Ice cores, air bubbles, and climate change

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Climate Literacy Network

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Melissa Headly (PhD thesis 2008 on Kr & Xe GISP2)

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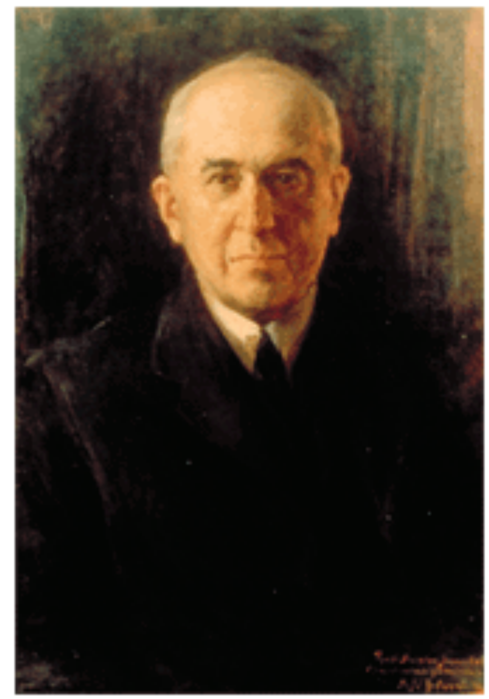
What causes ice age cycles?
TAKE-HOME MESSAGES:

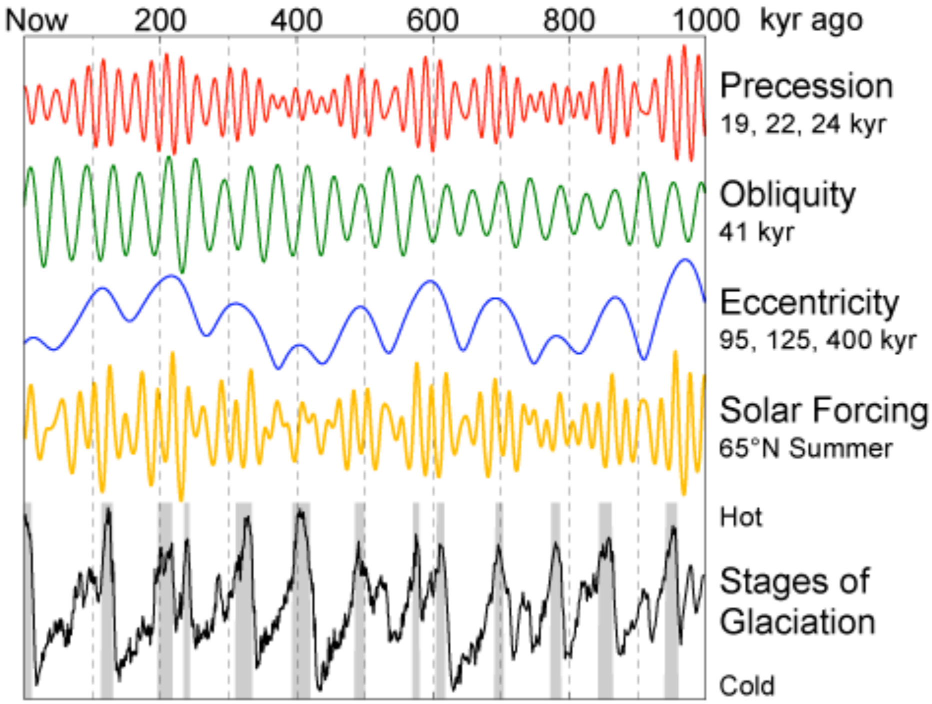
1. Wobble and tilt of Earth’s spin axis
2. Amplified by CO2 variations
3. Meltdowns aided by abrupt shutdown of Atlantic ocean circulation

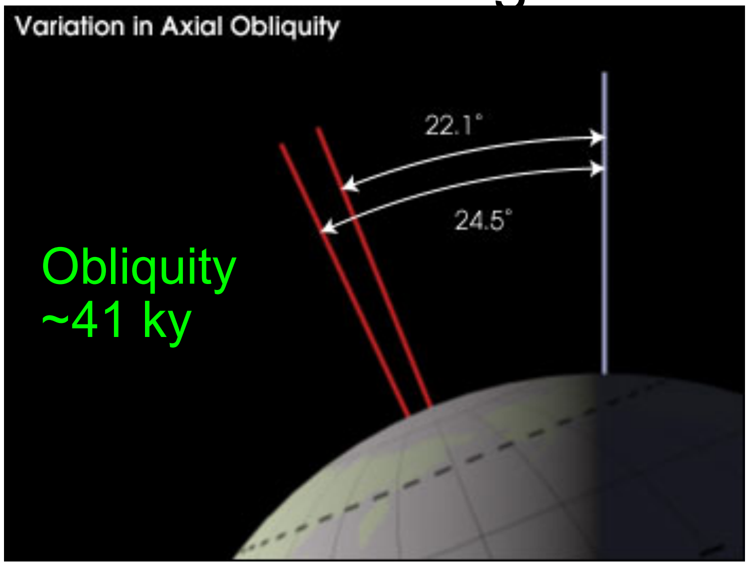
Milankovitch theory

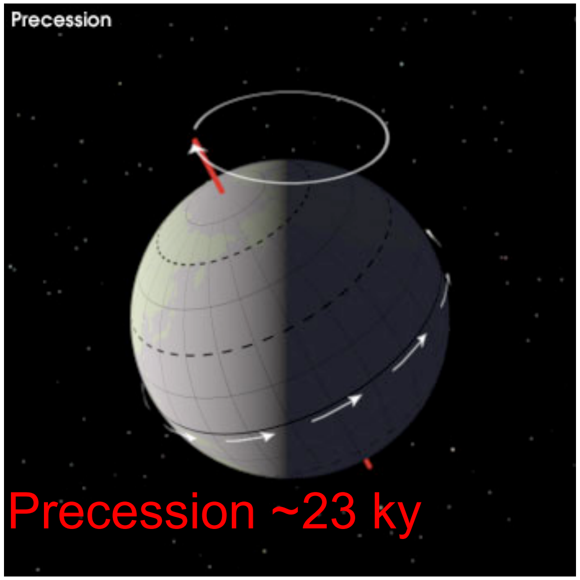
High-latitude northern summer sunshine intensity influences growth/decay of Northern Hemisphere ice sheets and thus global climate.

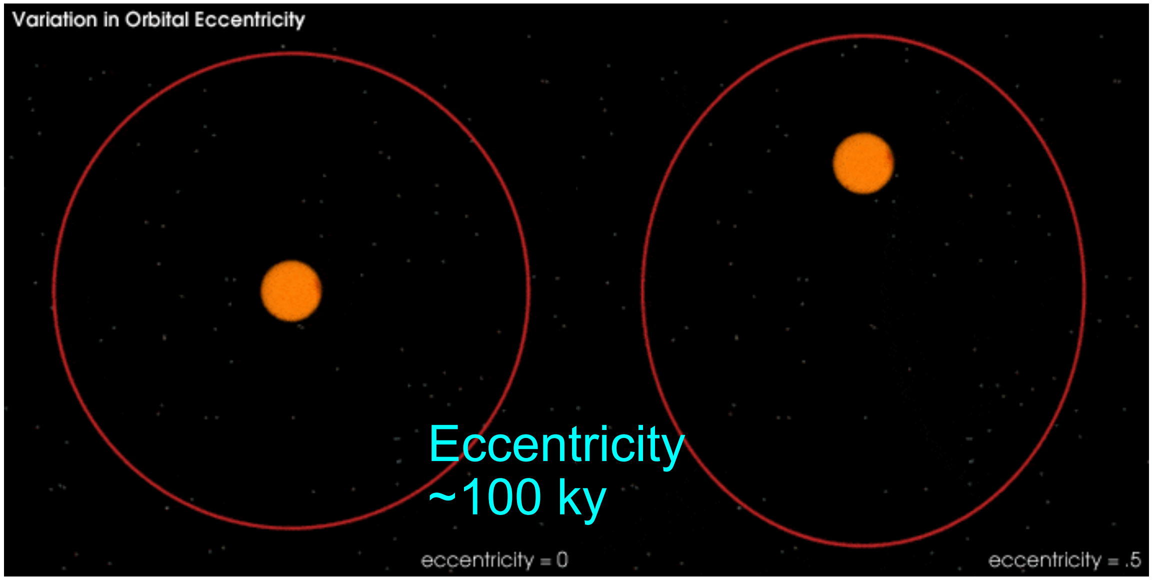


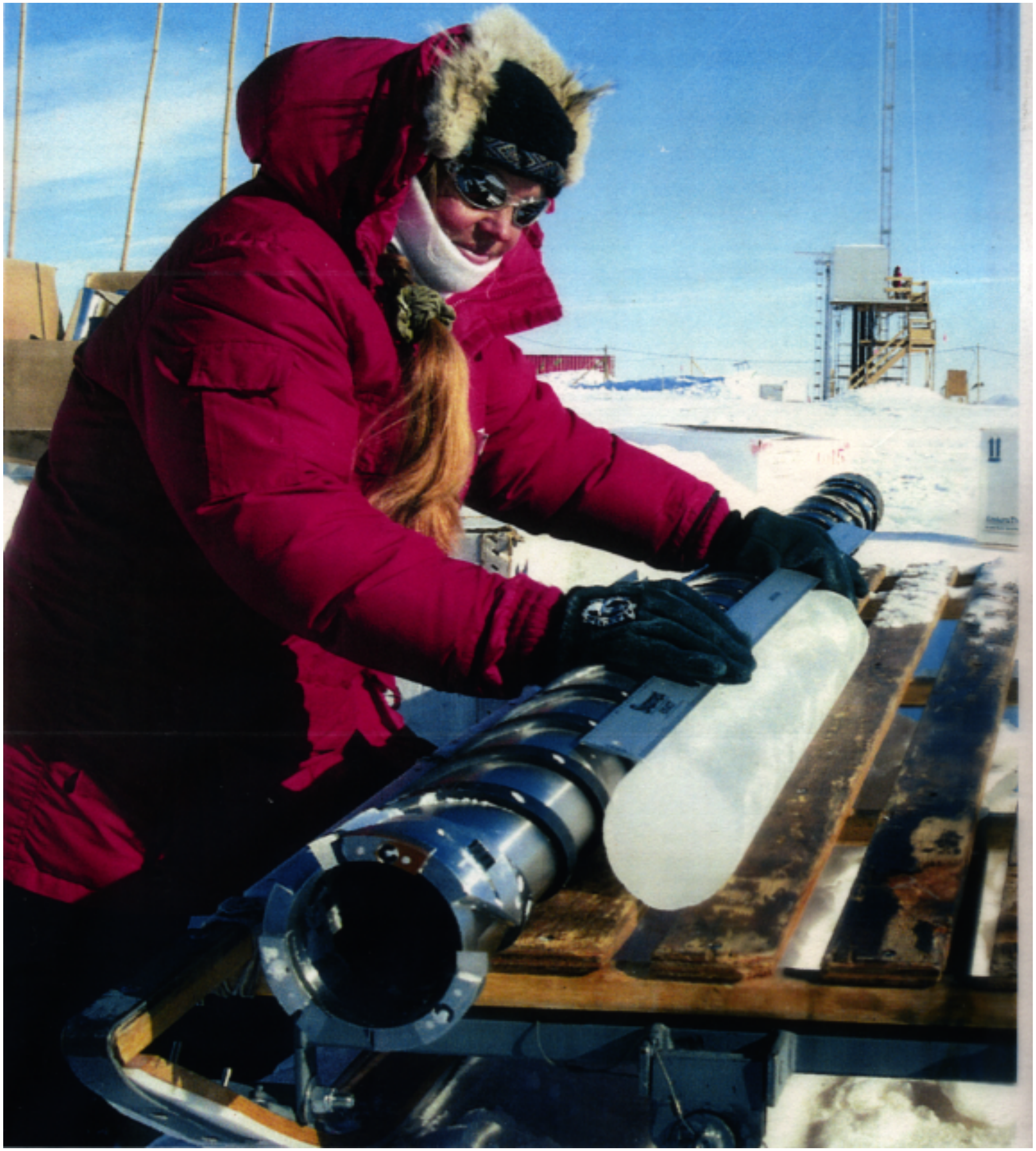
Earth's orbit: pacemaker of the ice ages





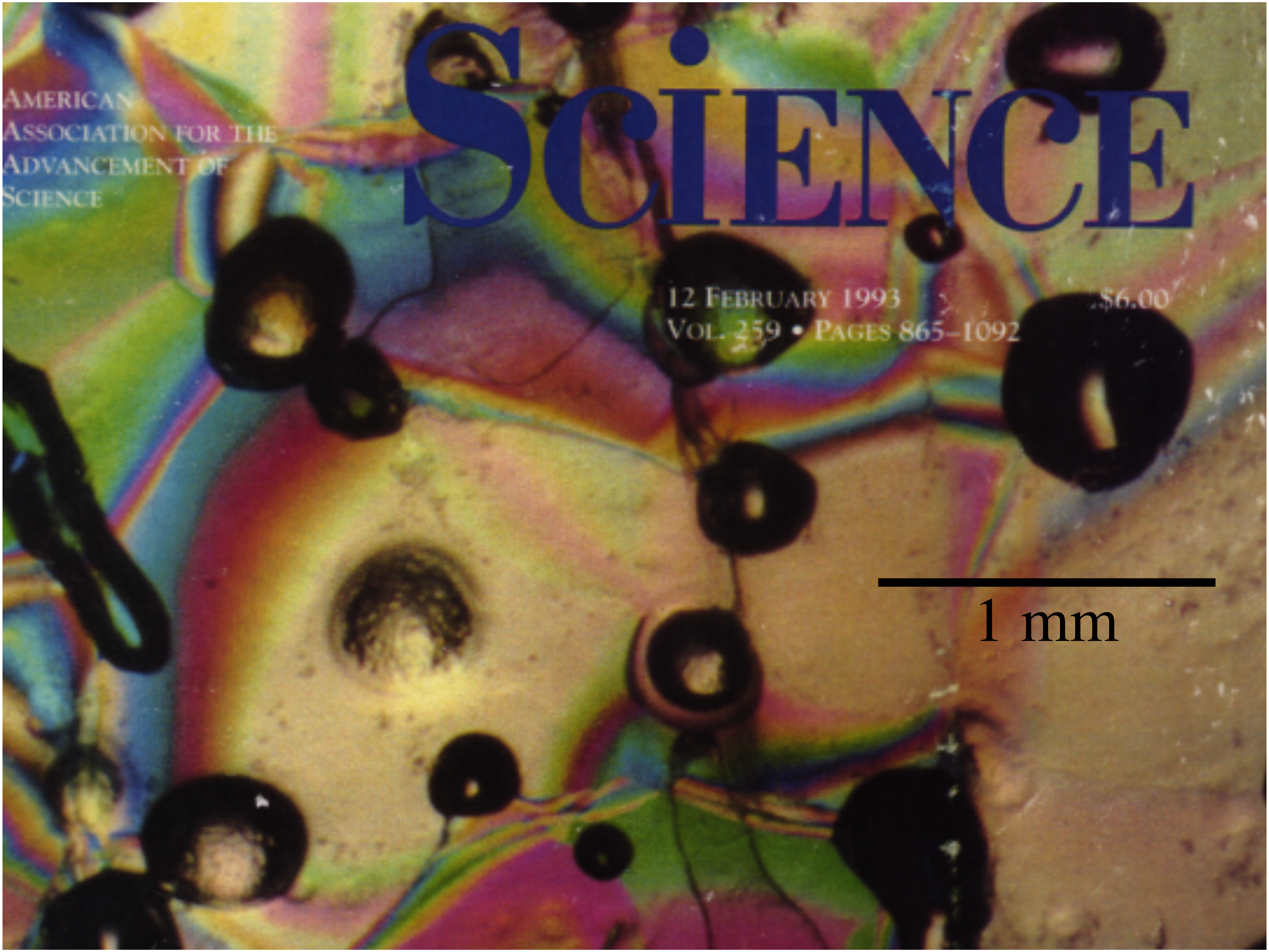






Polar ice cores:

- Dated by counting annual layers
- Preserve past atmospheres in air bubbles in the ice!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Science
Science
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Vol. 259 • Pages 865–1092
1 mm

Trapped gases reveal a cornucopia of information about past climate and its feedbacks:

Climate forcing via greenhouse effect: CO_2, CH_4, N_2O

Astronomical dating of ice cores: O_2/N_2

Mean ocean temperature: Kr/N_2, Xe/N_2

Rapid temperature change at ice sheet surface: $^{15}N/^{14}N$ of N_2

$^{40}Ar/^{36}Ar$, $^{86}Kr/^{82}Kr$

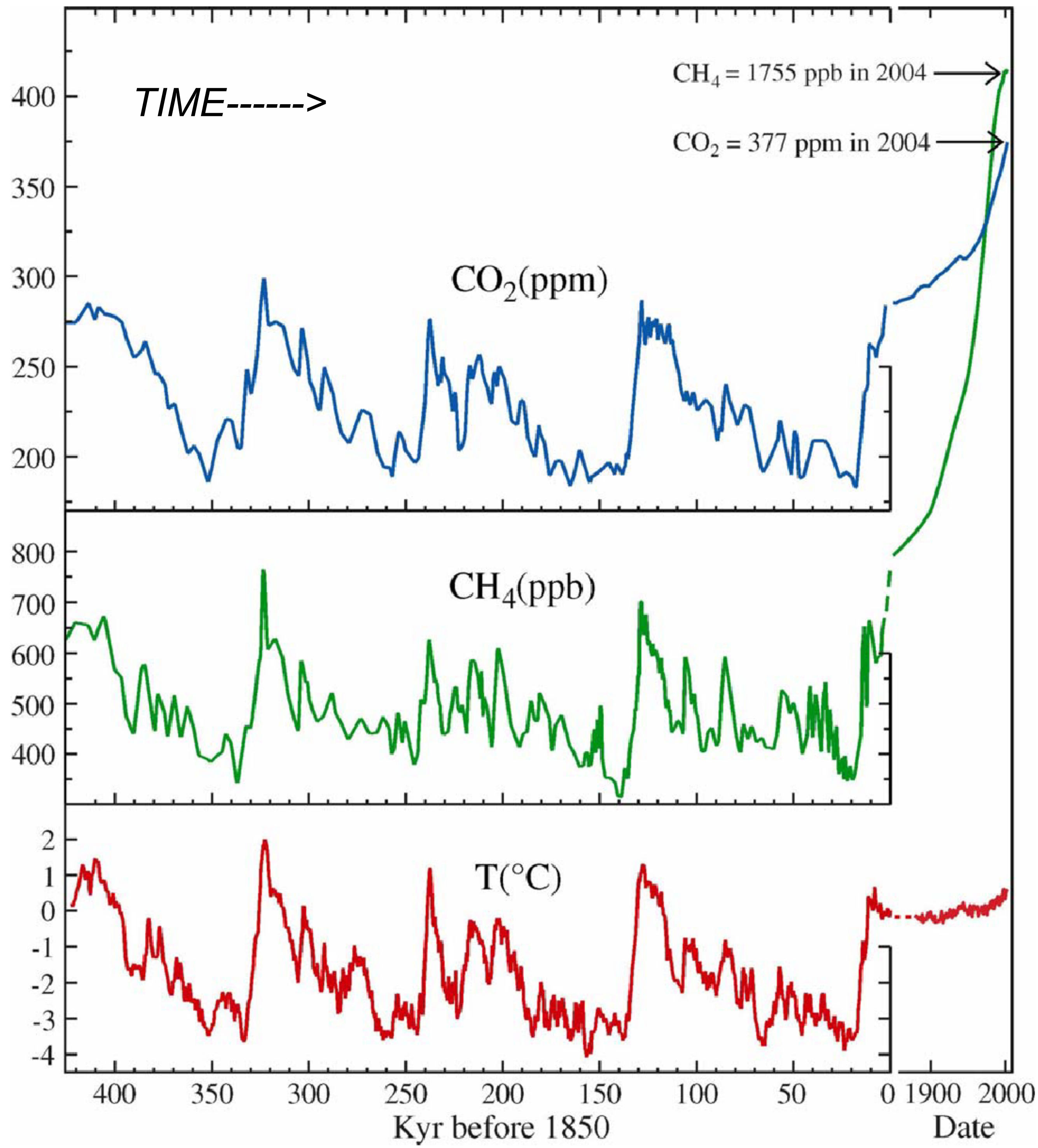
Asian and African monsoon strength: $^{18}O/^{16}O$ of O_2

Fossil vs. biological sources of methane: $^{14}C/^{12}C$ of CH_4

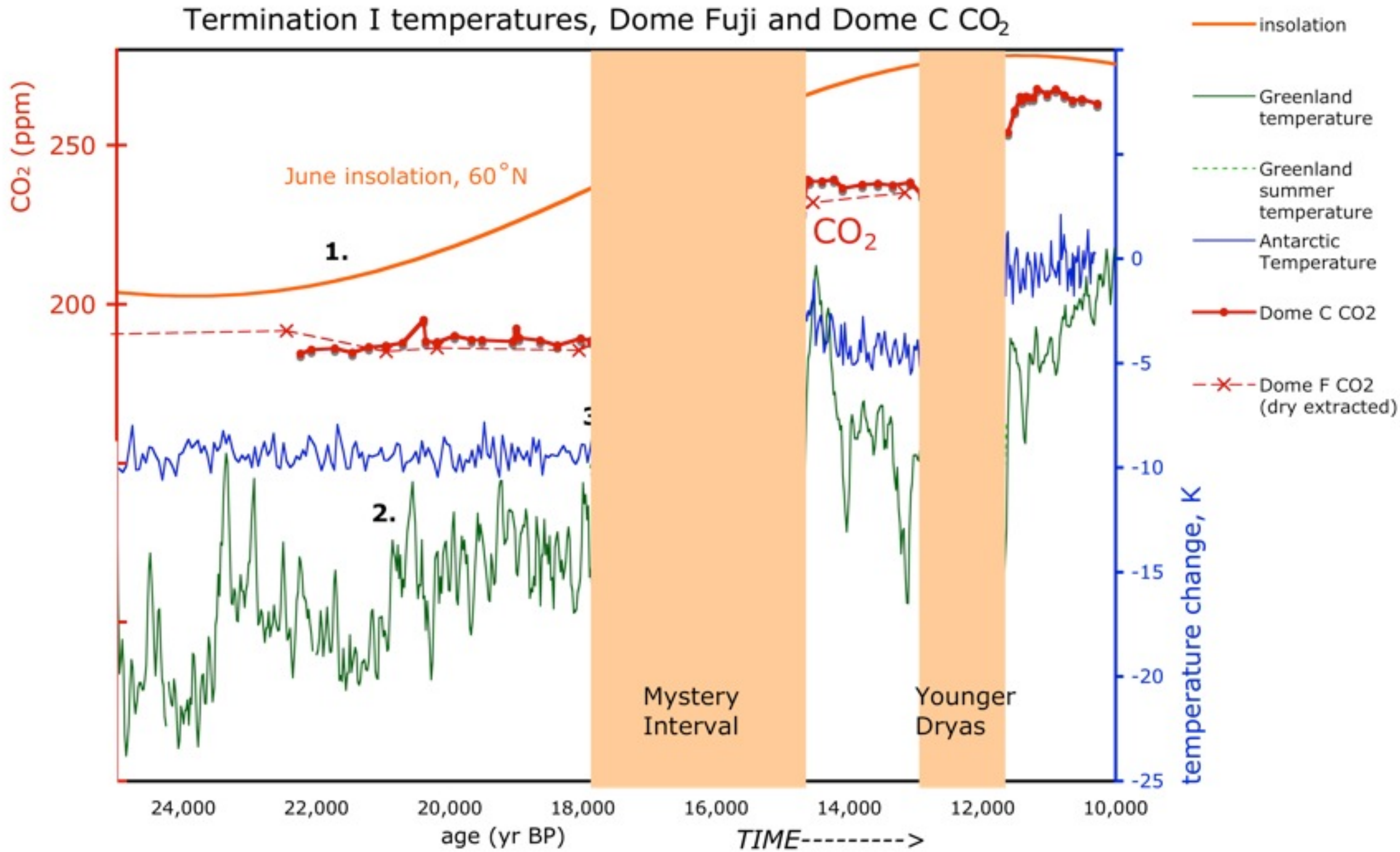
(list goes on….)

Ice cores give us past CO_2 concentrations

CO_2,CH_4 and estimated global temperature (Antarctic $\Delta T/2$ in ice core era)



Source: Hansen, *Clim. Change*, **68**, 269, 2005.


Termination I temperatures, Dome Fuji and Dome C CO2
CO2 (ppm)
250
200
June insolation, 60˚N
1.
2.
CO2
Mystery
Interval
Younger
Dryas
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
age (yr BP)
TIME--------->
temperature change, K
0
-5
-10
-15
-20
-25
insolation
Greenland temperature
Greenland summer temperature
Antarctic Temperature
Dome C CO2
Dome F CO2 (dry extracted)

Paradox #1:

Why does Antarctic temperature remain in a stable, cold state despite several thousand years (22-18 ka) of orbital forcing?

And why does it begin to warm rather abruptly at 18 ka?

Atmosphere is well-mixed, so long-lived gases are the same everywhere
(same core, so no relative dating problem!)

ADVANTAGE: integrates all sources
DISADVANTAGE: no information about location of sources

Methane responds rapidly due to short lifetime (8 yr)

O_2 lifetime ~1000 yr

Kr, Xe ~constant in ocean-atmosphere system

Oxygen-18/16 ratio of atmospheric O_2 = **d18Oatm**

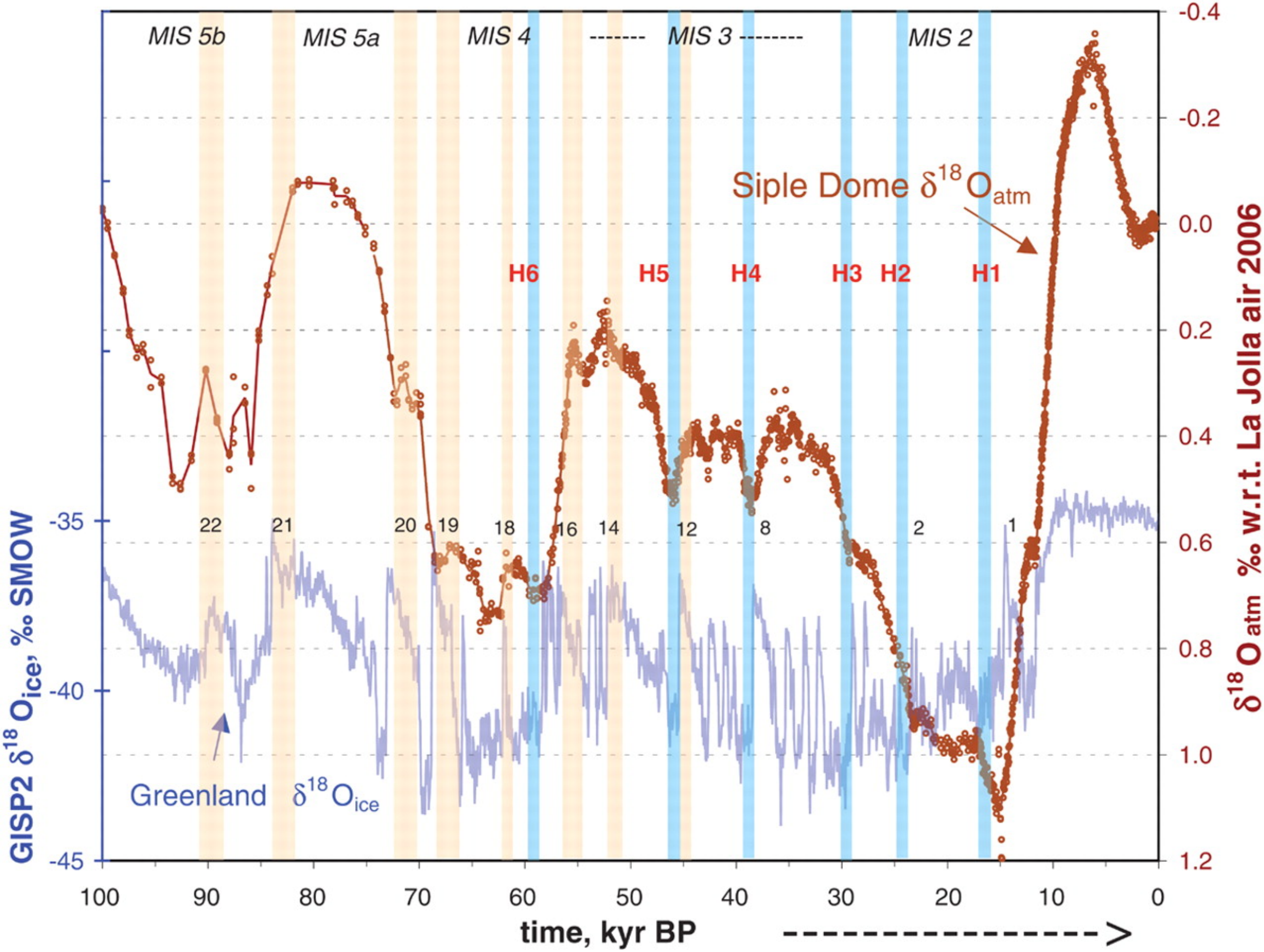
$d^{18}O = \{[^{18}O/^{16}O_{sample}]/[^{18}O/^{16}O_{standard}] - 1\}\ 10^3$‰

Standard is contemporary La Jolla air

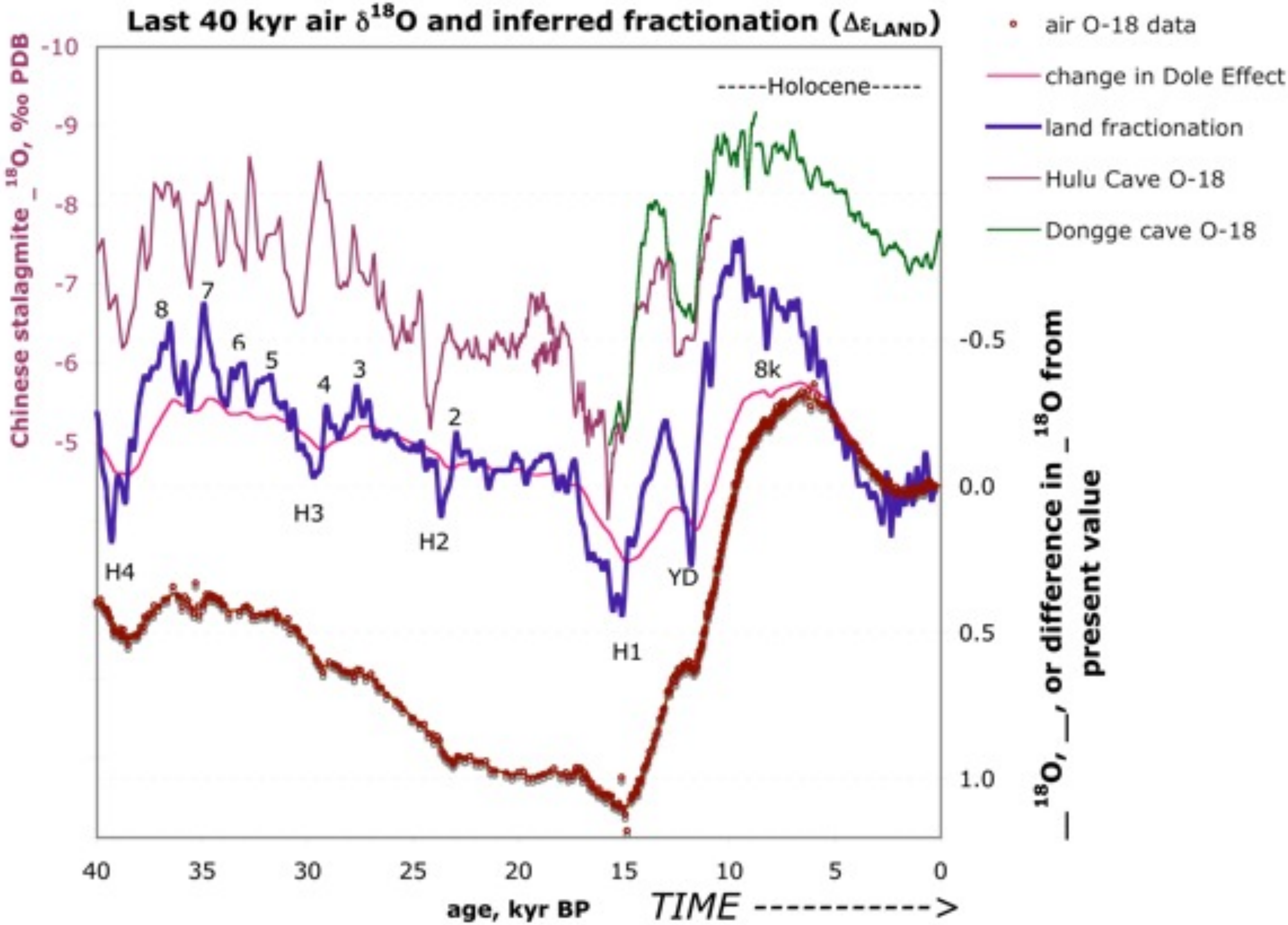
METHOD

Measure isotopes of O_2 in air from ice core bubbles,following procedure of Sowers et al. (1989) with modification to remove CO_2 cryogenically. Correct for gravitational/thermal fractionation in firn layer:

$$d^{18}O_{atm} = d^{18}O_{measured} - 2\ d^{15}N_{measured}$$

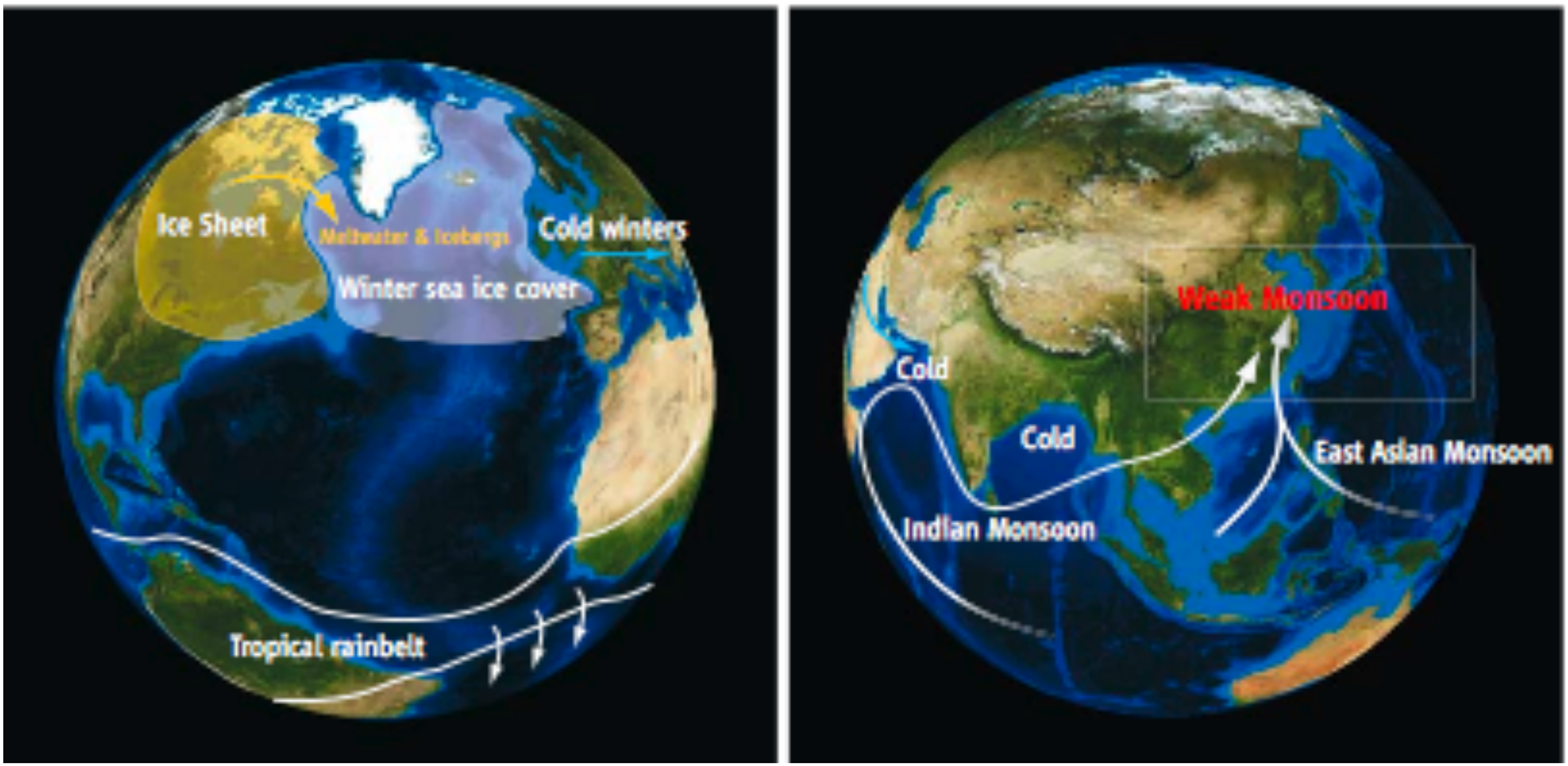


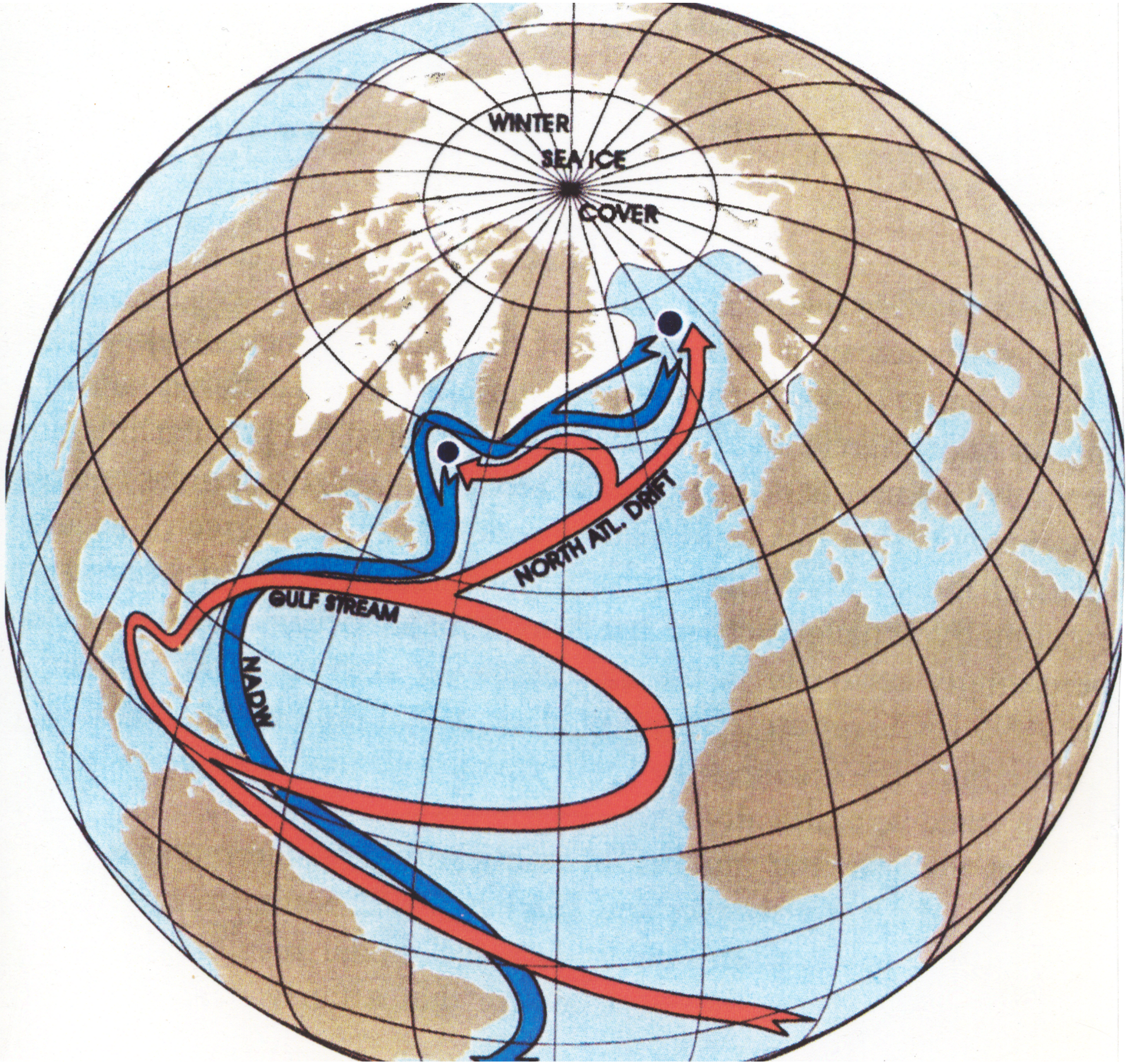
MIS 5b
MIS 5a
MIS 4
MIS 3
MIS 2
H6
H5
H4
H3
H2
H1
22
21
20
19
18
16
14
12
8
2
1
Siple Dome $\delta^{18}O_{atm}$
Greenland $\delta^{18}O_{ice}$
GISP2 $\delta^{18}O_{ice}$, ‰ SMOW
$\delta^{18}O_{atm}$ ‰ w.r.t. La Jolla air 2006
time, kyr BP

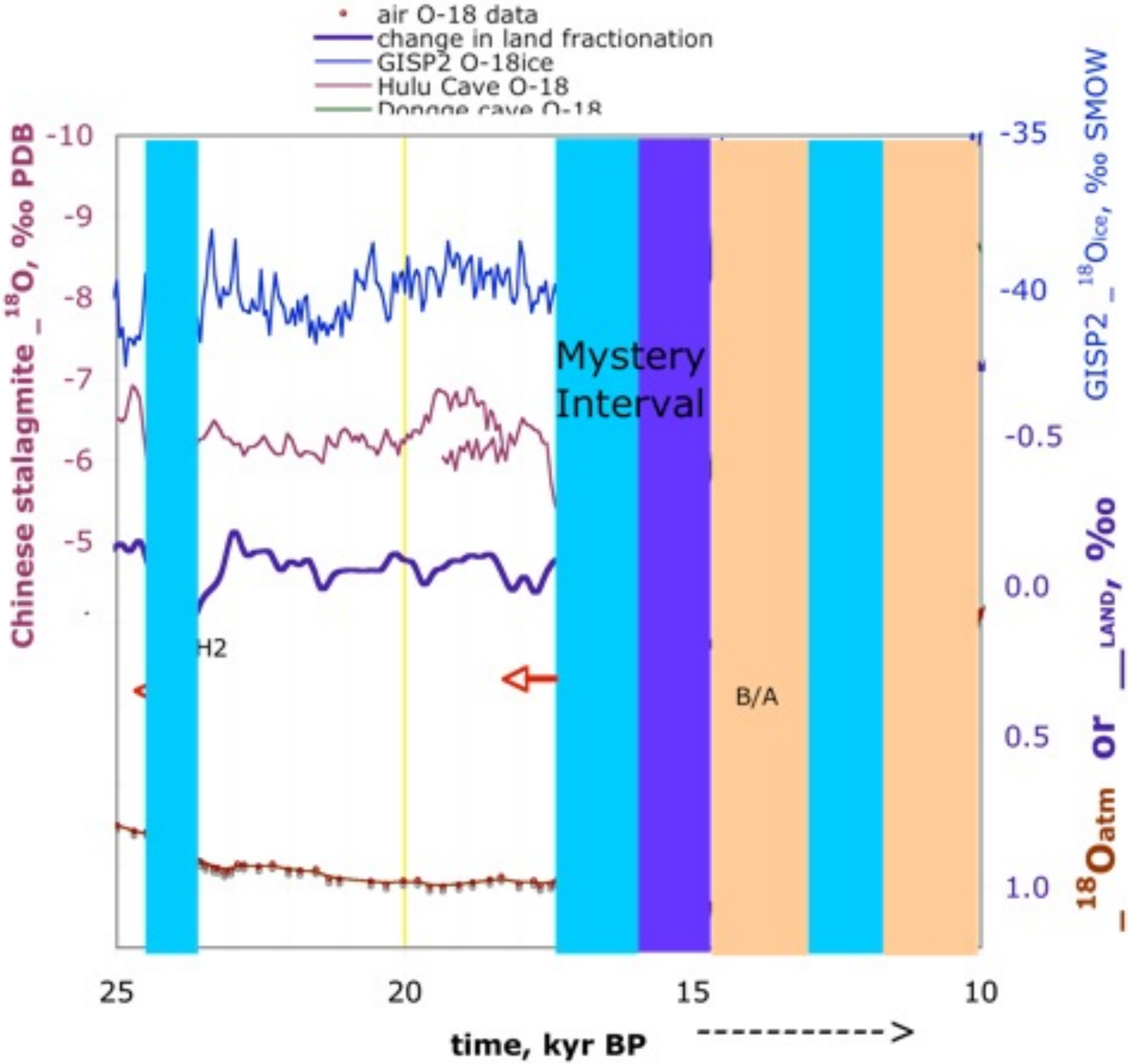


Last 40 kyr air δ18O and inferred fractionation (ΔεLAND)
air O-18 data
change in Dole Effect
land fractionation
Hulu Cave O-18
Dongge cave O-18
-----Holocene-----
Chinese stalagmite _18O, ‰ PDB
-10
-9
-8
-7
-6
-5
8
7
6
5
4
3
2
H4
H3
H2
H1
YD
8k
-0.5
0.0
0.5
1.0
_18O, _, or difference in _18O from present value
40
35
30
25
20
15
10
5
0
age, kyr BP
TIME ----------->

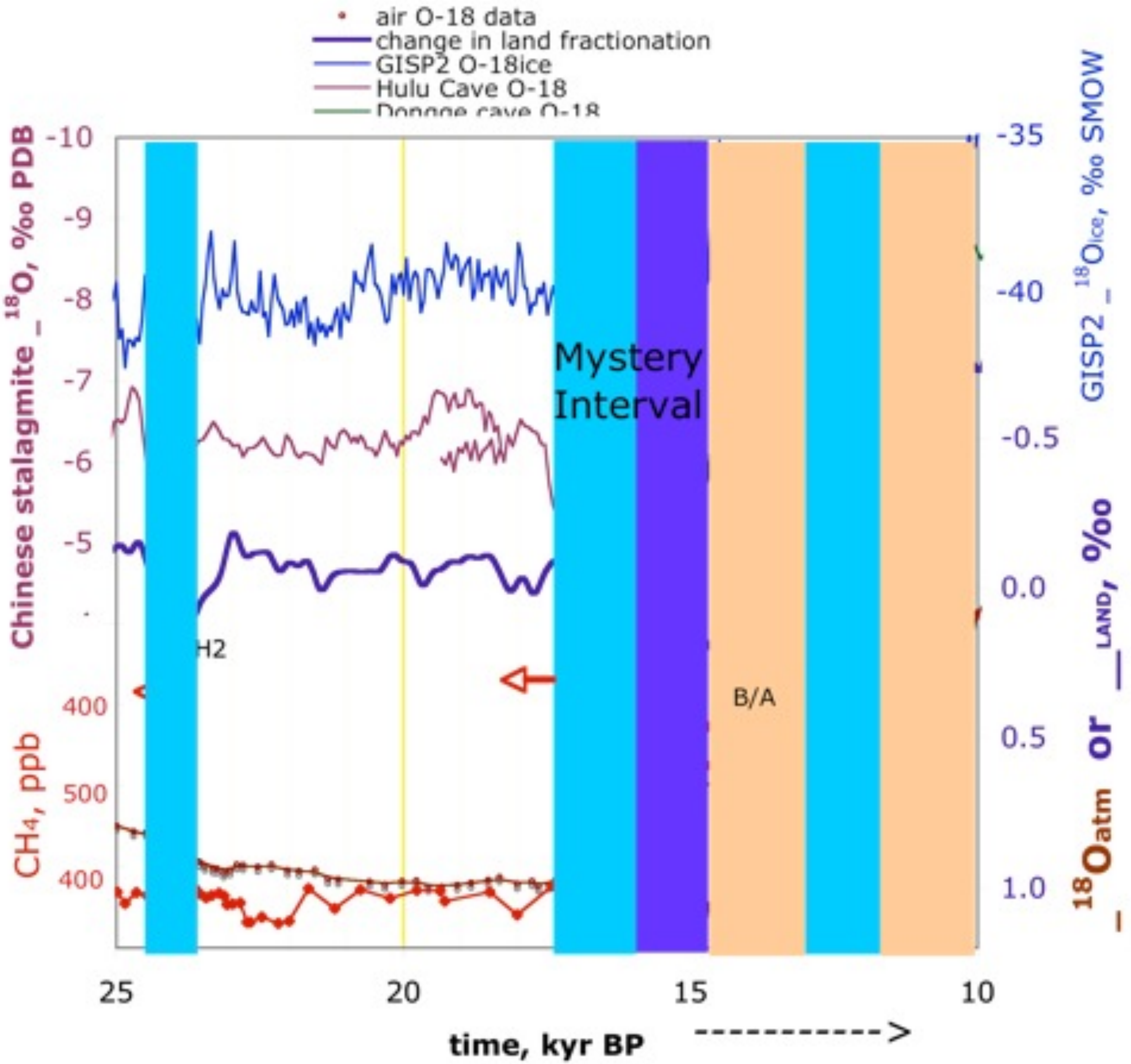
How does a melting ice sheet suppress the Asian monsoon?
Cheng et al. (2009) hypothesis




WINTER
SEA ICE
COVER
NORTH ATL. DRIFT
GULF STREAM
NADW

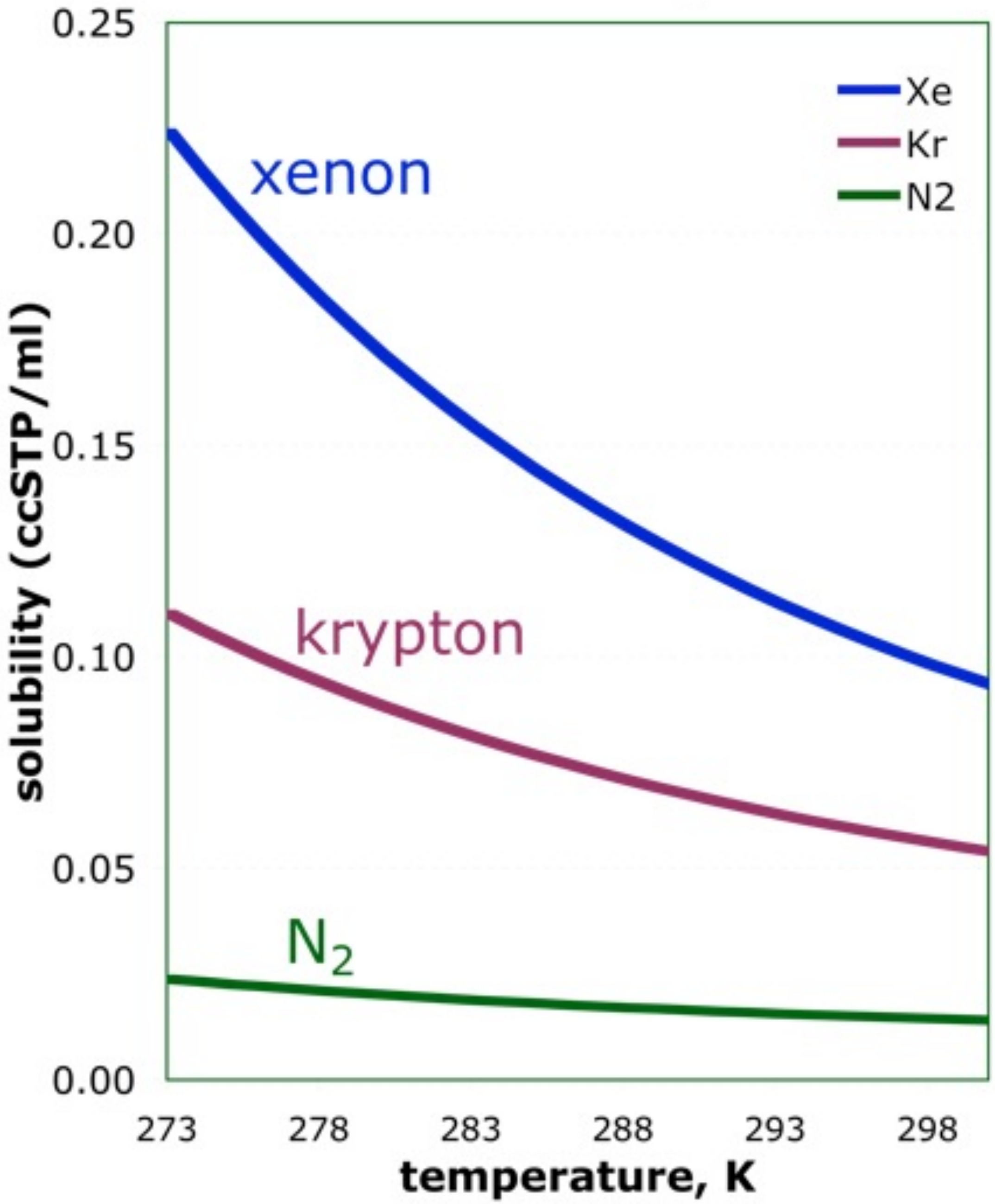


air O-18 data
change in land fractionation
GISP2 O-18ice
Hulu Cave O-18
Chinese stalagmite _18O, ‰ PDB
-10
-9
-8
-7
-6
-5
-35
-40
-0.5
0.0
0.5
1.0
GISP2 _18Oice, ‰ SMOW
_18Oatm or __LAND, ‰
Mystery Interval
H2
B/A
25
20
15
10
time, kyr BP



air O-18 data
change in land fractionation
GISP2 O-18ice
Hulu Cave O-18
Chinese stalagmite _18O, ‰ PDB
-10
-9
-8
-7
-6
-5
GISP2 _18Oice, ‰ SMOW
-35
-40
-0.5
0.0
0.5
1.0
_18Oatm or __LAND, ‰
CH4, ppb
400
500
400
Mystery Interval
H2
B/A
25
20
15
10
time, kyr BP

Gas solubility is a function of temperature



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A method to measure Kr/N_2 ratios in air bubbles trapped in ice cores and its application in reconstructing past mean ocean temperature

Melissa A. Headly[1] and Jeffrey P. Severinghaus[1]

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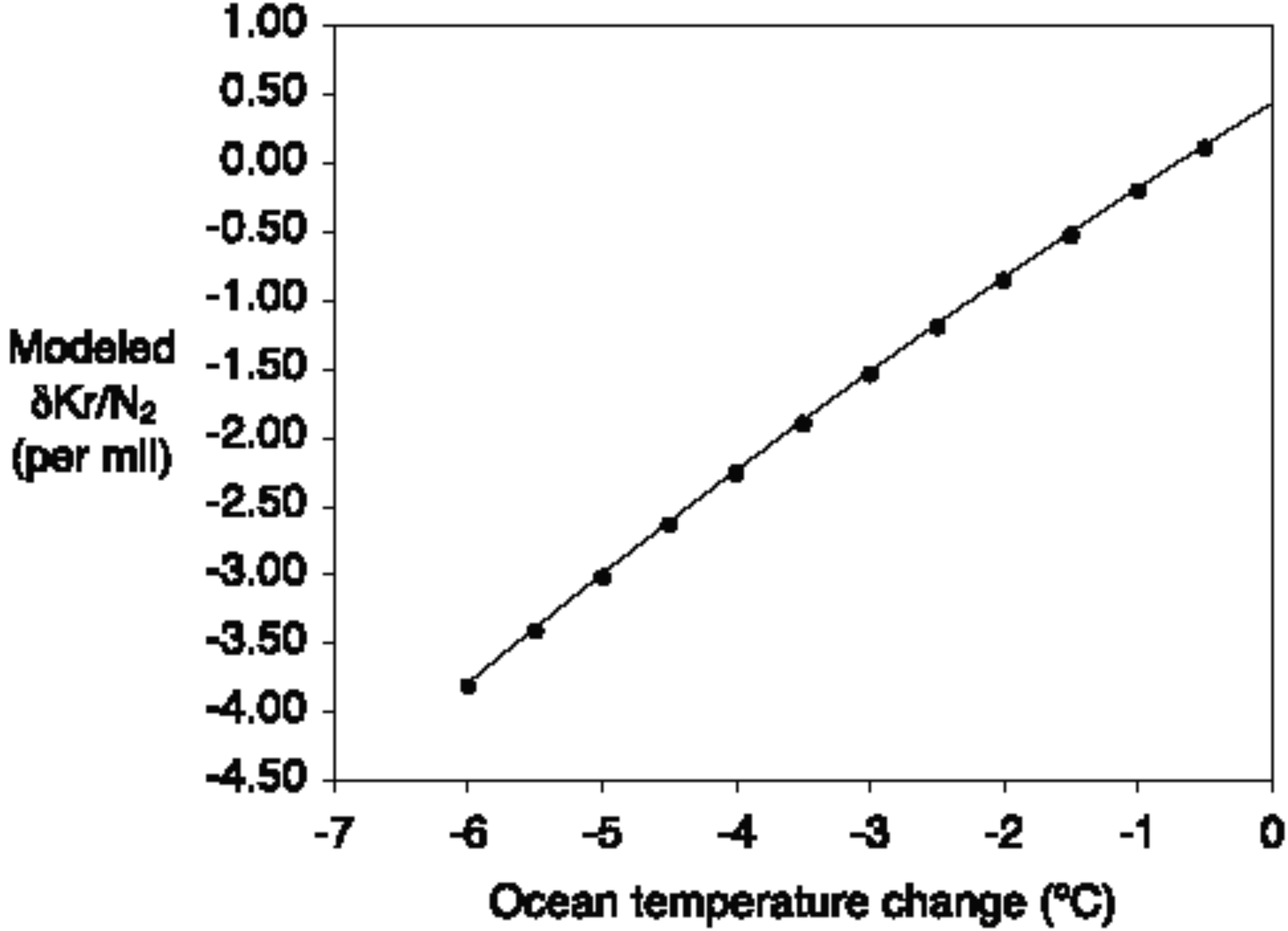
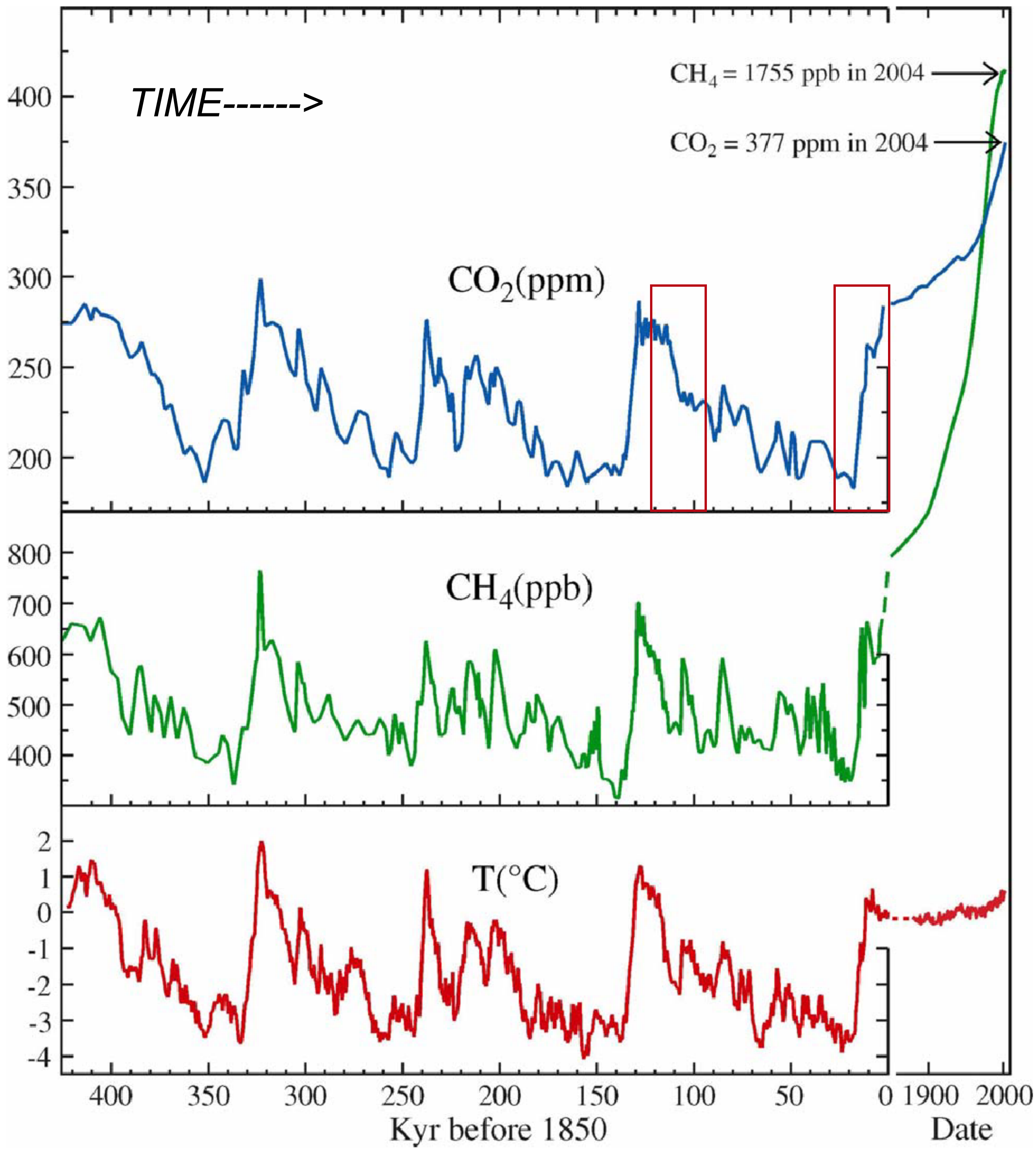
[1] We describe a new method for precise measurement of Kr/N_2 ratios in air bubbles trapped in ice cores and the first reconstruction of atmospheric Kr/N_2 during the last glacial maximum (LGM) ~20,000 years ago. After gravitational correction, the Kr/N_2 record in ice cores should represent the atmospheric ratio, which in turn should reflect past ocean temperature change due to the dependence of gas solubility on temperature.



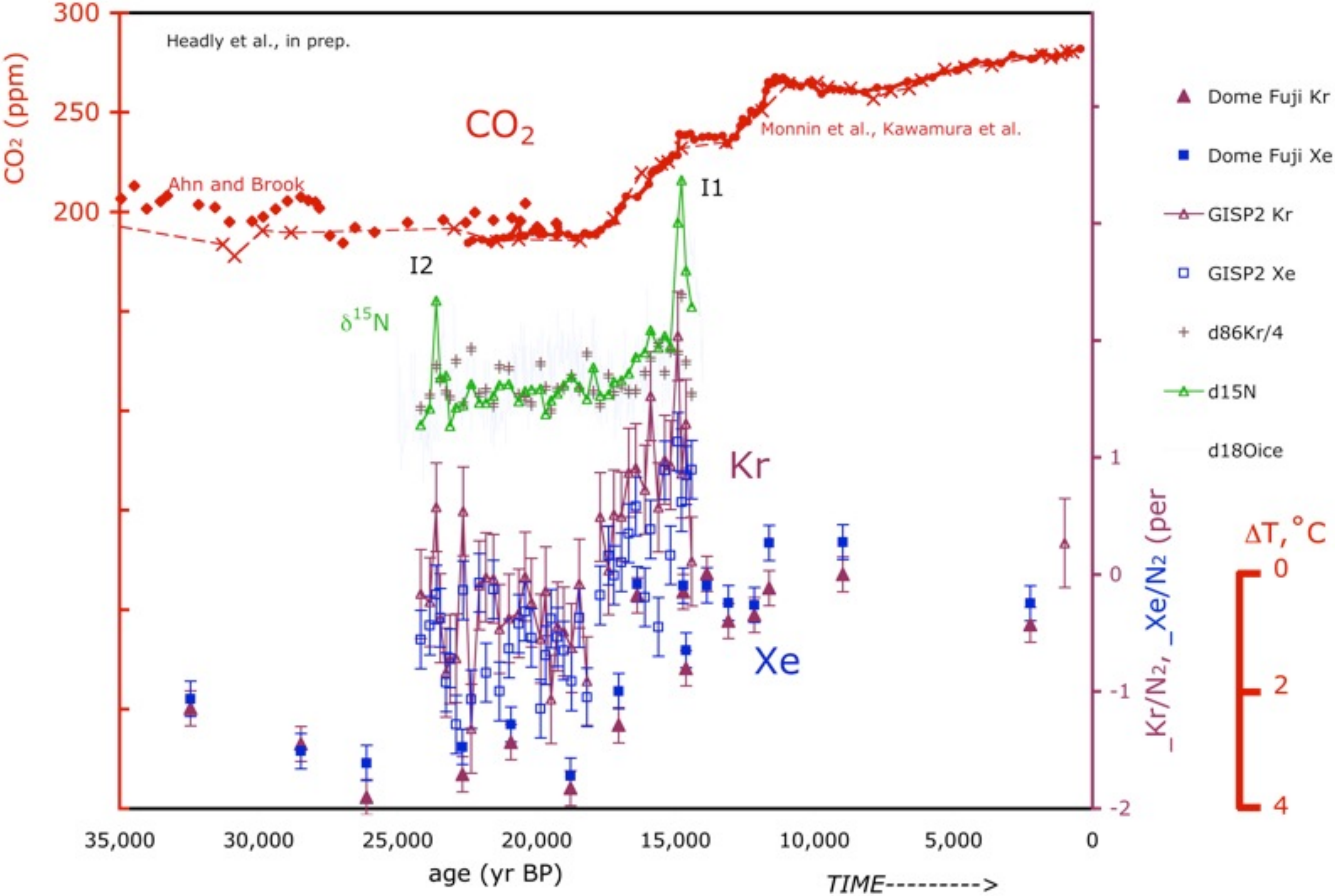
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
Modeled
δKr/N2
(per mil)
-7
-6
-5
-4
-3
-2
-1
0
Ocean temperature change (°C)

CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era)

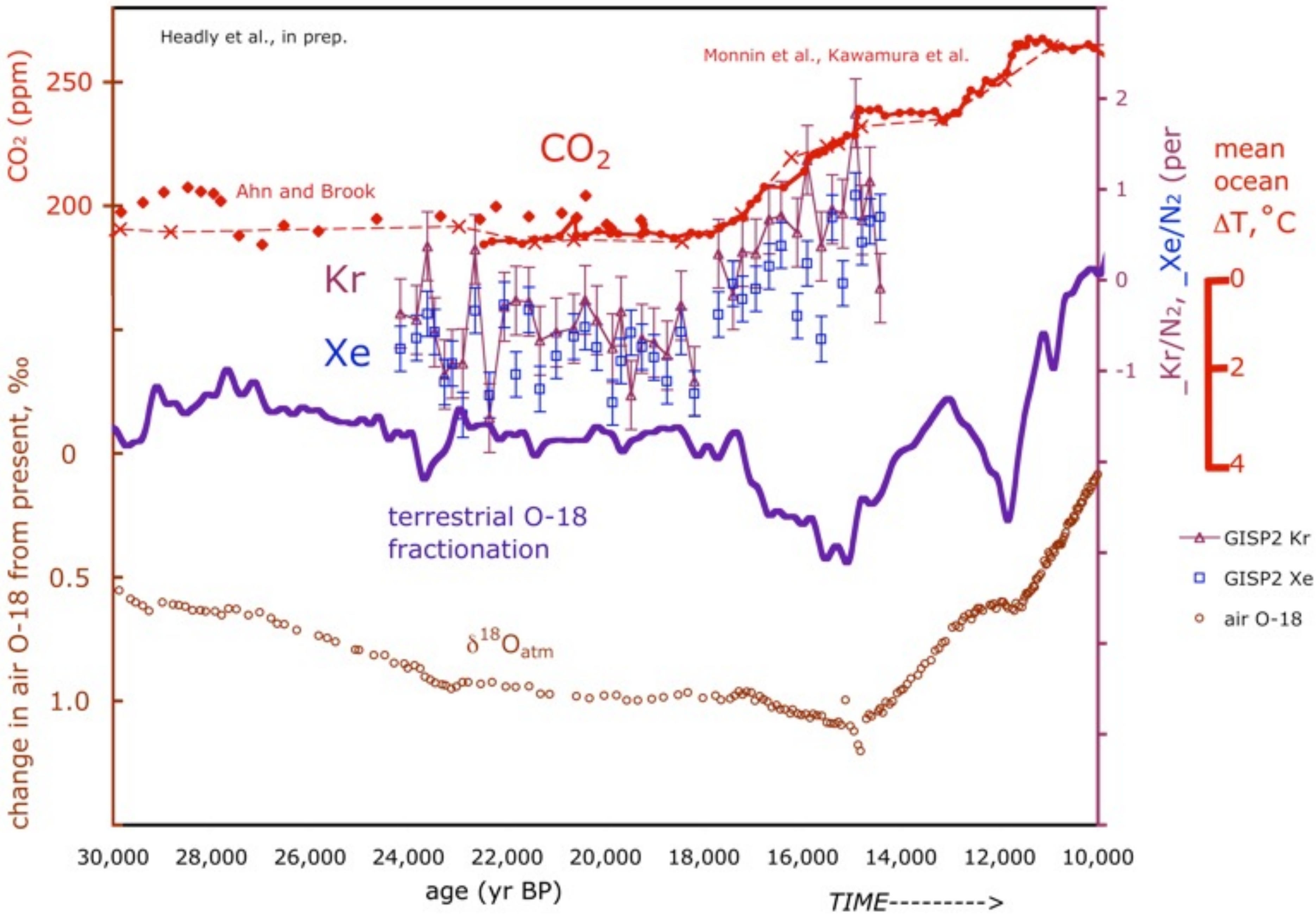


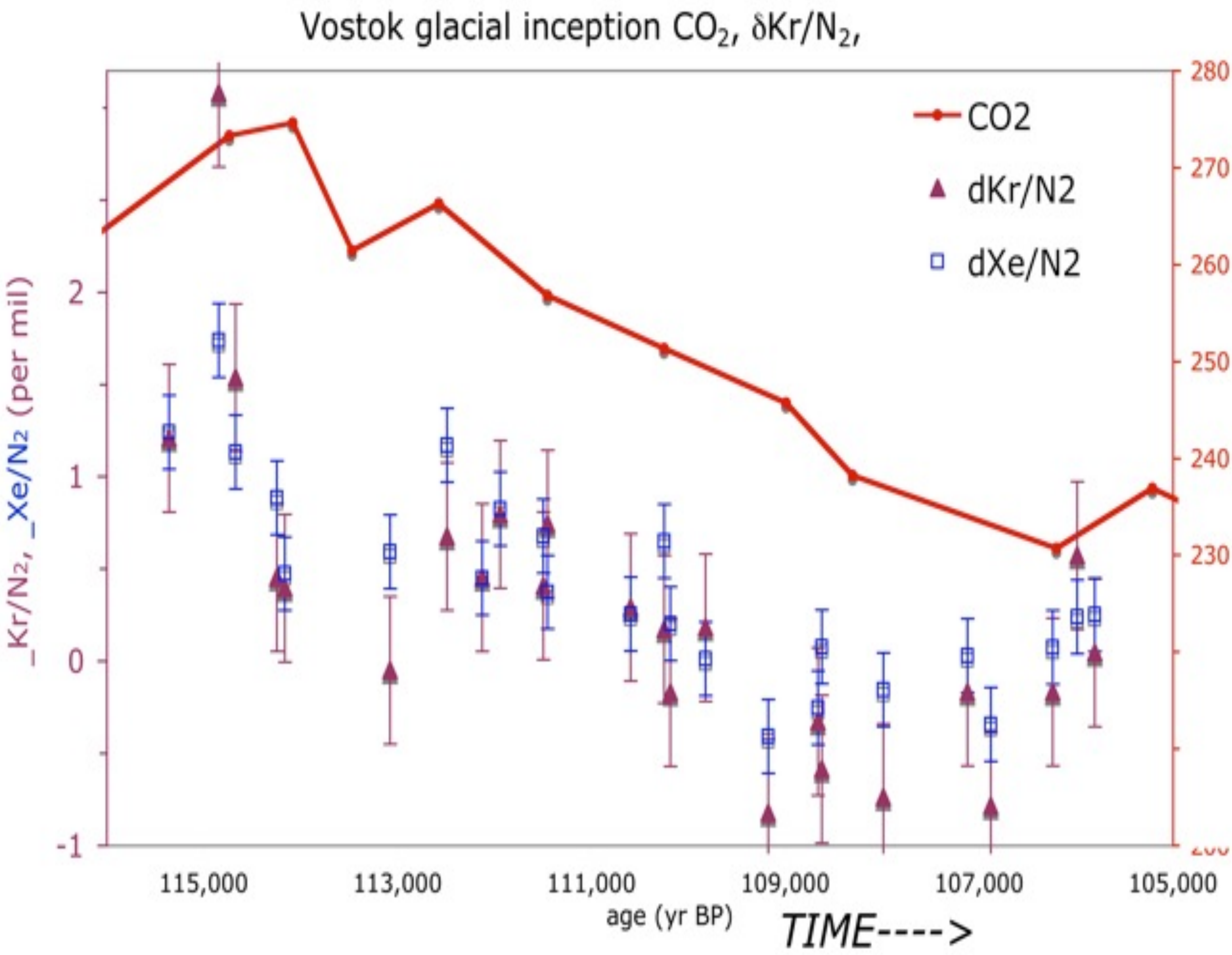
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

GISP2 and Dome Fuji $\delta Kr/N_2$, $\delta Xe/N_2$, Dome Fuji and Dome C

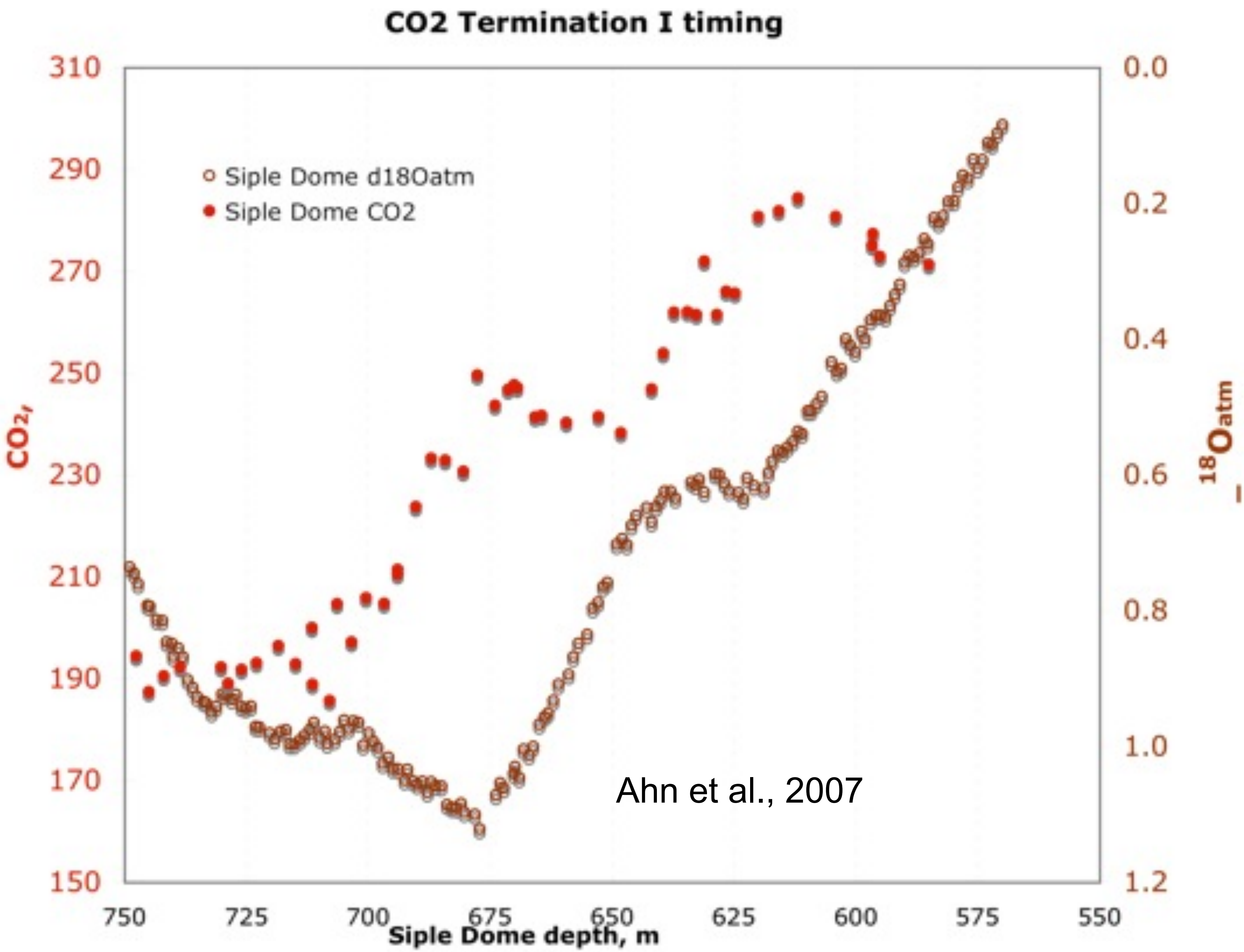


GISP2 and Dome Fuji $\delta Kr/N_2$, $\delta Xe/N_2$, Dome Fuji and Dome C





Vostok glacial inception CO_2, $\delta Kr/N_2$,
CO2
dKr/N2
dXe/N2
_Kr/N₂, _Xe/N₂ (per mil)
CO_2 (ppm)
2
1
0
-1
280
270
260
250
240
230
115,000
113,000
111,000
109,000
107,000
105,000
age (yr BP)
TIME---->



Ahn et al., 2007

Why would the deep ocean warm 2˚C when the bipolar see-saw was in its warm-south mode?

- volume of the deep ocean is dominated by Antarctic waters
- less deep water formation by sea-ice brine rejection
  with more open-ocean convection?

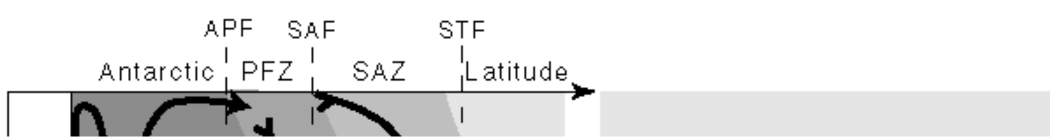
Reduction in Antarctic sea ice would also increase atmospheric CO2

Wind-Driven Upwelling in the Southern Ocean and the Deglacial Rise in Atmospheric CO_2

R. F. Anderson,[1,2]* S. Ali,[1,2] L. I. Bradtmiller,[1,2]† S. H. H. Nielsen,[3] M. Q. Fleisher,[1] B. E. Anderson,[1] L. H. Burckle[1]

Wind-driven upwelling in the ocean around Antarctica helps regulate the exchange of carbon dioxide (CO_2) between the deep sea and the atmosphere, as well as the supply of dissolved silicon to the euphotic zone of the Southern Ocean. Diatom productivity south of the Antarctic Polar Front and the subsequent burial of biogenic opal in underlying sediments are limited by this silicon supply. We show that opal burial rates, and thus upwelling, were enhanced during the termination of the last ice age in each sector of the Southern Ocean. In the record with the greatest temporal resolution, we find evidence for two intervals of enhanced upwelling concurrent with the two intervals of rising atmospheric CO_2 during deglaciation. These results directly link increased ventilation of deep water to the deglacial rise in atmospheric CO_2.

Scientists have long sought to unravel the combination of physical and biogeochemical processes responsible for the tight coupling between atmospheric CO_2 concentrations and Earth's climate that has persisted for at least the last 600,000 years (*1*), with the expectation that knowledge of the processes linking CO_2 and climate in the past will improve projections of future climate change under rising anthropogenic CO_2 levels. It is believed that no single mechanism can account for the full amplitude of past CO_2 variability (*2*, *3*). Although multiple processes operating synergistically may be involved (*4*, *5*), there is general agreement that lower CO_2 upper ocean and atmosphere during deglaciation (*4*, *15*, *16*); and the precipitous drop during deglaciation in ^{14}C activity of dissolved inorganic carbon (DIC) in North Pacific intermediate waters, requiring injection of carbon from a reservoir long isolated from the atmosphere, such as the deep sea (*17*). However, until now there has been no direct evidence for a change in Southern Ocean circulation that could have altered substantially the partitioning of CO_2 between the atmosphere and the deep sea.



Biogenic opal as an upwelling proxy. Burial of biogenic opal, the microscopic tests of marine diatoms, provides a link to past changes in upwelling and ventilation of deep-water masses in the Southern Ocean. Diatoms live in the euphotic zone where they use dissolved silicic acid (H_4SiO_4) to form opal tests. The zone of maximum production of biogenic silica (opal) occurs just south of the Antarctic Polar Front (APF) (*18*, *19*), corresponding to the region of maximum supply of dissolved nutrients (including Si) to surface waters by upwelling of nutrient-rich deep-water masses (Fig. 1) (*20*).

Within the zone of maximum opal production, diatom growth throughout spring and summer typically depletes surface waters of dissolved Si supplied during the previous winter (*20*, *21*). Consequently, although the physiological status and growth rate of individual diatom cells may be limited by iron (*22*), the total amount of biogenic opal produced each year within this region is ultimately limited by the supply of dissolved Si (*18*–*20*). Therefore, past changes in the production and burial of opal within this region are tied directly, although not necessarily linearly, to the rate of upwelling.

Deglacial changes in upwelling. Three sediment cores (TN057-13PC, NBP9802-6PC, and E27-23PC; Fig. 2) with relatively high accumulation rates [10 to 20 cm/kyr (10^3 years)] were

Conclusions

Oxygen-18 of O2 confirms widespread low-latitude rainfall shifts during abrupt climate change

Oxygen-18 of O2 and methane have interesting differences - southern hemisphere sources of methane?

Kr and Xe suggest ~2 deg of mean ocean temperature warming between 18-15 ka, synchronous with CO2 rise. [We still need to refine the gravitational correction, though.]

Glacial inception also shows synchronous CO2, Kr, Xe.

Consistent with existing models of atmospheric CO2 control by deep stratification (Toggweiler, 1999) or Antarctic sea ice (Stephens and Keeling, 2000).

CO2, methane, southern tropical rain all start rising at 18 ka, when mean ocean warms 2˚C and Antarctica warms!

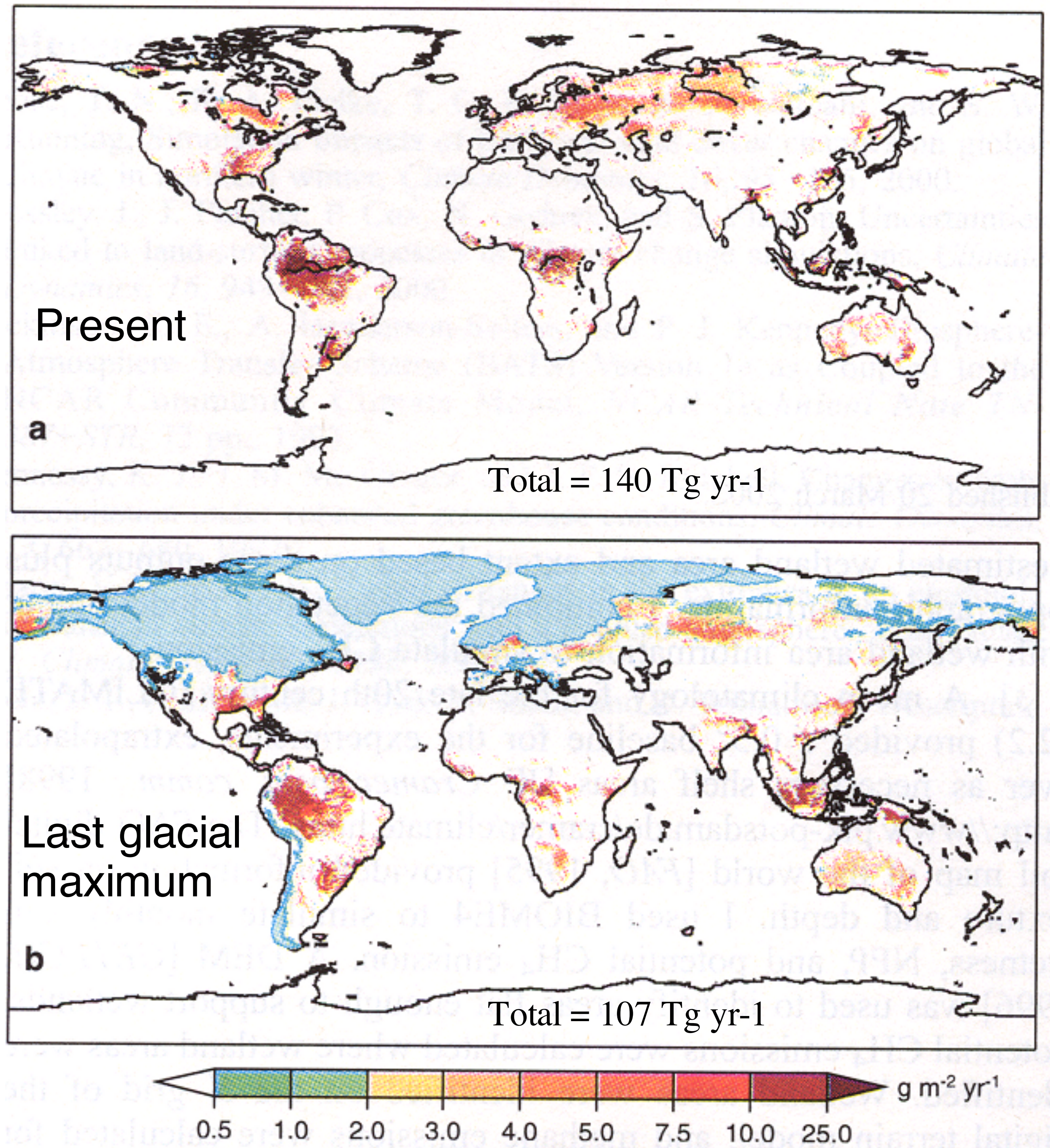
Does the bipolar seesaw play a key role in Terminations?

Wetlands: the dominant natural source of methane to the atmosphere

- Methanogenic bacteria produce methane in anaerobic conditions in wetlands -- the leading natural source of methane in the atmosphere today
- The end-of-Younger-Dryas event made climate both warmer and wetter
- Wetlands respond to warmer and wetter conditions with increased methane production
- A warmer, wetter climate should also increase the extent of wetlands

Modeled natural wetland methane emissions

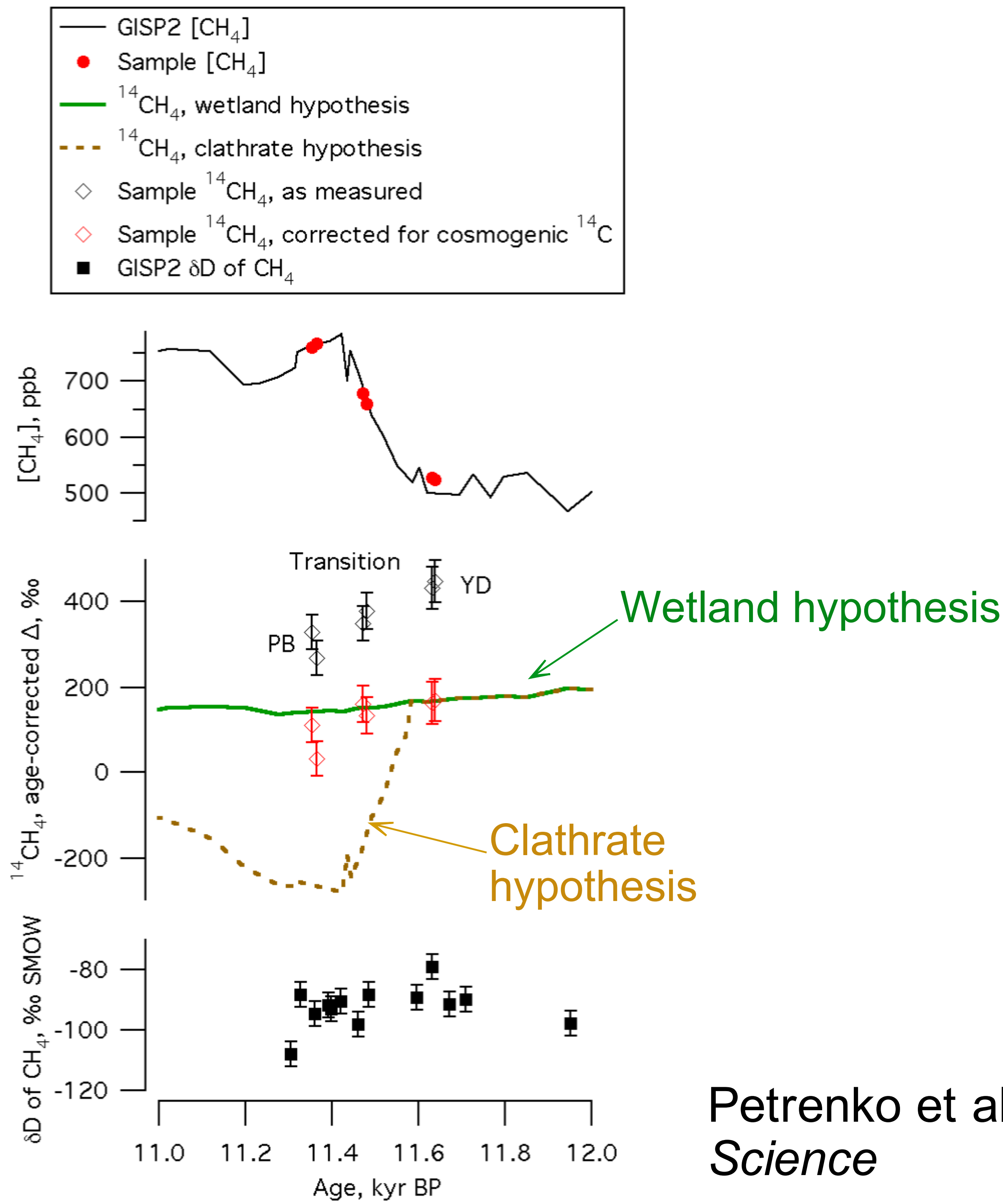
Kaplan, 2002 GRL



The Hydrate Hypothesis

- Methane hydrate is an ice-like compound composed of water and methane
- Widely distributed on continental shelves in the oceans and in permafrost
- Stable at low temperatures and high pressures
- As the oceans warmed at the end of the Younger Dryas event, large quantities of methane hydrate may have destabilized; some of the released methane may have made it into the atmosphere

Pakitsoq, West Greenland: The hunt for ancient methane C-14 samples



Petrenko et al., 2009 *Science*