Atmospheric krypton and xenon from ice cores suggest a two degree deep ocean warming from 18 ka to 16 ka

Jeffrey P. Severinghaus

Scripps Institution of Oceanography, La Jolla, USA

Kenji Kawamura

National Institute for Polar Research, Tokyo, Japan

Argonne National Lab, Physics Division

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Outline

1. Motivation
2. Expected Kr/N_2 and Xe/N_2 change
3. Measurements
4. Gravitational and thermal correction
5. Potential complications: Firn air disequilibrium, melt layers, gas loss?
6. Summary

Motivation

Earth system will respond to human forcing.

"FEEDBACKS"

How?

How much?

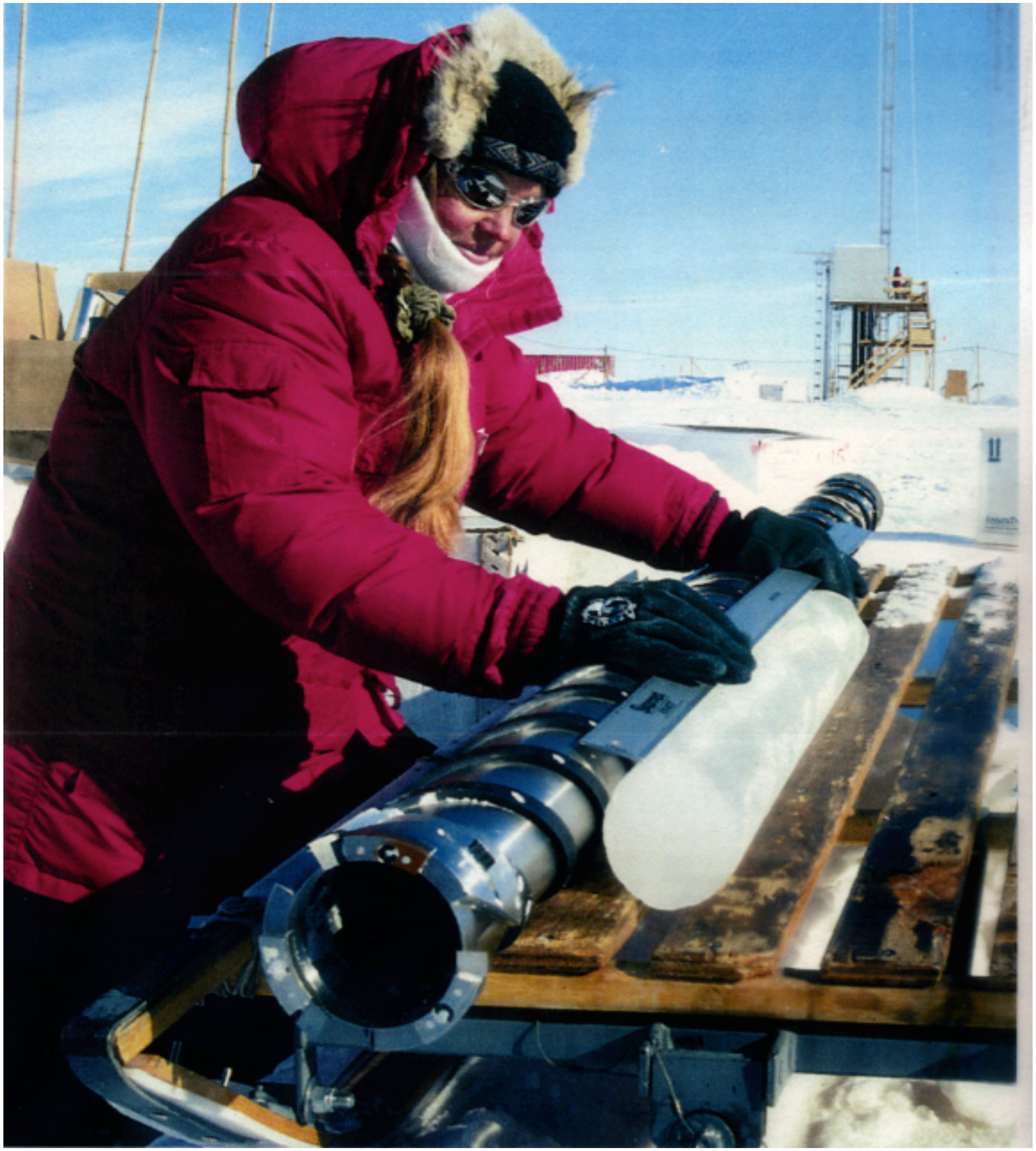
Study of past climate can help to shed light.

Problems:

Ocean temperature records uncertain: benthic ^{18}O ambiguity

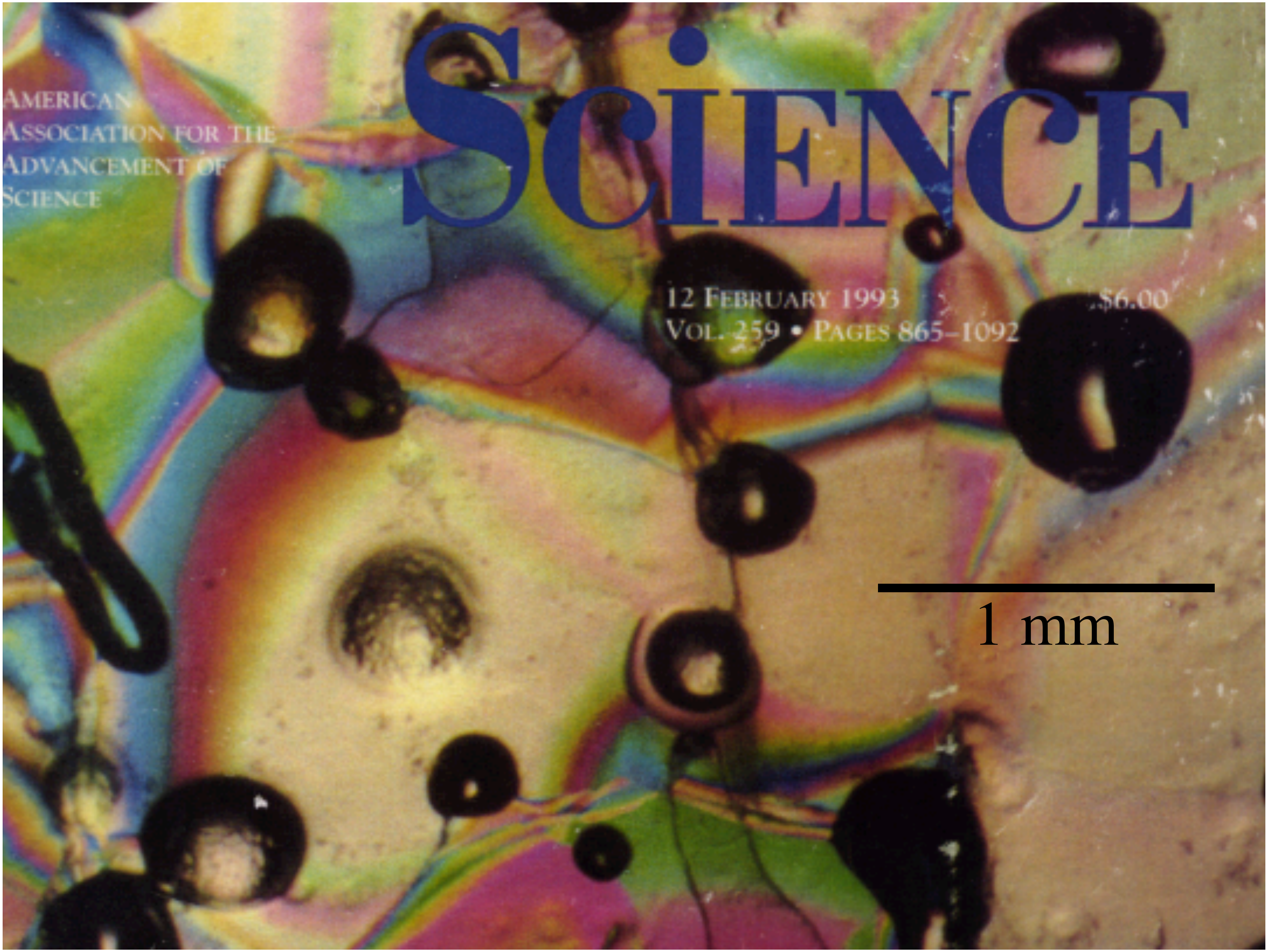
Spatial heterogeneity of ocean

Timing of ocean temperature change vs. greenhouse gases uncertain



Polar ice cores:

- Dated by counting annual layers (up to ~40k)
- Preserve past atmospheres in air bubbles in the ice!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Science
12 February 1993
$6.00
Vol. 259 • Pages 865–1092
1 mm

Trapped gases reveal a cornucopia of information about the Earth's feedback response to perturbation:

(a partial list….)

Climate forcing via greenhouse effect: CO_2, CH_4, N_2O

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

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

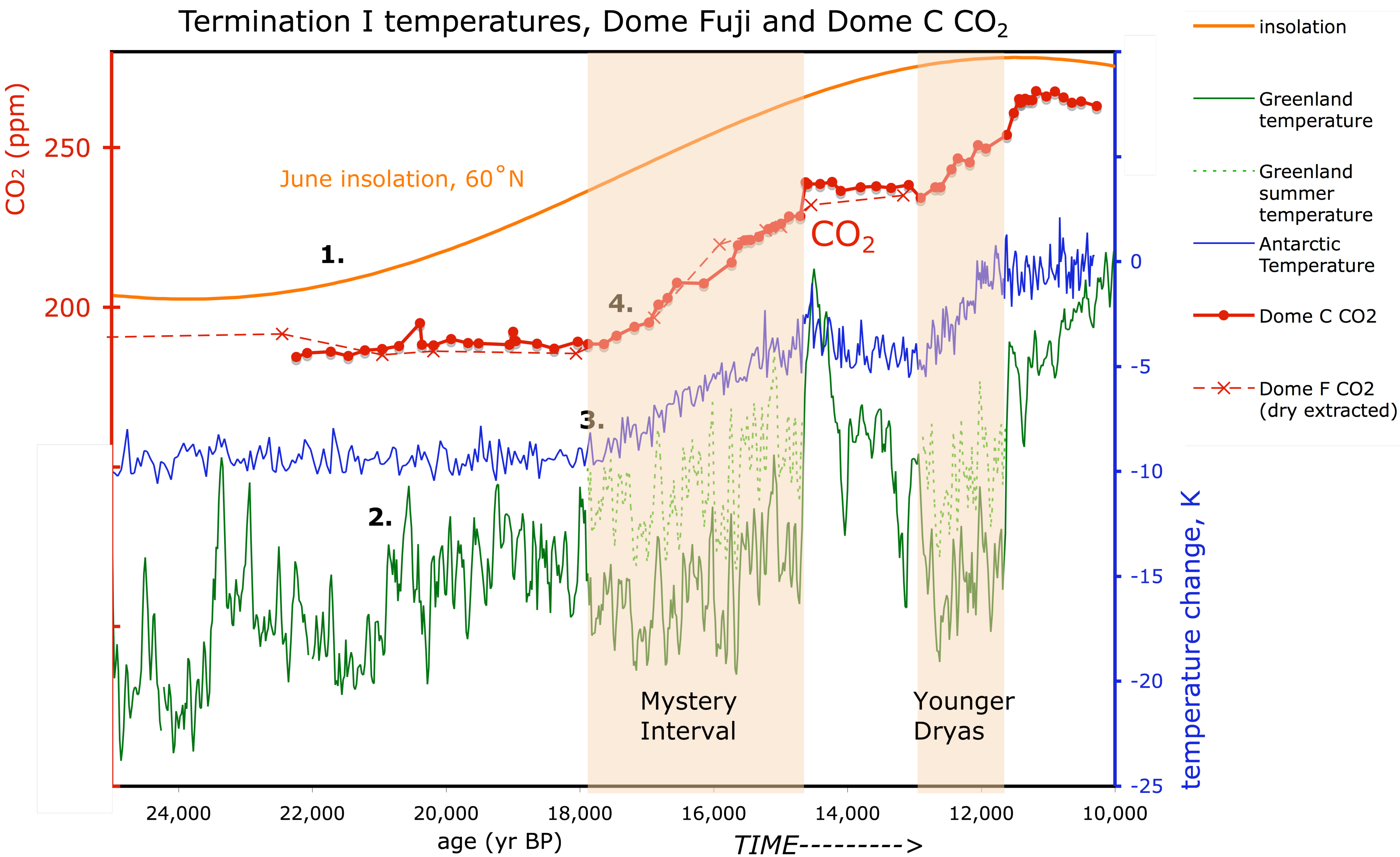
Asian monsoon strength: $^{18}O/^{16}O$ of O_2

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

Synchronization of ice cores: CH_4, $^{18}O/^{16}O$ of O_2

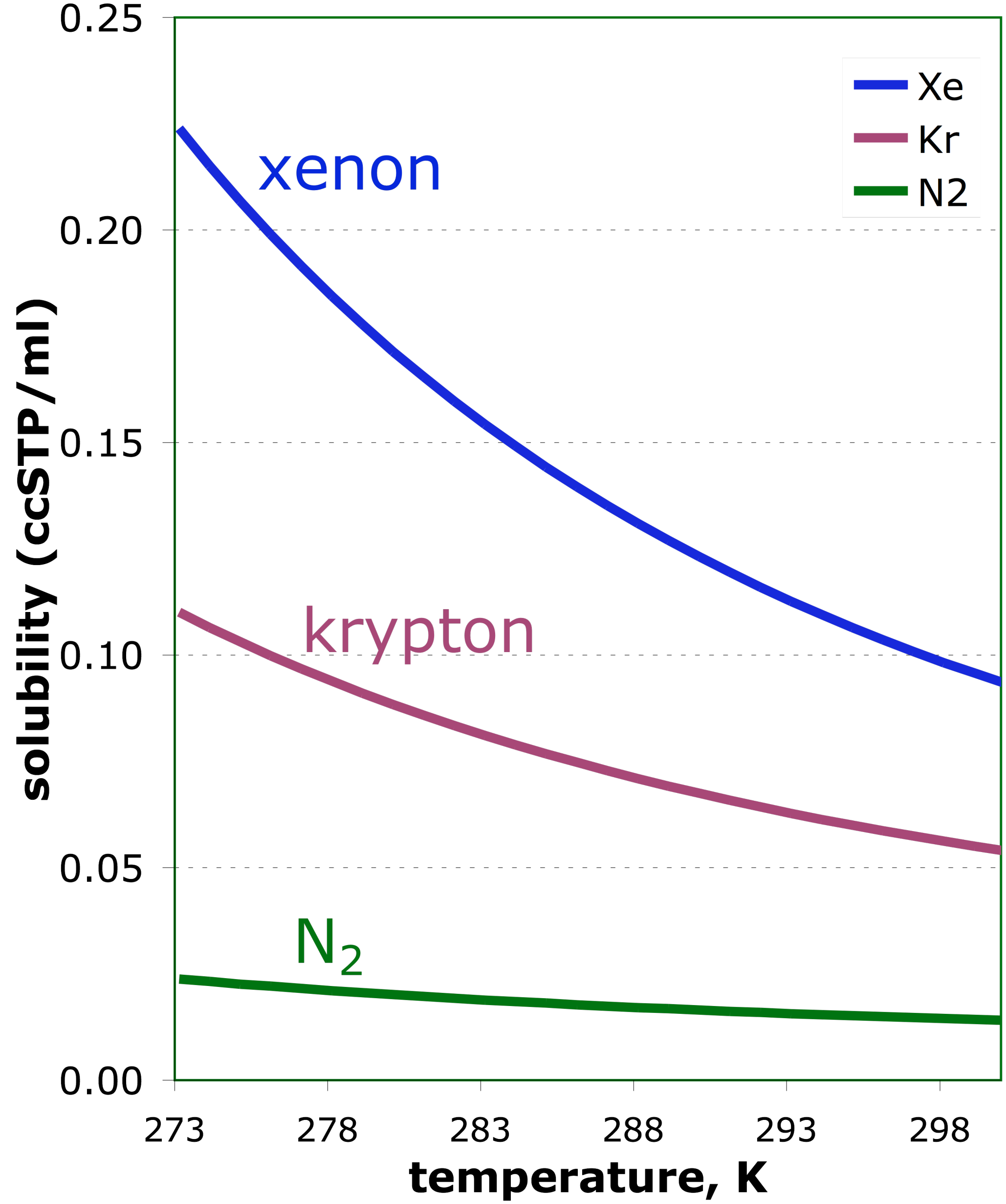
? Mean ocean temperature: Kr/N_2, Xe/N_2 ?

MOTIVATION: WHY DID CO_2 CHANGE WITH ICE AGE?



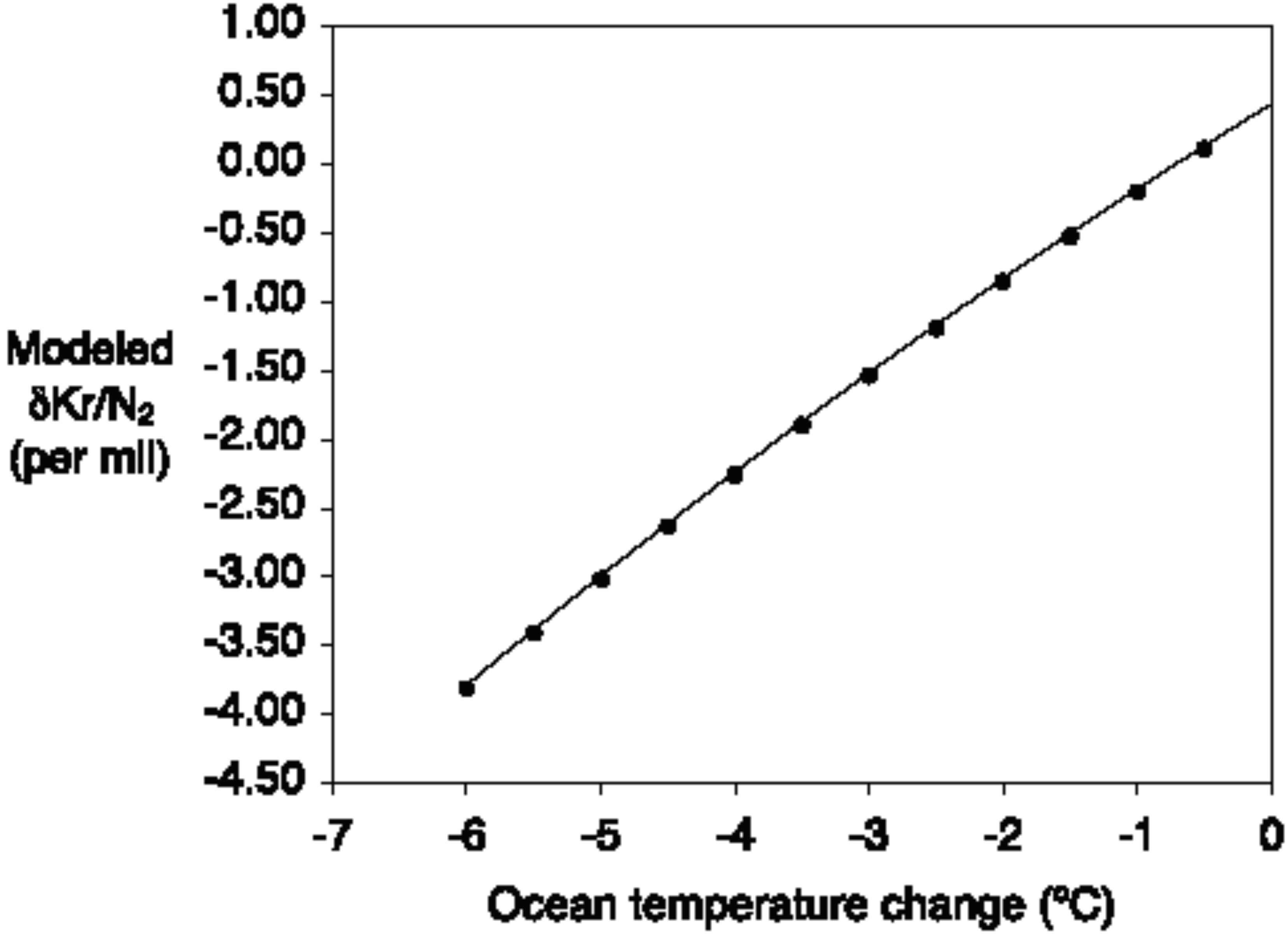
2. Expected Kr/N_2 and Xe/N_2 at LGM: simple model

Gas solubility is a function of temperature

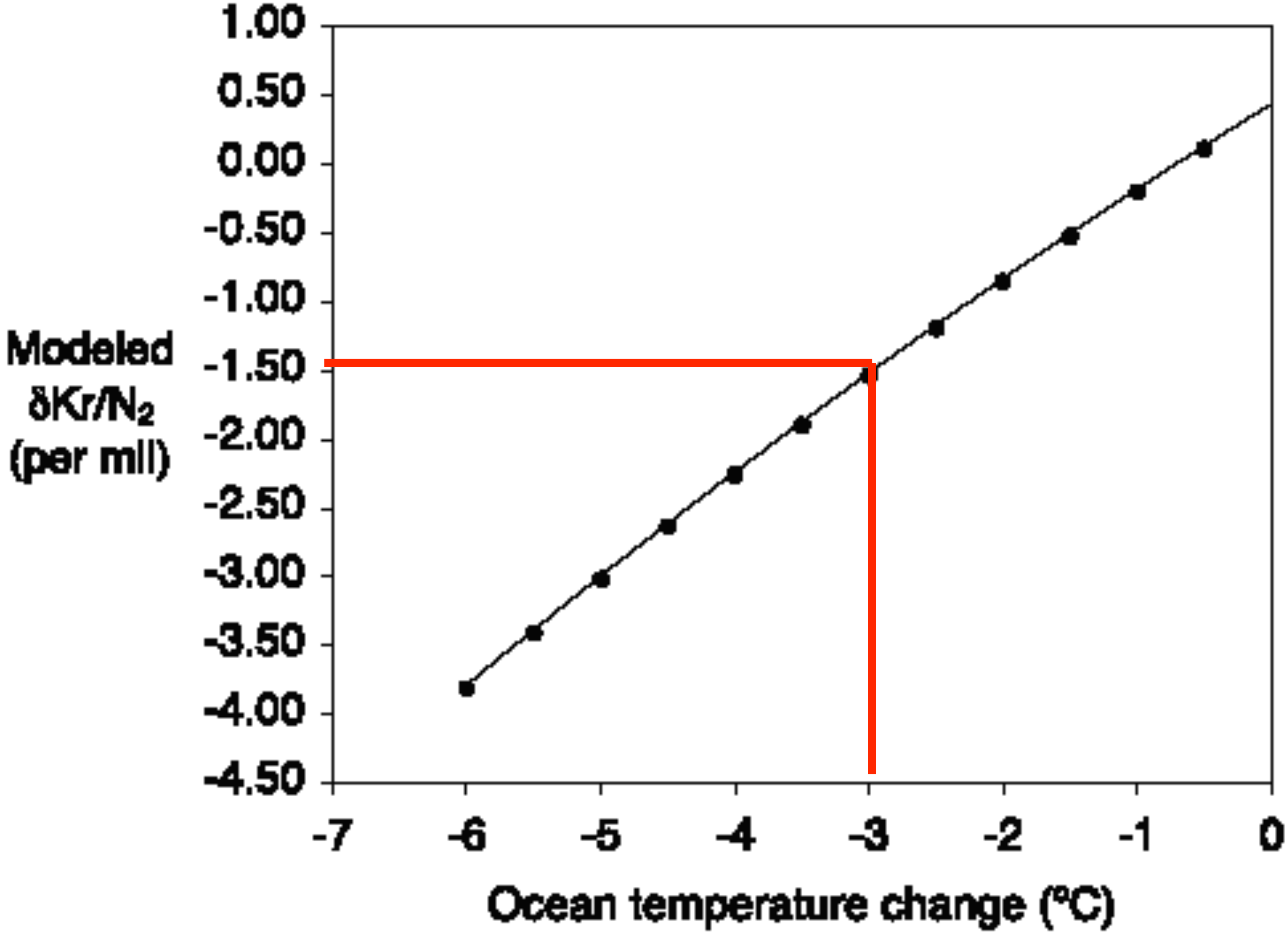


Model:

Includes	Levitus T, S spatial distribution
	120 m lower sea level
	3% smaller ocean volume
	3% increase in salinity ("salting-out")
	1.6% increase in sea level pressure
	Uniformly applied temperature change
Neglects	possible dissolved gas disequilibrium
	lower density of ice sheet vs. water
	high-altitude ice displaces fewer air molecules
	variations in salinity structure of ocean
	biogeochemical changes in N_2 inventory



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)



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)

3. Measurements

Typical measurement conditions and precisions

Gas	Sample size (mlSTP air)	Resistors (Ω)	Beam current (nA)	Integration time (s)
$\delta^{29}N_2/^{28}N_2$	2	3e8 / 3e10	13 / 0.1	16
$\delta^{40}Ar/^{36}Ar$	50	3e8 / 1e11	20 / 0.07	16
$\delta^{86}Kr/^{82}Kr$	50	1e12 / 1e12	9e-4	16
$\delta^{84}Kr/^{36}Ar$	50	1e12 / 1e11	2e-3/ 0.07	16
$\delta^{132}Xe/^{36}Ar$	50	1e12 / 1e11	3e-4/ 0.07	16

Gas	Changeover cycles	1σ error (per mil)	Δm	error/Δm (per mil)
$\delta^{29}N_2/^{28}N_2$	90	0.002	1	0.002
$\delta^{40}Ar/^{36}Ar$	64	0.008	4	0.002
$\delta^{86}Kr/^{82}Kr$	96	0.016	4	0.004
$\delta^{84}Kr/^{36}Ar$	2	0.2	48	0.005
$\delta^{132}Xe/^{36}Ar$	2	0.4	96	0.005

4. Gravitational and thermal correction

Gravitational fractionation

(Dalton, 1826; Gibbs, 1928; Craig + Sowers, 1988)

$$\delta = [\ \exp(\Delta mgz/RT) - 1\ ]\ 10^3\ ‰$$

Δm	mass difference
g	gravitational accelleration
z	depth
R	gas constant
T	temperature, K

Example: $\Delta m = 1$, $z = 80$ m, $T = 230$ K

$\delta^{15}N = +0.4$ ‰

Thermal diffusion in gases

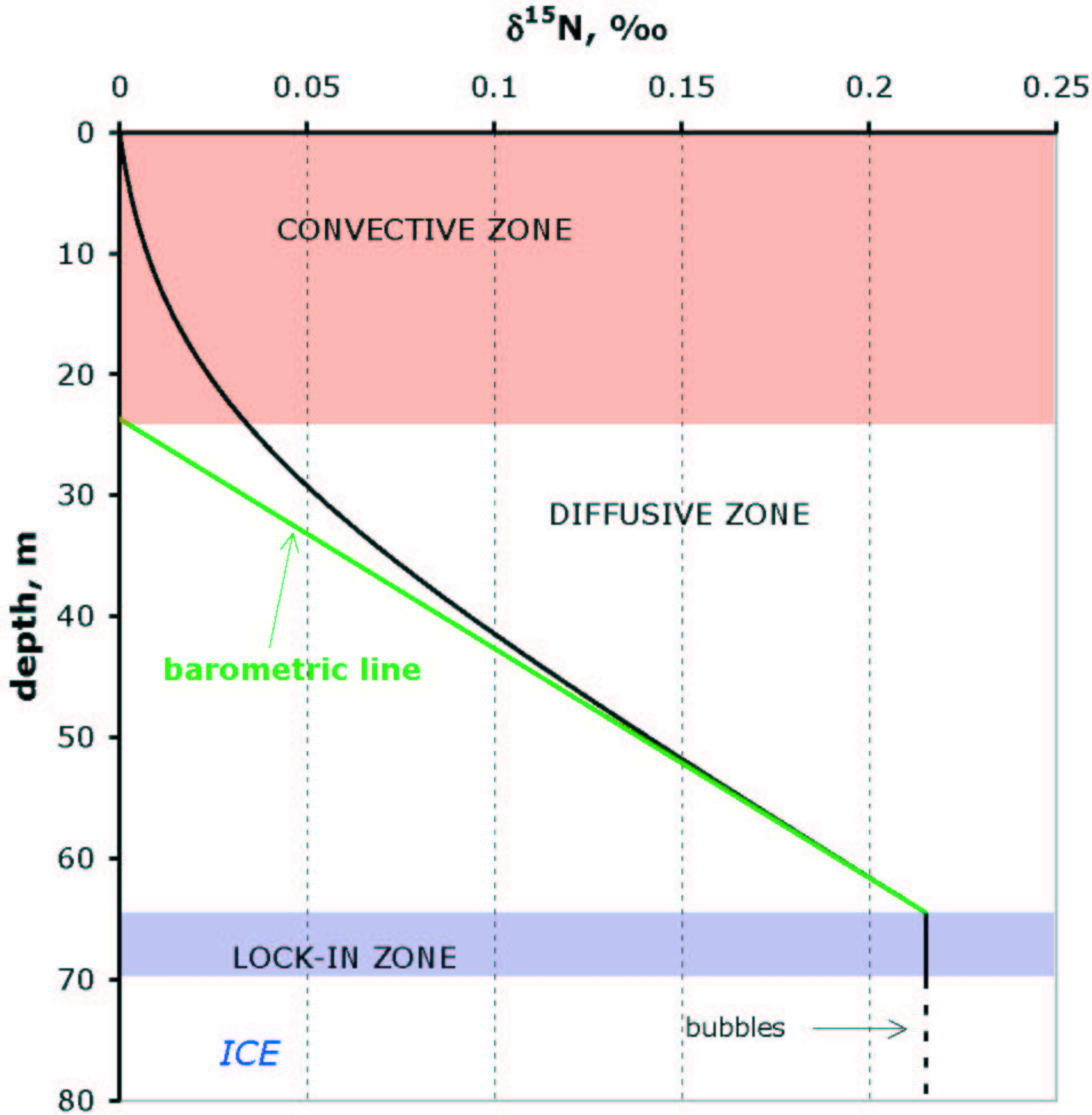
$$\delta = \Omega \, \Delta T$$

δ isotopic enrichment ($\delta^{15}N$)

Ω thermal diffusion sensitivity

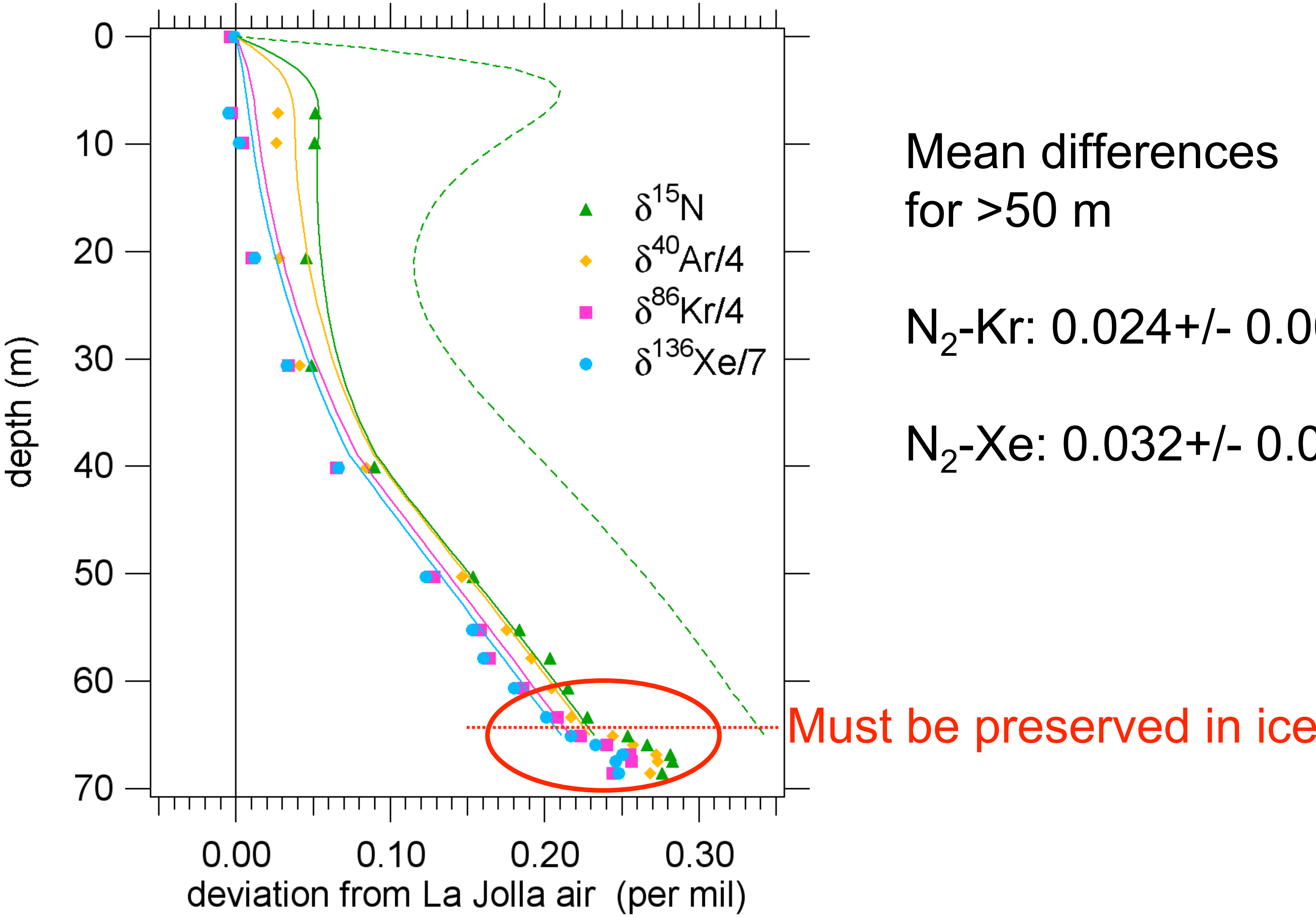
T temperature

5. Potential complications: Firn air disequilibrium, melt layers, gas loss?



δ15N, ‰
0
0.05
0.1
0.15
0.2
0.25
0
10
20
30
40
50
60
70
80
depth, m
CONVECTIVE ZONE
DIFFUSIVE ZONE
barometric line
LOCK-IN ZONE
bubbles
ICE

Zero-accumulation site: 23-m convective zone. Heavy noble gases are less fractionated



Mean differences for >50 m

N_2-Kr: 0.024+/- 0.005

N_2-Xe: 0.032+/- 0.005

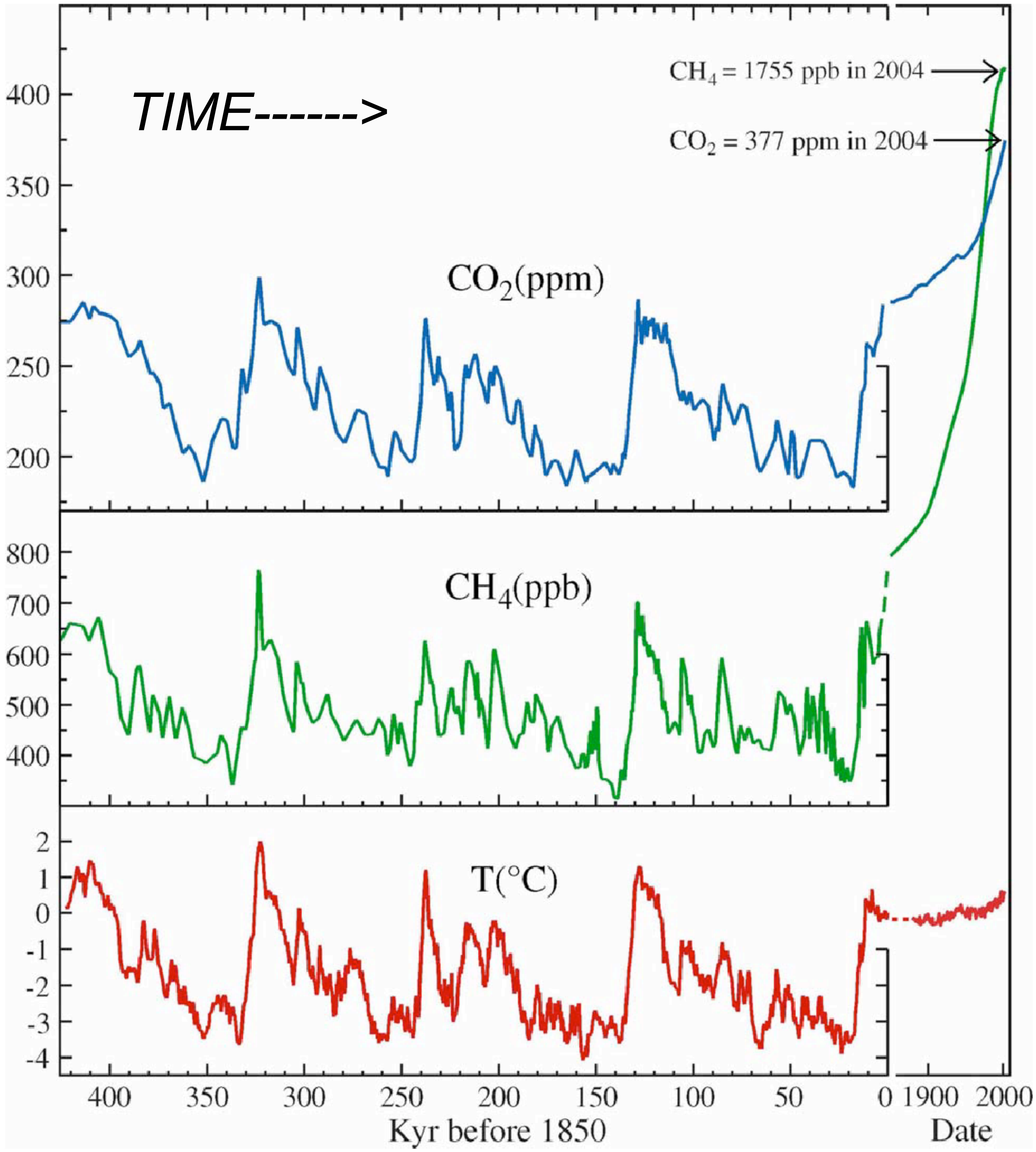
Cracks greatly aid air flow through firn!

- at least 6 m deep

-polygonal plan

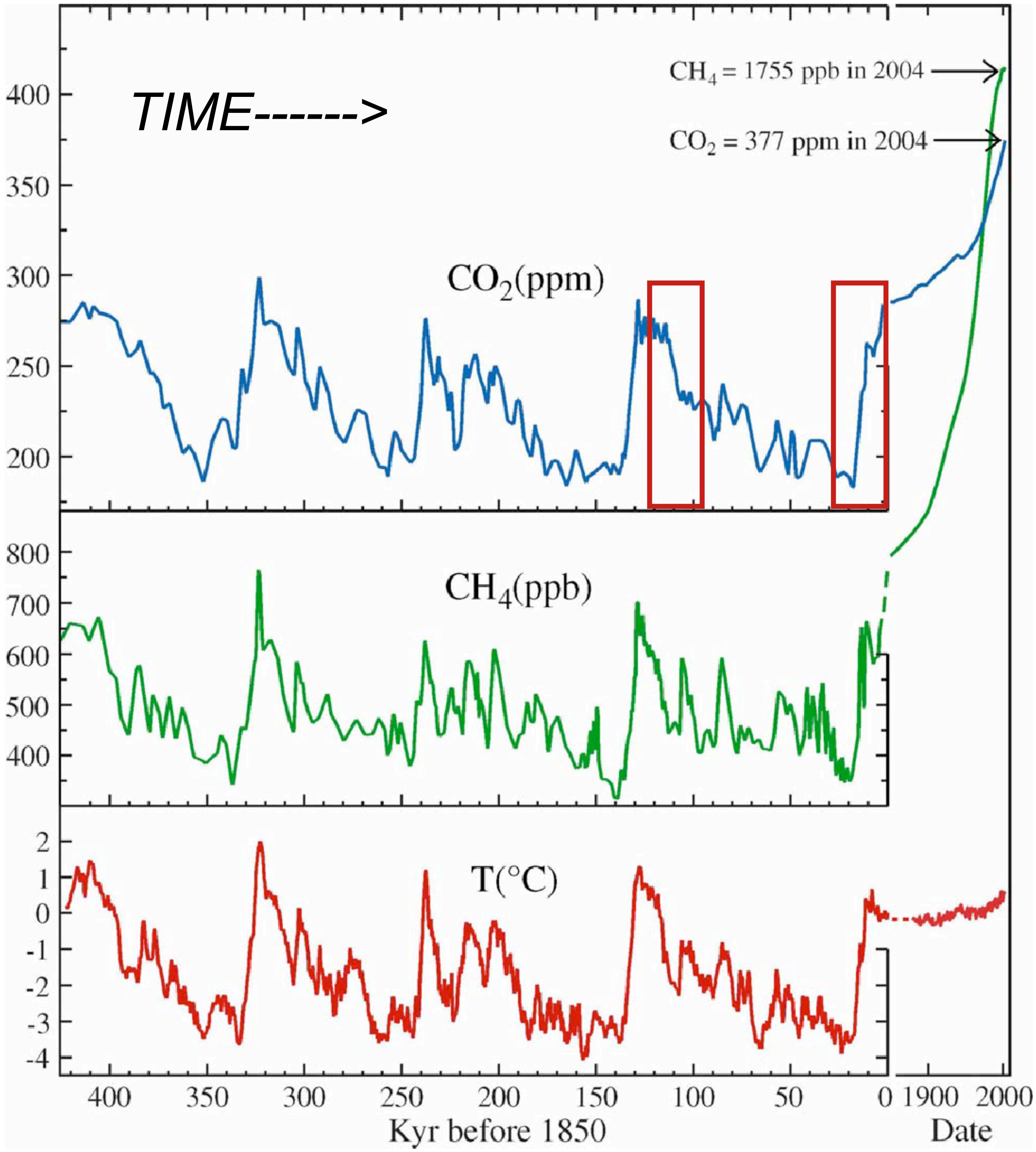
- formed by thermal contraction plus sublimation?

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



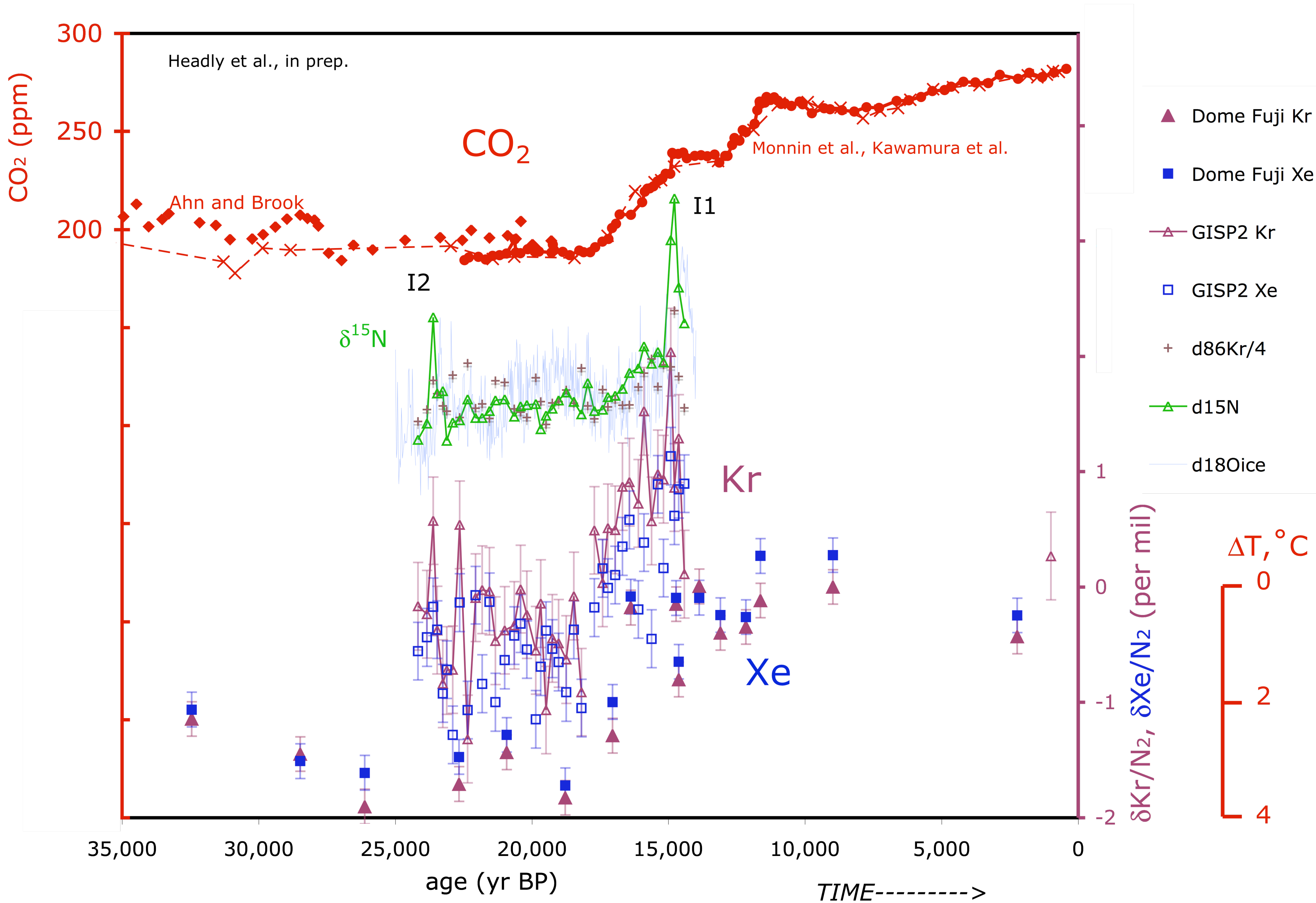
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

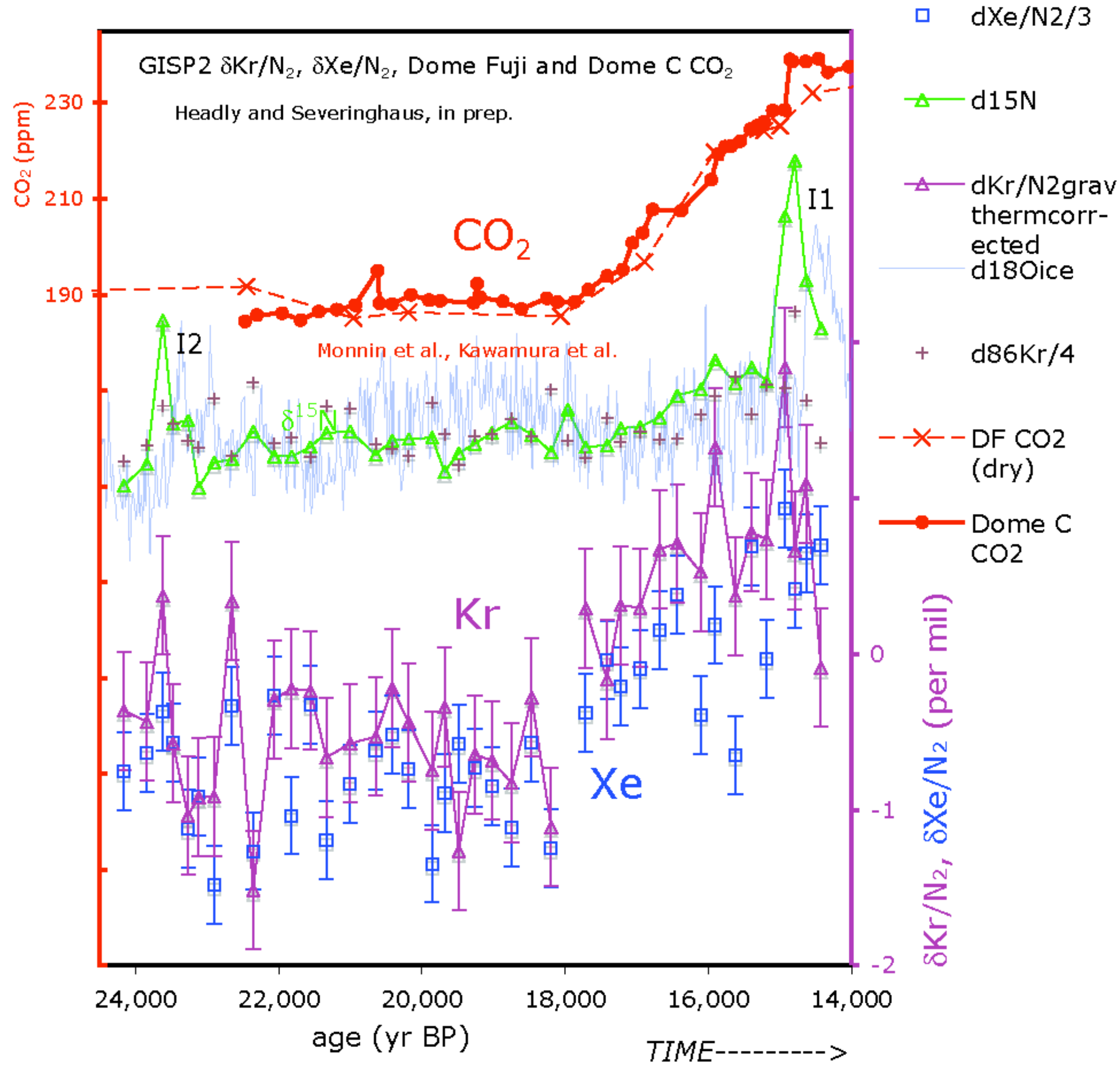
CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era)



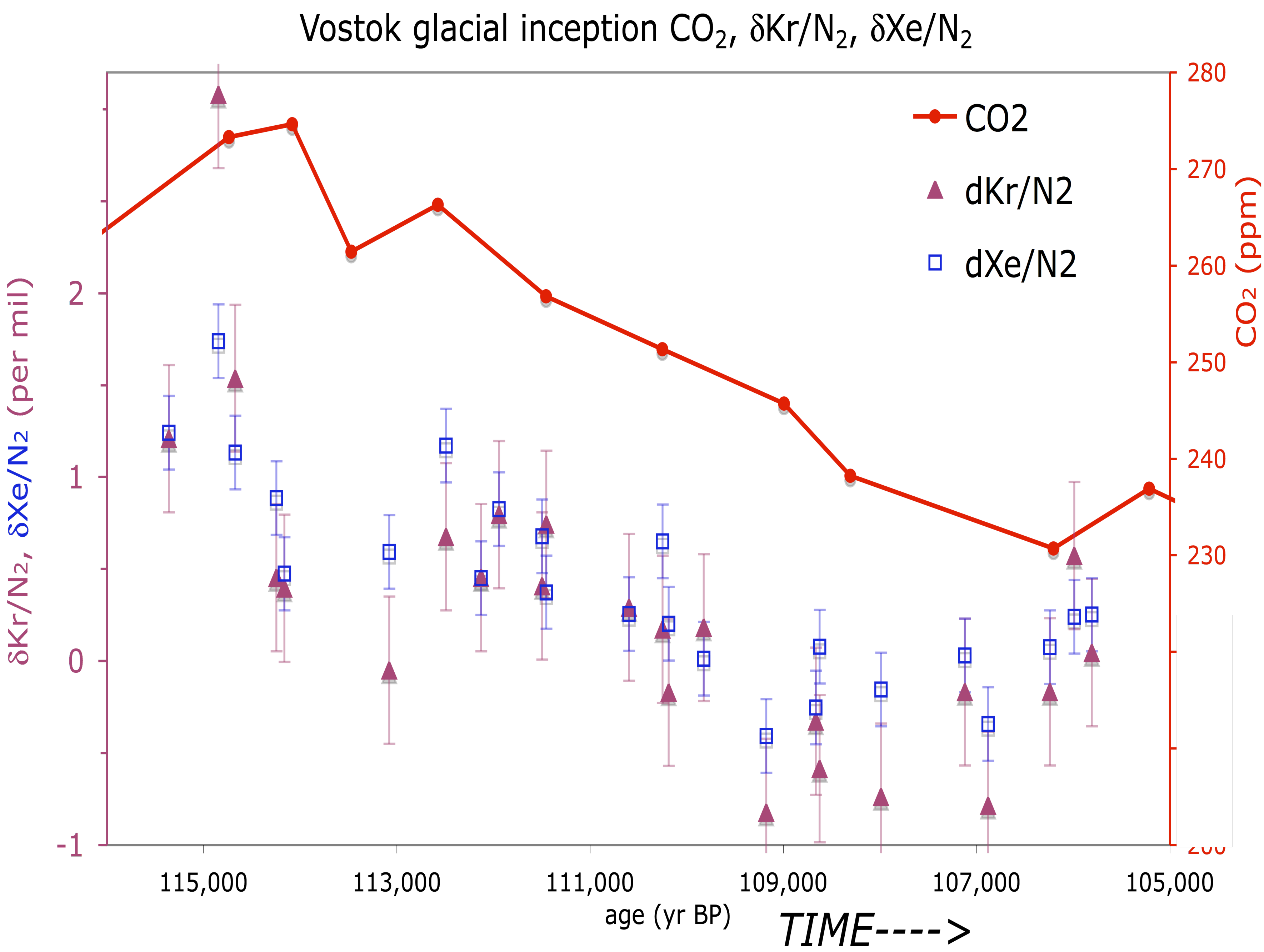
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

GISP2 and Dome Fuji δKr/N₂, δXe/N₂, Dome Fuji and Dome C





GISP2 δKr/N2, δXe/N2, Dome Fuji and Dome C CO2
Headly and Severinghaus, in prep.
CO2 (ppm)
230
210
190
CO2
I2
I1
Monnin et al., Kawamura et al.
δ15N
Kr
Xe
0
-1
-2
δKr/N2, δXe/N2 (per mil)
24,000
22,000
20,000
18,000
16,000
14,000
age (yr BP)
TIME--------->
dXe/N2/3
d15N
dKr/N2grav thermcorr-ected
d18Oice
d86Kr/4
DF CO2 (dry)
Dome C CO2


Vostok glacial inception CO_2, $\delta Kr/N_2$, $\delta Xe/N_2$
CO2
dKr/N2
dXe/N2
$\delta Kr/N_2$, $\delta Xe/N_2$ (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---->

Conclusions

Kr and Xe suggest ~2 deg of mean ocean temperature warming between 18-15 ka. [We still need to deal with the gas loss issue, though.]

Glacial inception also shows synchronous CO_2, Kr, Xe.

Consistent with existing models of atmospheric CO_2 control by deep stratification (Toggweiler, 1999) or Antarctic sea ice (Stephens and Keeling, 2000).