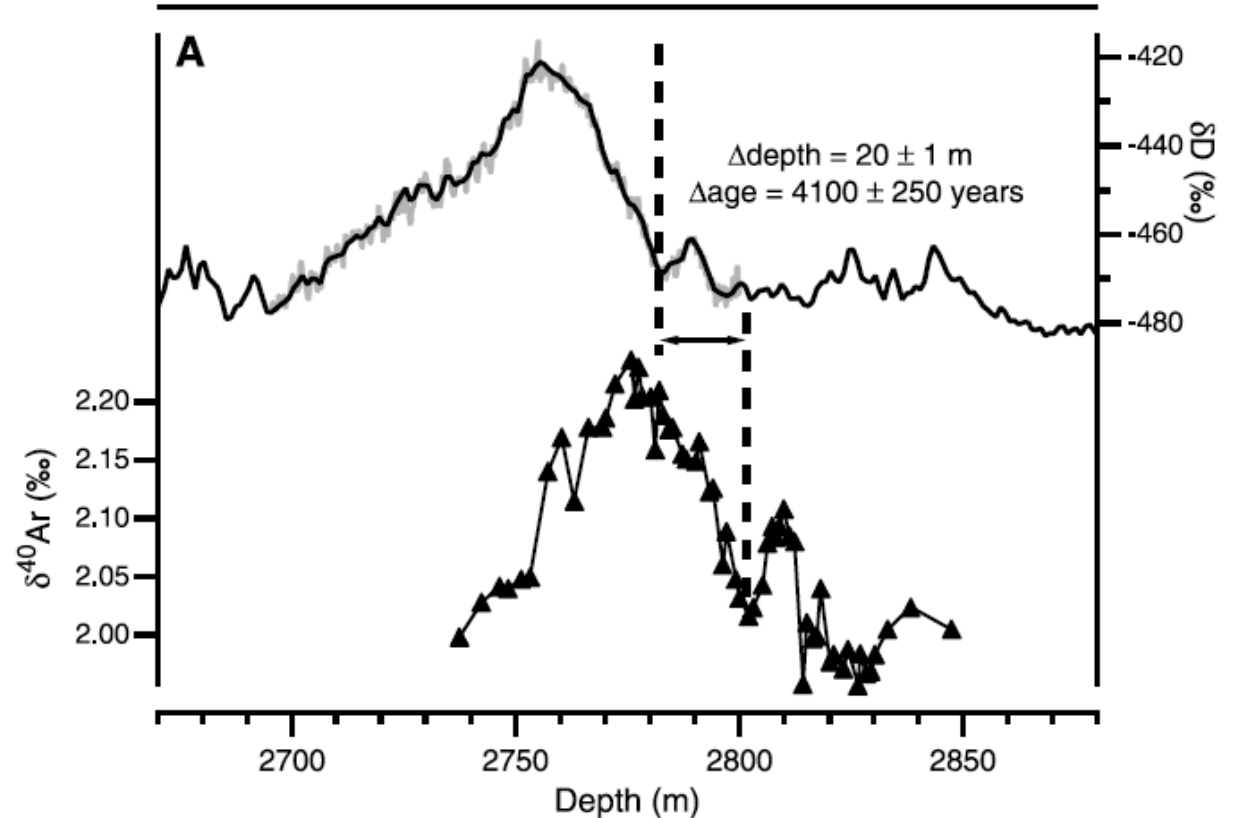


Ruddiman 2001

Termination 3

- Ar isotopes affected by gravitational and thermal fractionation
- $\delta^{40}\text{Ar}$ is used as temperature proxy in gas phase ($r = 0.85$)
- ice-gas age (Δt) is 4100 ± 250 y

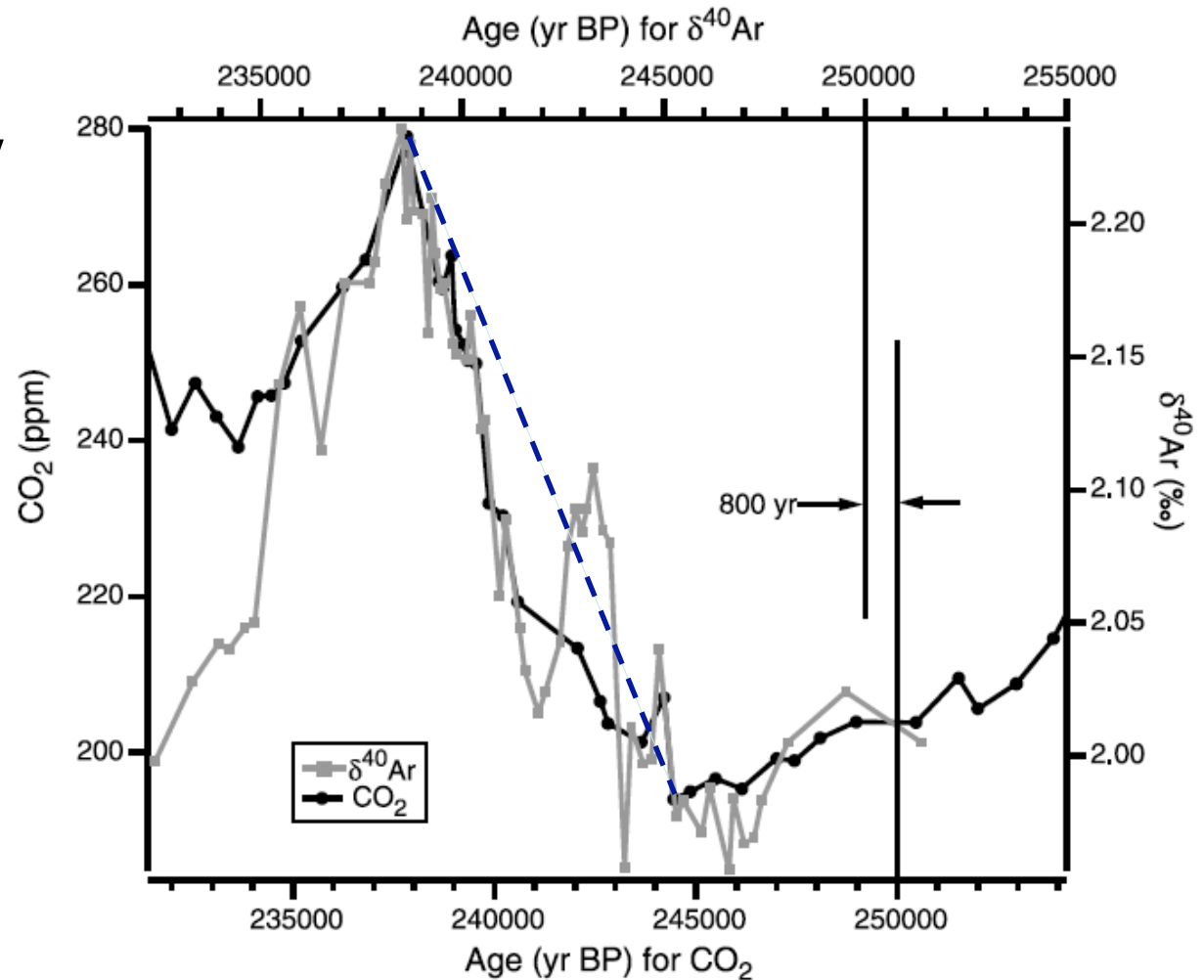
Caillon et al., 2003
Science 299: 1728
(Vostok)



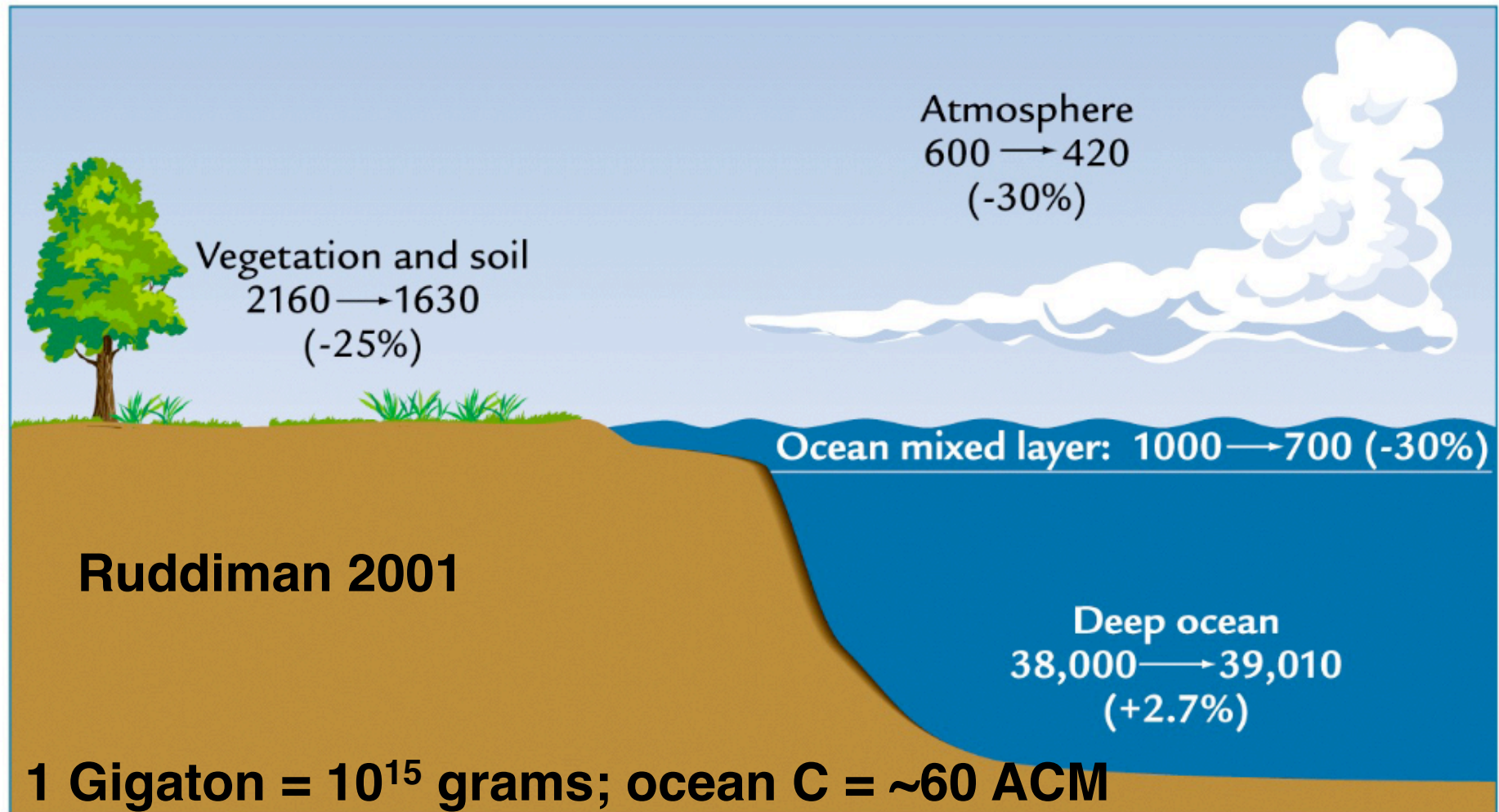
Termination 3

- CO₂ lags temperature increase by 800 ± 200 y
- lag/common duration = $800/6000$ y (13%)
- “CO₂ plays... a key role in amplifying the initial orbital forcing.”

Caillon et al., 2003
Science 299: 1728
(Vostok)

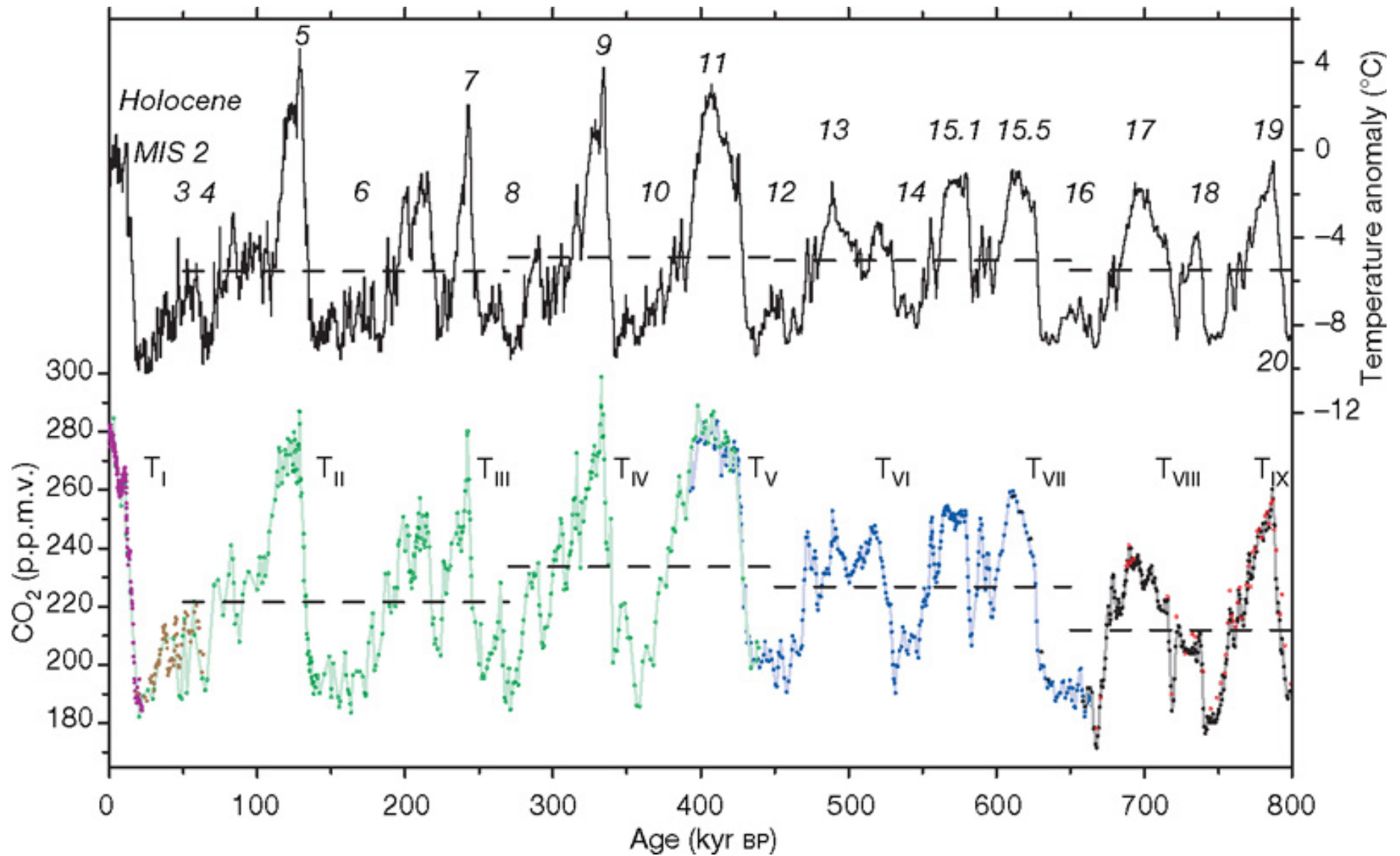


Interglacial-glacial changes in carbon



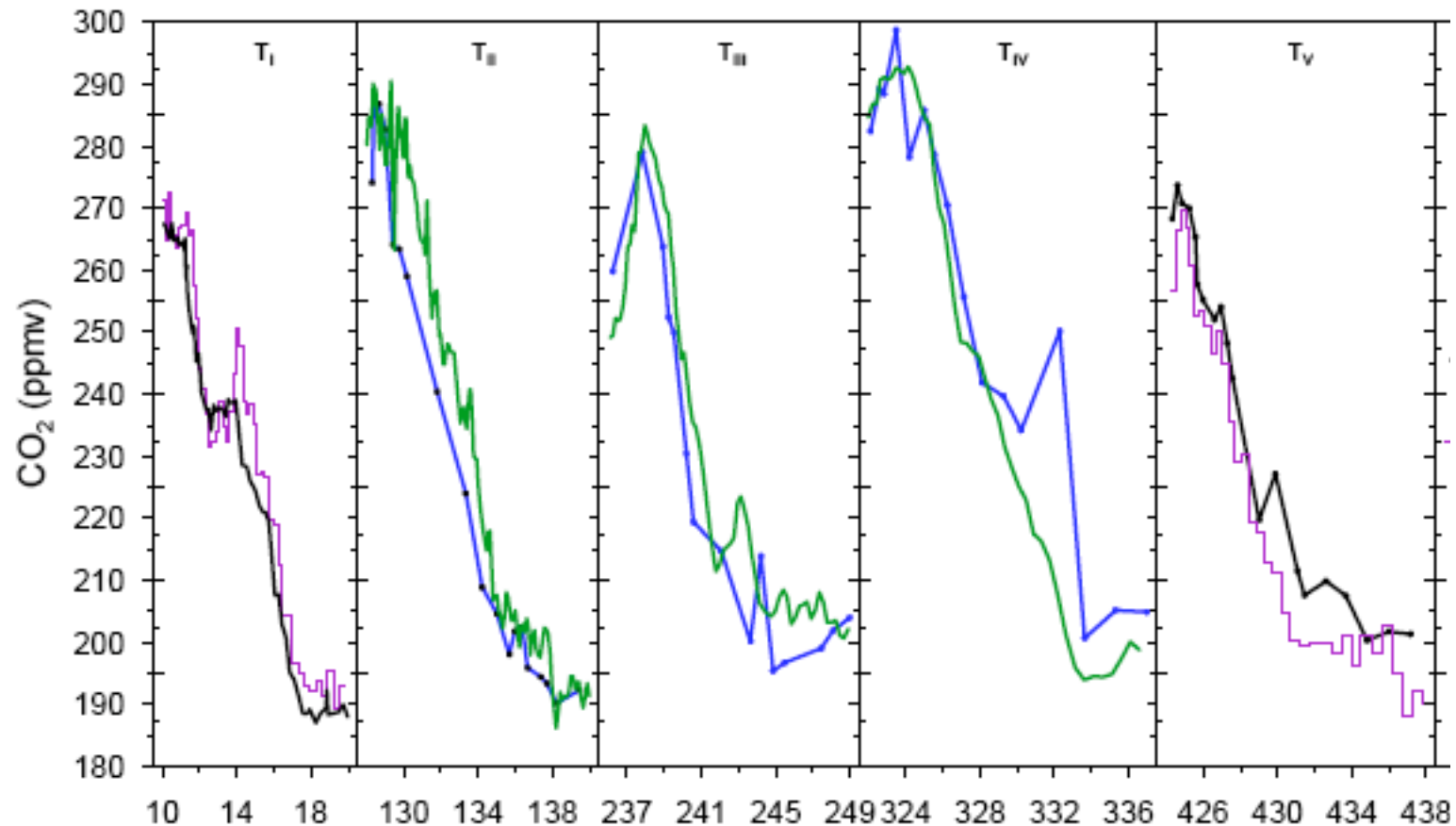
- Lag/common duration of ~800/6000 is expected for deep ocean release of CO₂ during terminations

Dome C CO₂ and Δ Temperature



Lüthi et al., 2008, *Nature* 453, 379-382, doi:10.1038/nature0694

Terminations 1-5



800±600/
6000

Monnin et al., 2001
(Dome C)

600±200/
8800

Lüthi et al., 2008

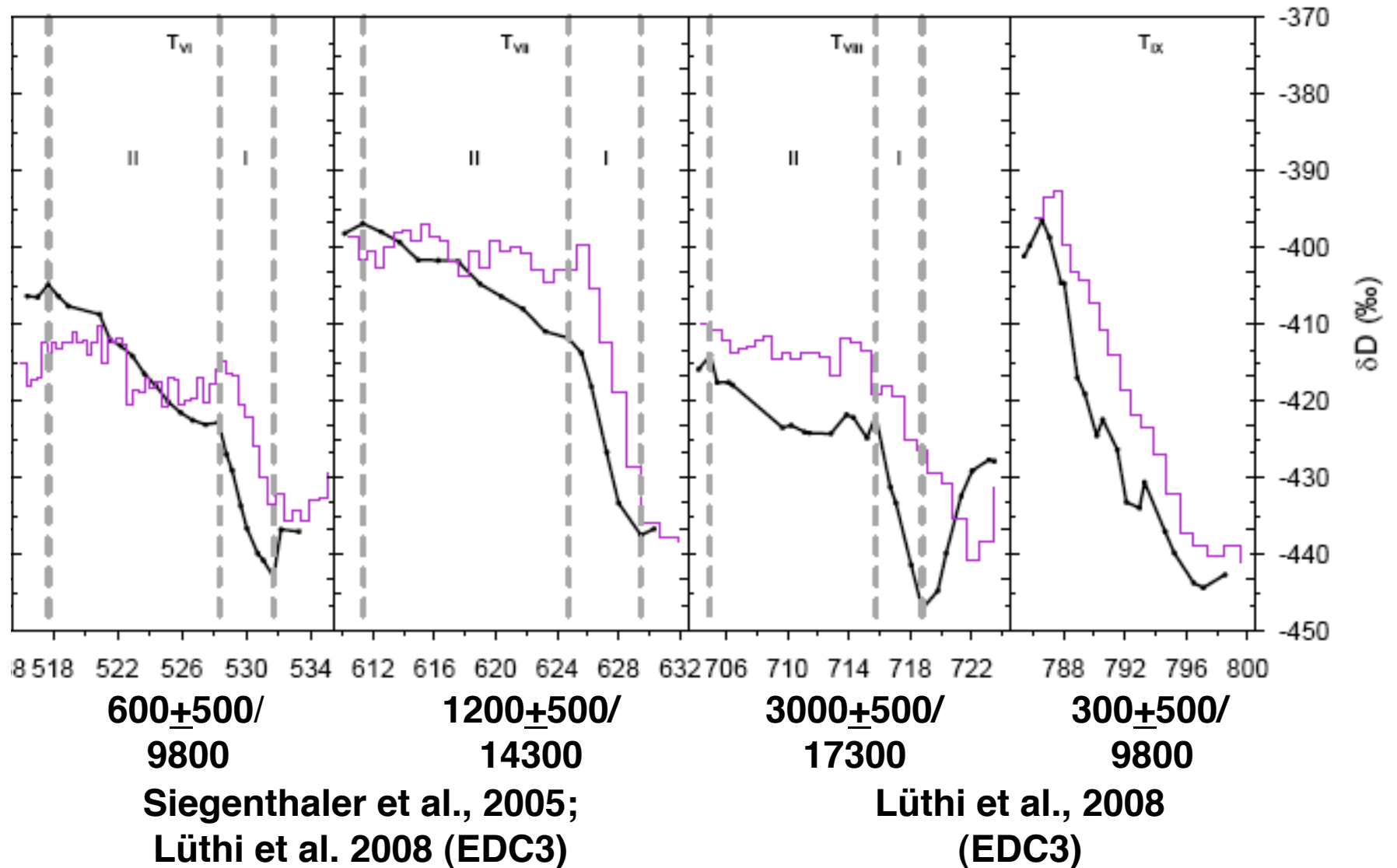
800±200/
6000

1100±500/
6500

Siegenthaler et al., 2005;
Lüthi et al. 2008 (EDC3)

2000±500/
10000

Terminations 6-9



Relevance to greenhouse warming

“Compared to the time scales of glacial cycles, these time lags are small and do not question the important role of CO₂ as an amplifier of the large temperature rise during deglaciations.”

(Lüthi et al., 2008)

Summary

- **CO₂ fluctuated between ~180 and 300 ppmv throughout the past 800 ky until ca. 1850**
- **CO₂ has tracked Antarctic air temperature, including the saw-tooth 100 ky cycle**
- **CO₂ lags Antarctic temperature by 300 to 3,000 years, but the lag depends on the gas/ice age difference**
- **Furthermore, the lag is small relative to the common duration (typically 800/6000 y), so CO₂ may not be a trigger for climate change, but an amplifier**