Ice core science

Past climate changes as seen from ice cores

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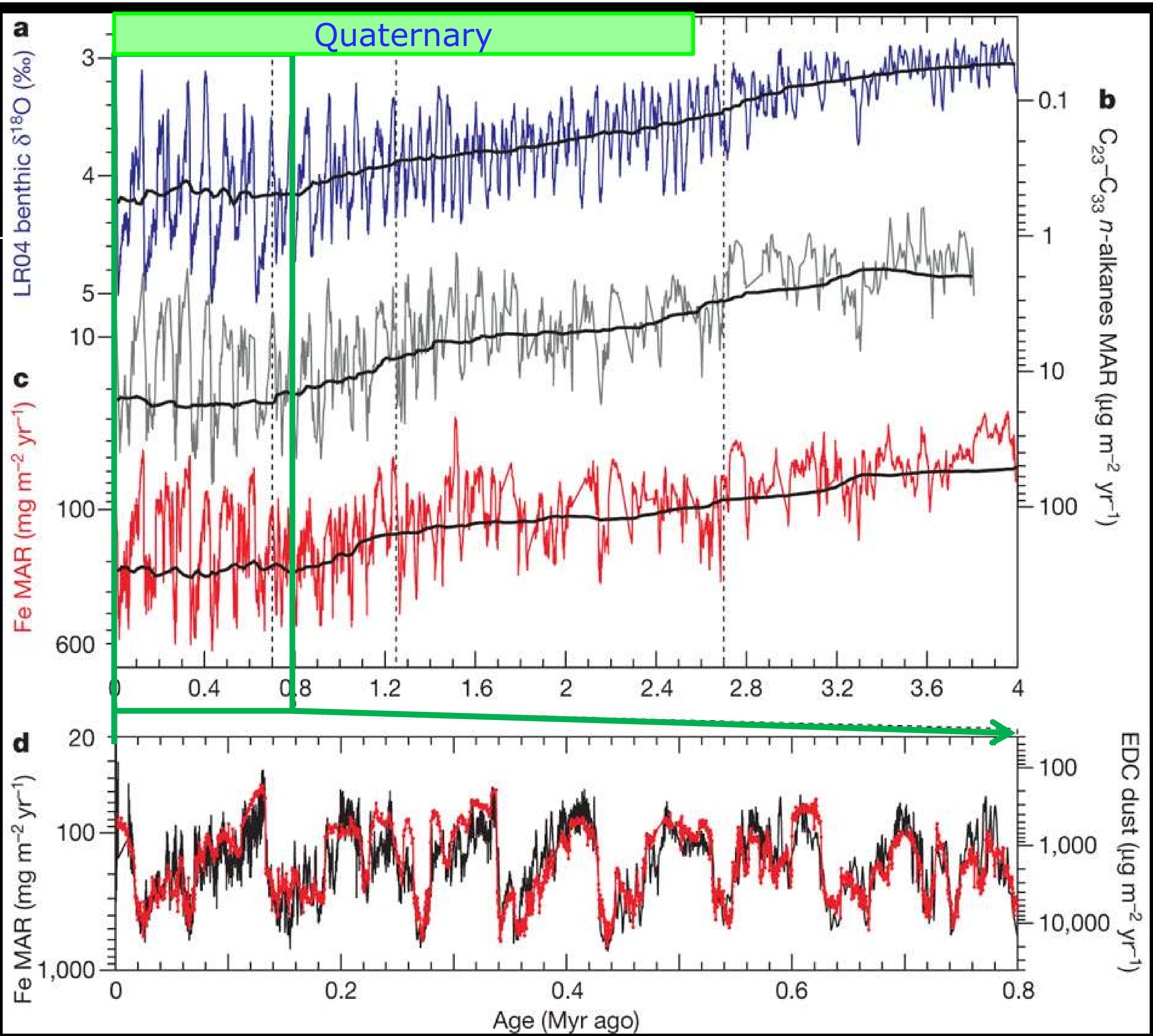
Climate from ice cores

- Long term climate change
- Abrupt climate variability
- Holocene and anthropocene

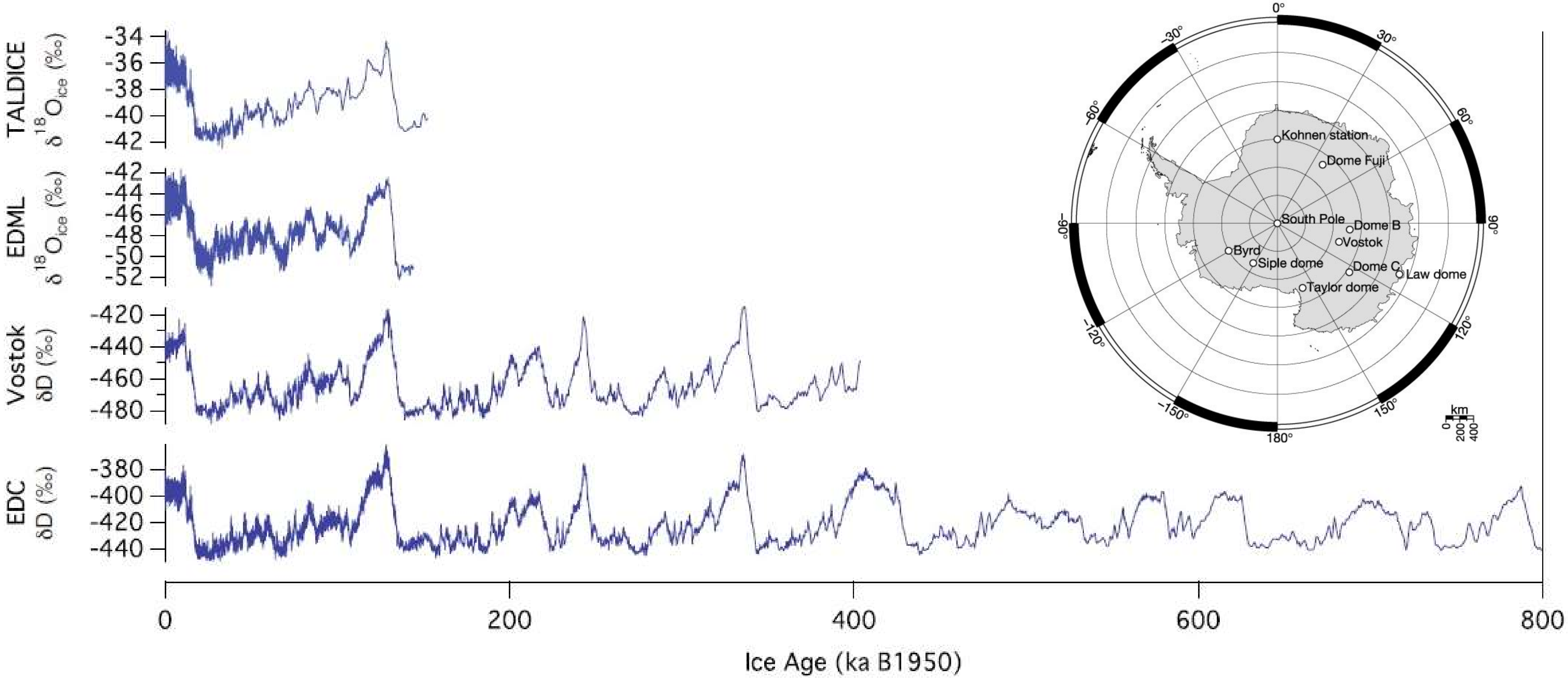
Long-term climate changes



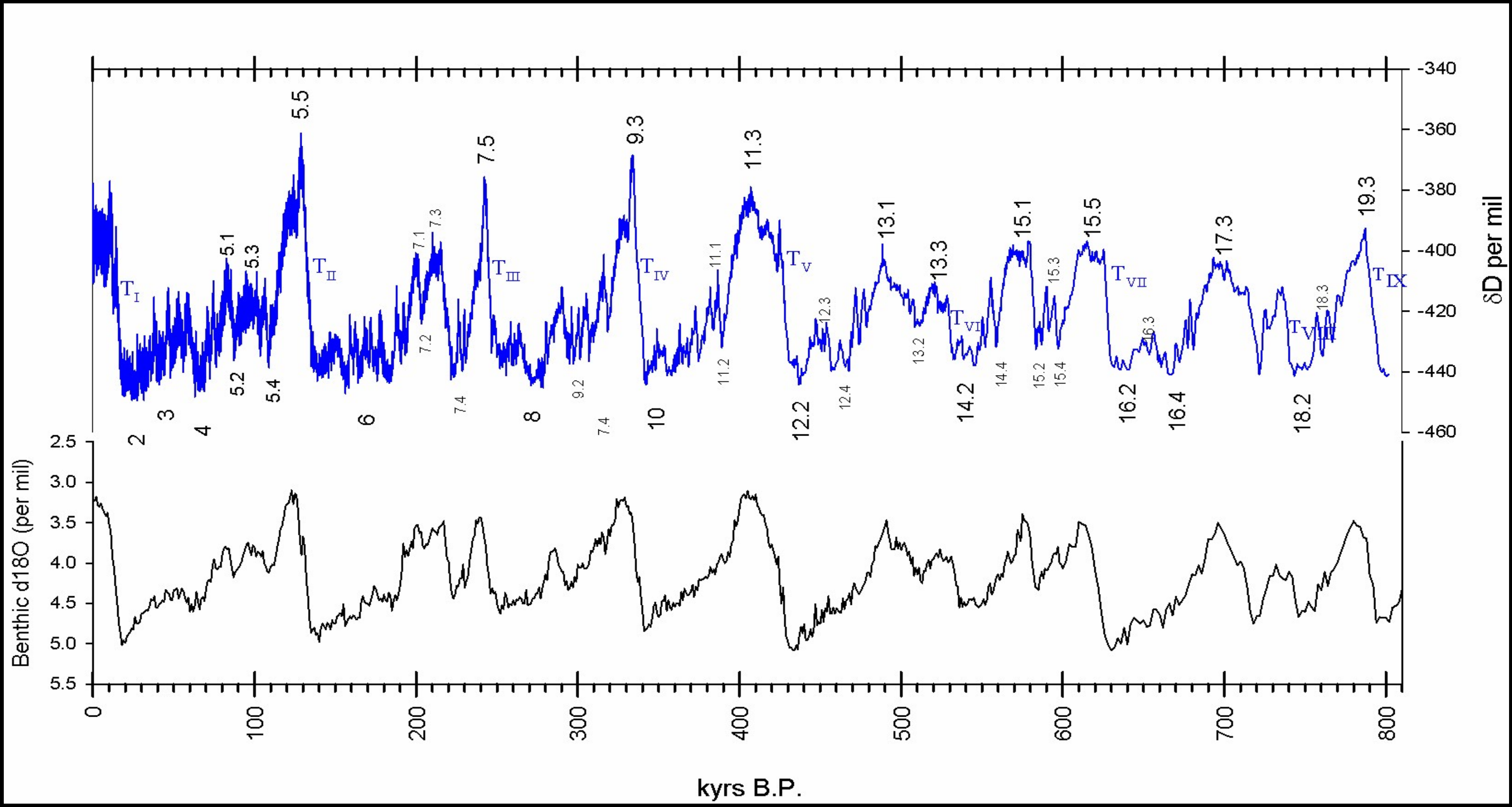
Modified from : Martínez-Garcia et al., 2011

Long-term climate change

In general terms, EDC, Vostok, EDML, Taldice show a coherent picture of glacial/interglacial Antarctic temperature and atmospheric compostion changes.



Modified from: Bazin et al., 2012

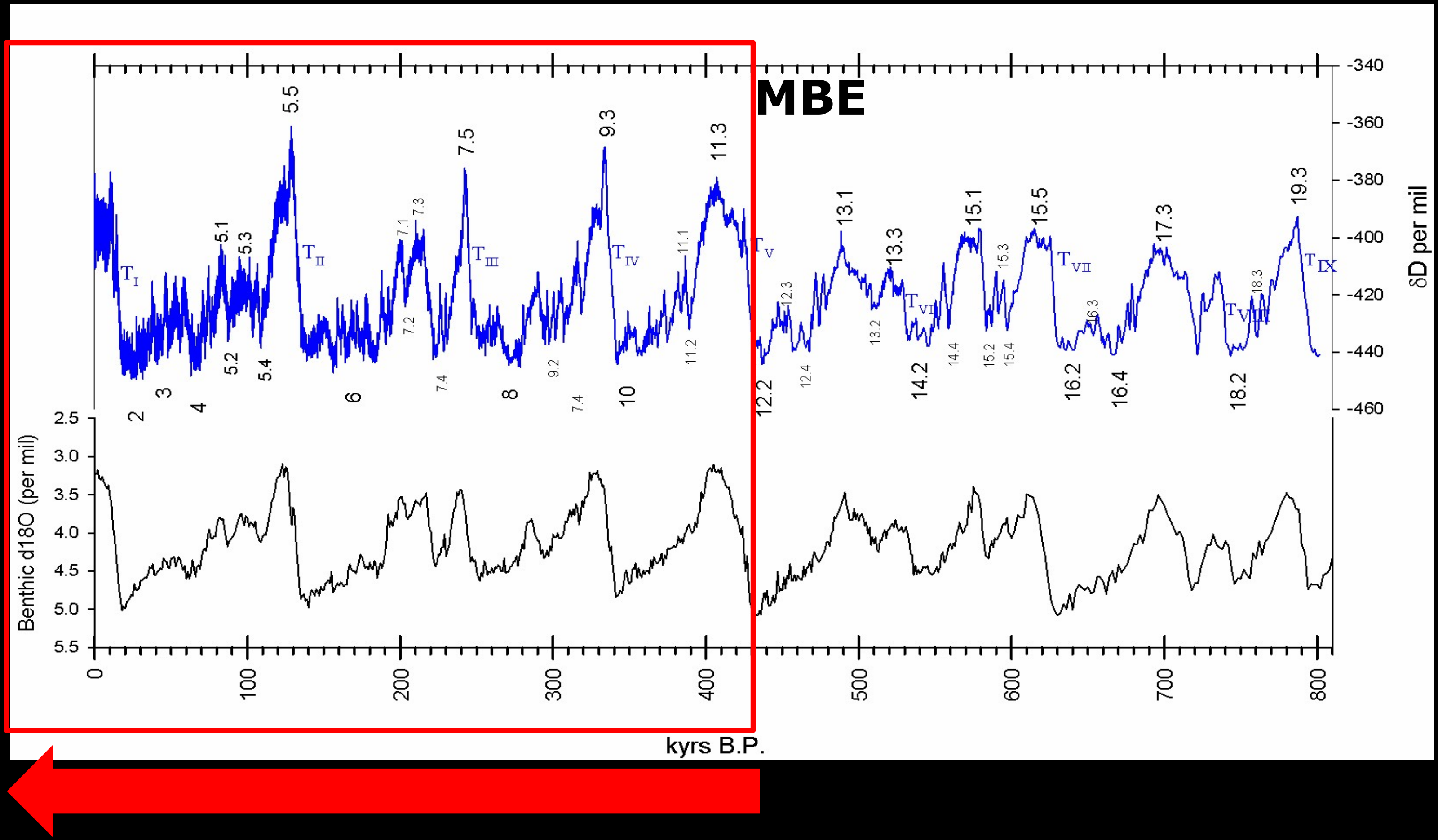


(Jouzel et al., 2007; Lisiecki and Raymo, 2005; EPICA Community Members, 2004, modidfied)

EPICA-Dome C ice core extends the Vostok ice core climate sequence back to **MIS 20.2** (ca. 810 kyr B.P.), providing the longest climate record available from ice cores.

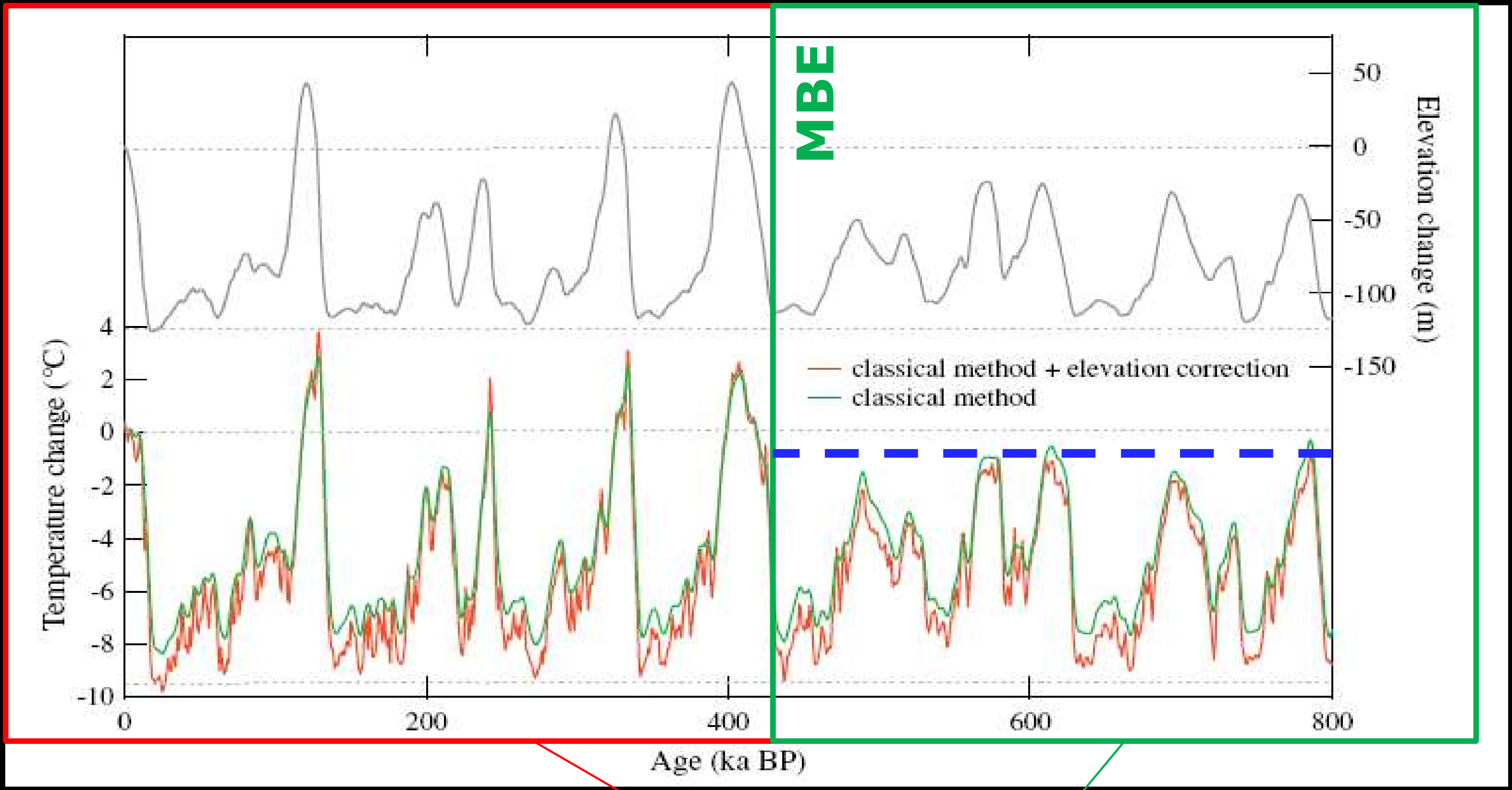
The Antarctic climate is marked by glacial–interglacial variations reaching 8–10 °C.

First-order agreement between global ice volume (benthic $\delta^{18}O$) and Antarctic temperature change.
MIS 11 appears to be the longest interglacial; MIS 5.5 (ca. 130 kyrs B.P.) was probably the warmest interglacial (about 5°C above present-day in Central Antarctica)



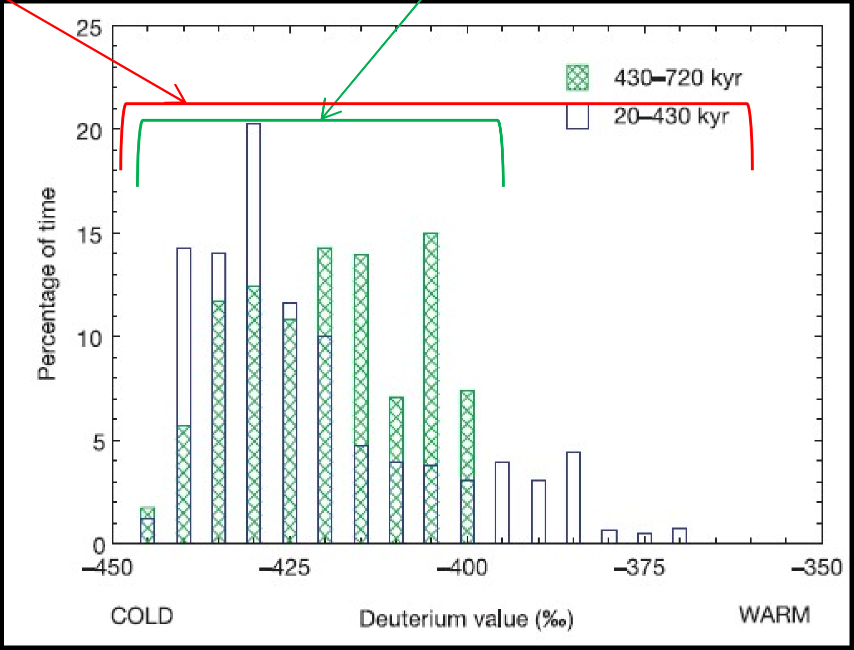
Greater amplitude of glacial–interglacial temperature changes after 430 kyrs B.P. (Termination V) compared to the earlier period.

before & after MBE



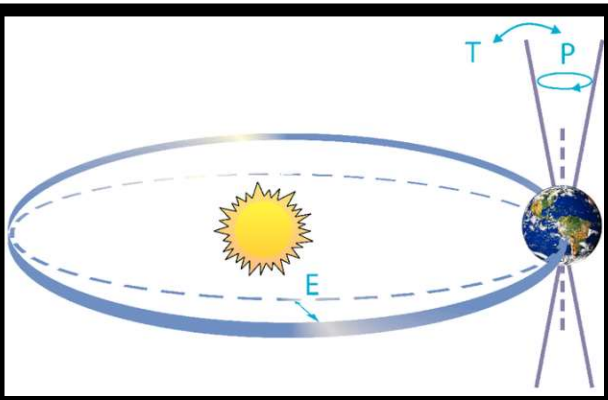
Before MBE less warm interglacials (1-3 °C colder than Holocene) occupied a larger proportion of each G/I cycle

»mean δD before and after 430 kyr is quite similar



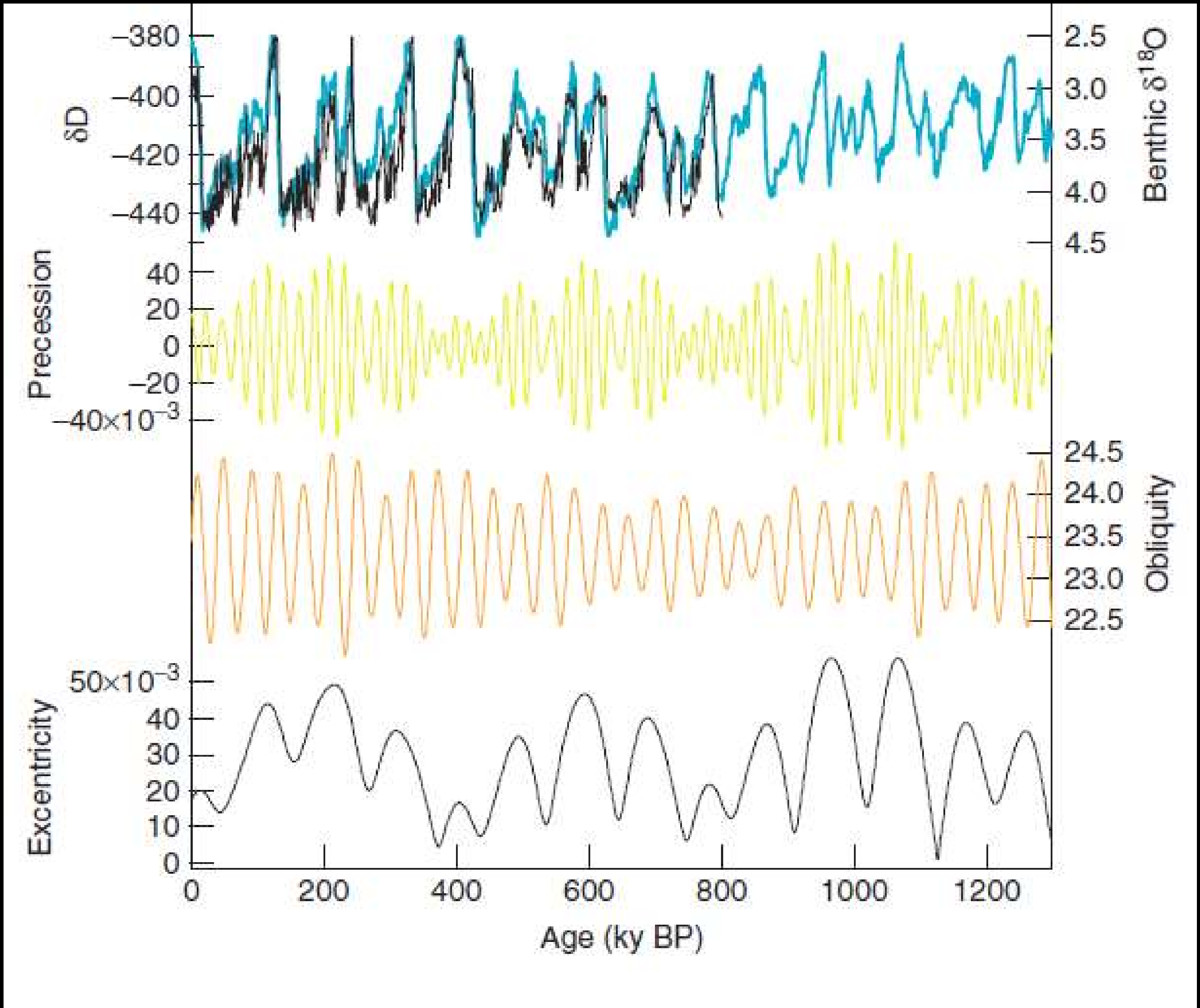
Past variations of Antarctic temperature are strongly imprinted by changes in Earth’s orbit:

-100 kyr periodicity (eccentricity)
-40 kyrs periodicity (obliquity)
-19-23 kyrs periodicity (precession)



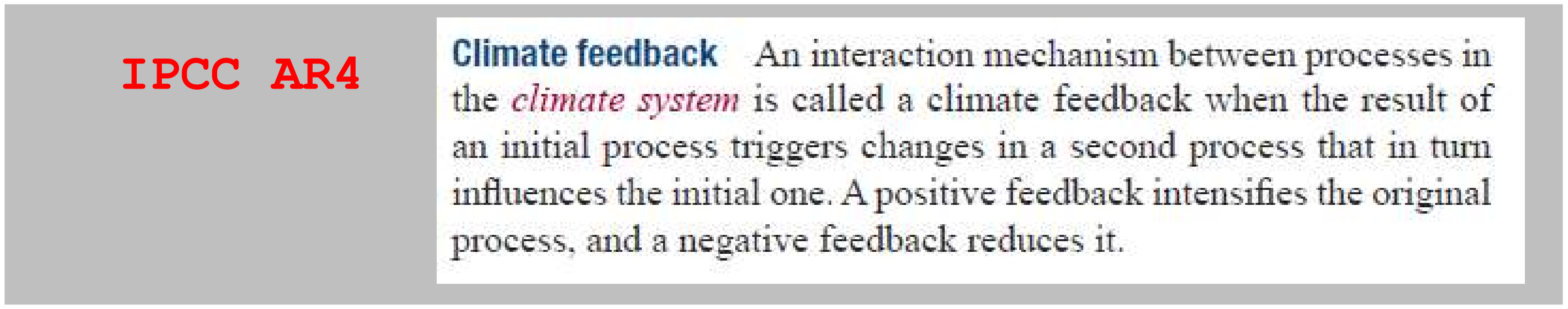
At the obliquity and precession timescales, Antarctic climate variability arises from a southern response to local summer duration (Huybers & Denton, 2008).

Therefore, the warmer interglacial climate from past to present was associated to the long-term modulation of the amplitude of Earth’s obliquity changes (*Jouzel et al., 2007*).



Climate feedbacks

- While G/I variations are *driven* by small orbital forcings, the full magnitude of temperature changes observed in Antarctica can be observed only when complex internal climate feedbacks are taken into account.



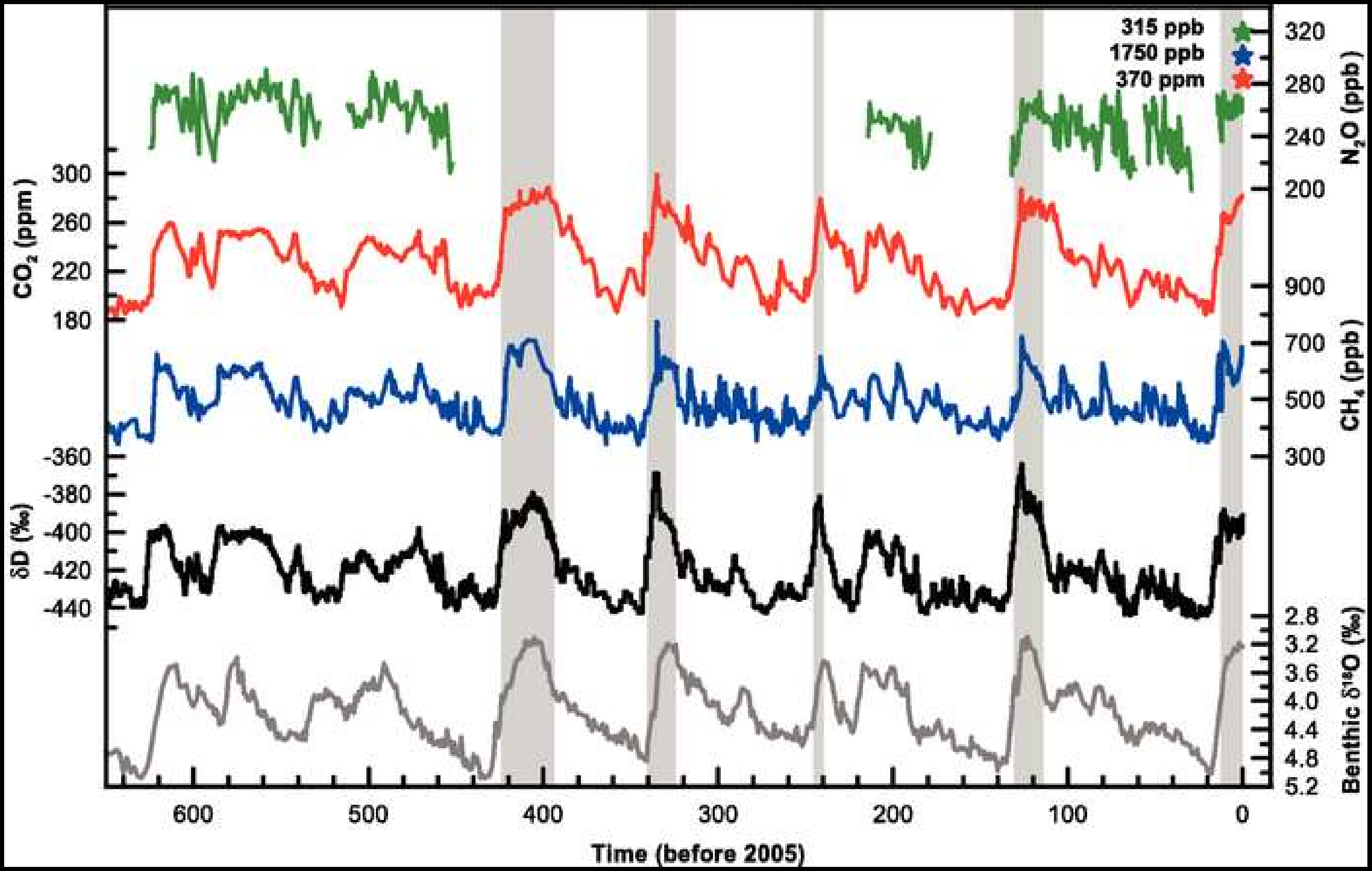
IPCC AR4

Climate feedback An interaction mechanism between processes in the *climate system* is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

- Feedbacks derive from greenhouse gases (CO_2, CH_4, N_2O) albedo of land ice sheets, annual mean snow cover, sea ice area, vegetation, aerosol in the atmosphere (e.g. mineral dust), etc.

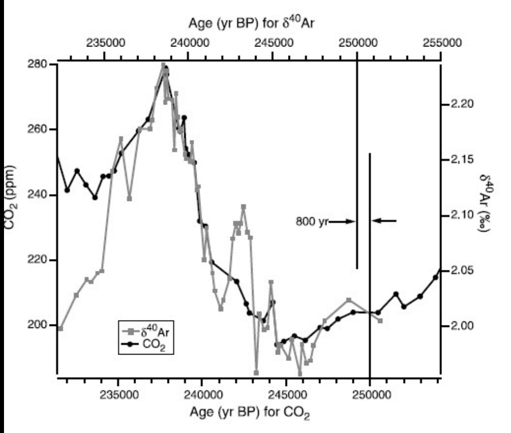
Chapter 6: Palaeoclimate
6.4: Glacial/interglacial climate variability and dynamics

IPCC Fourth Assessment Report 2007



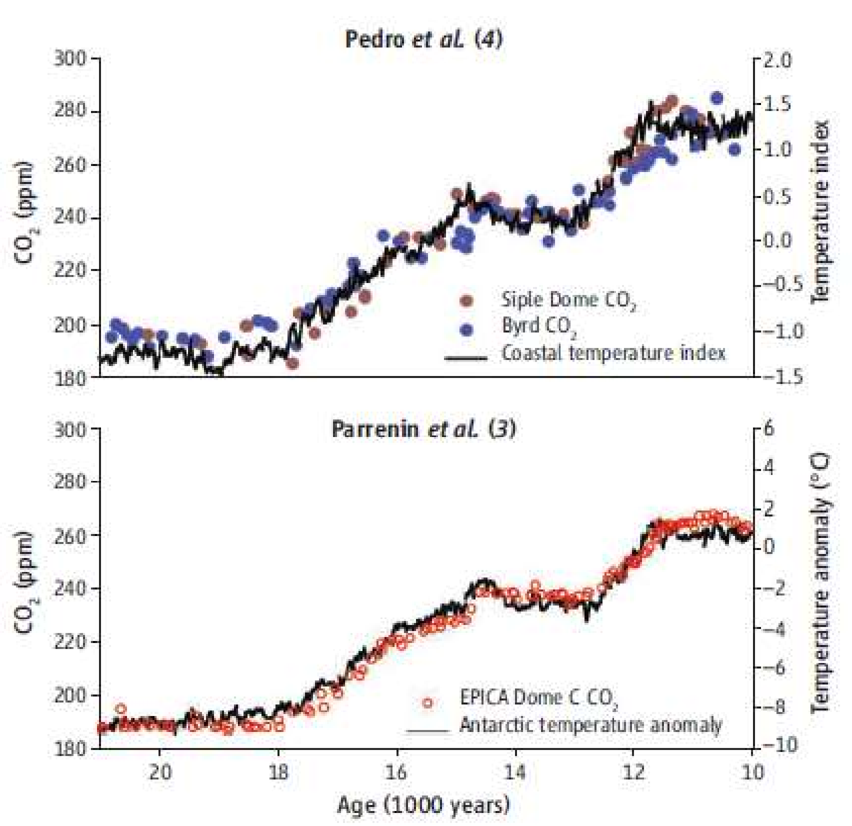
greenhouse gases co-varied with Antarctic temperature over glacial-interglacial cycles, suggesting a close link between natural atmospheric greenhouse gas variations and temperature

Reconciling leads and lags between CO2 and temperature

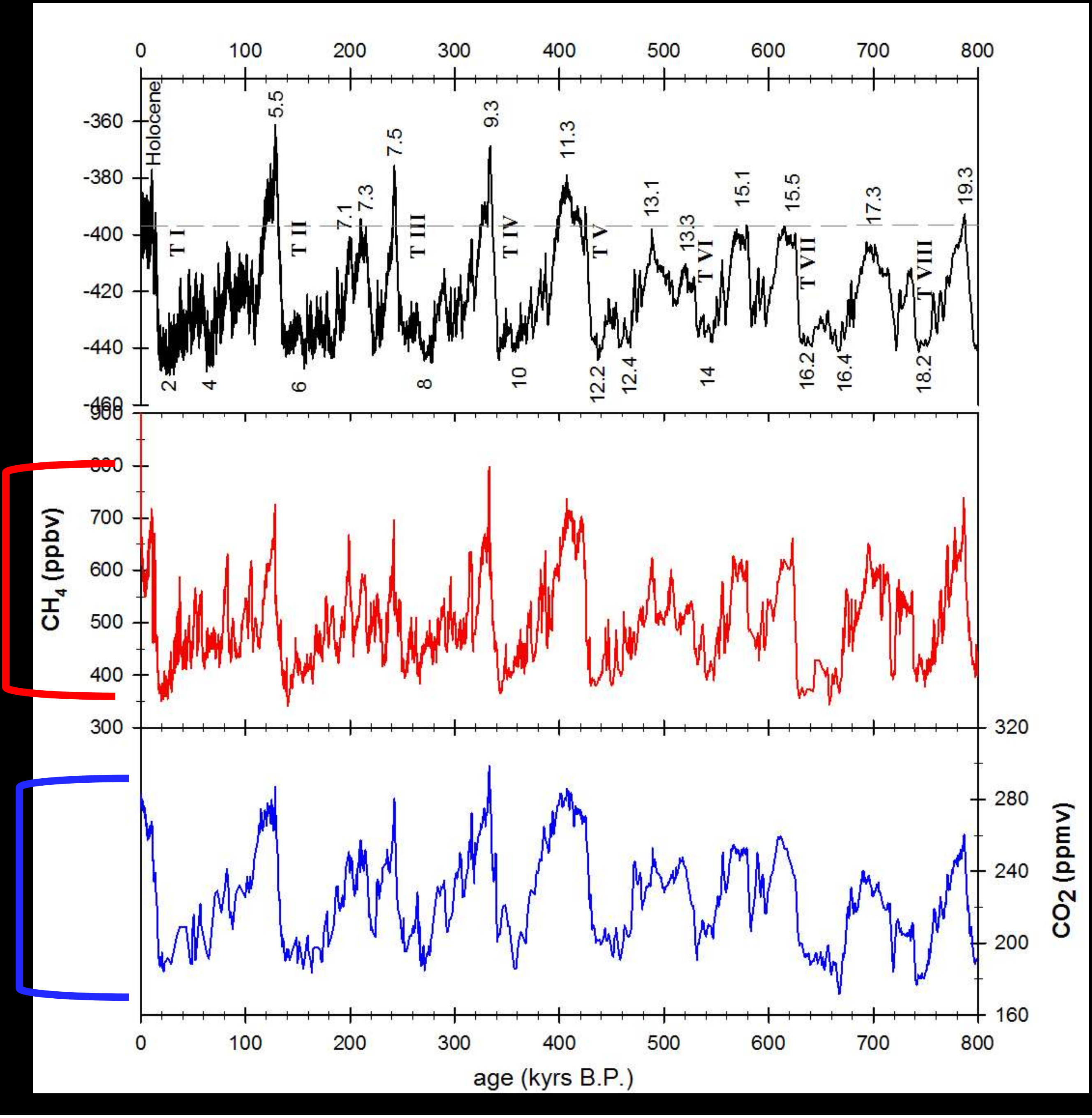


Early suggestions from Vostok indicated a CO_2 lag of 800±200 years with respect to Antarctic warming by (Caillon et al., 2003)

Some novel studies (Pedro et al., 2012, Parrenin et al., 2013) on high accumulation sites suggest a CO2 increase that is almost synchronous with Antarctic warming.



Since AR4, new and higher resolved records of CO_2, CH_4 and N_2O variations were obtained



CH_4 natural variability:
800 ppb (I) – 350 ppb (G)

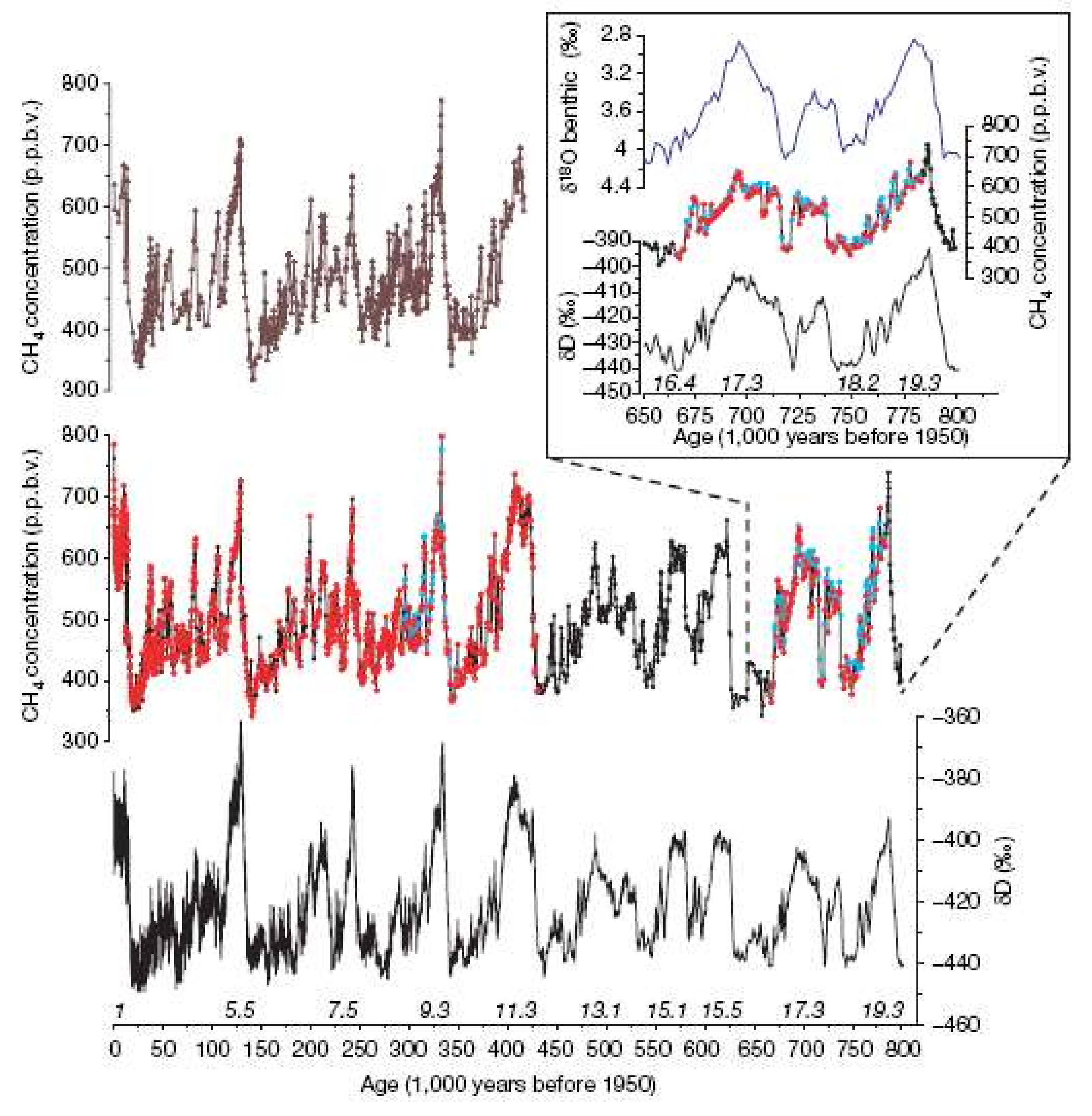
(Loulergue et al., 2008)

CO_2 natural variability:
300 ppm (I) – 172 ppm (G)

(Luthi et al., 2008)

Vostok CH_4

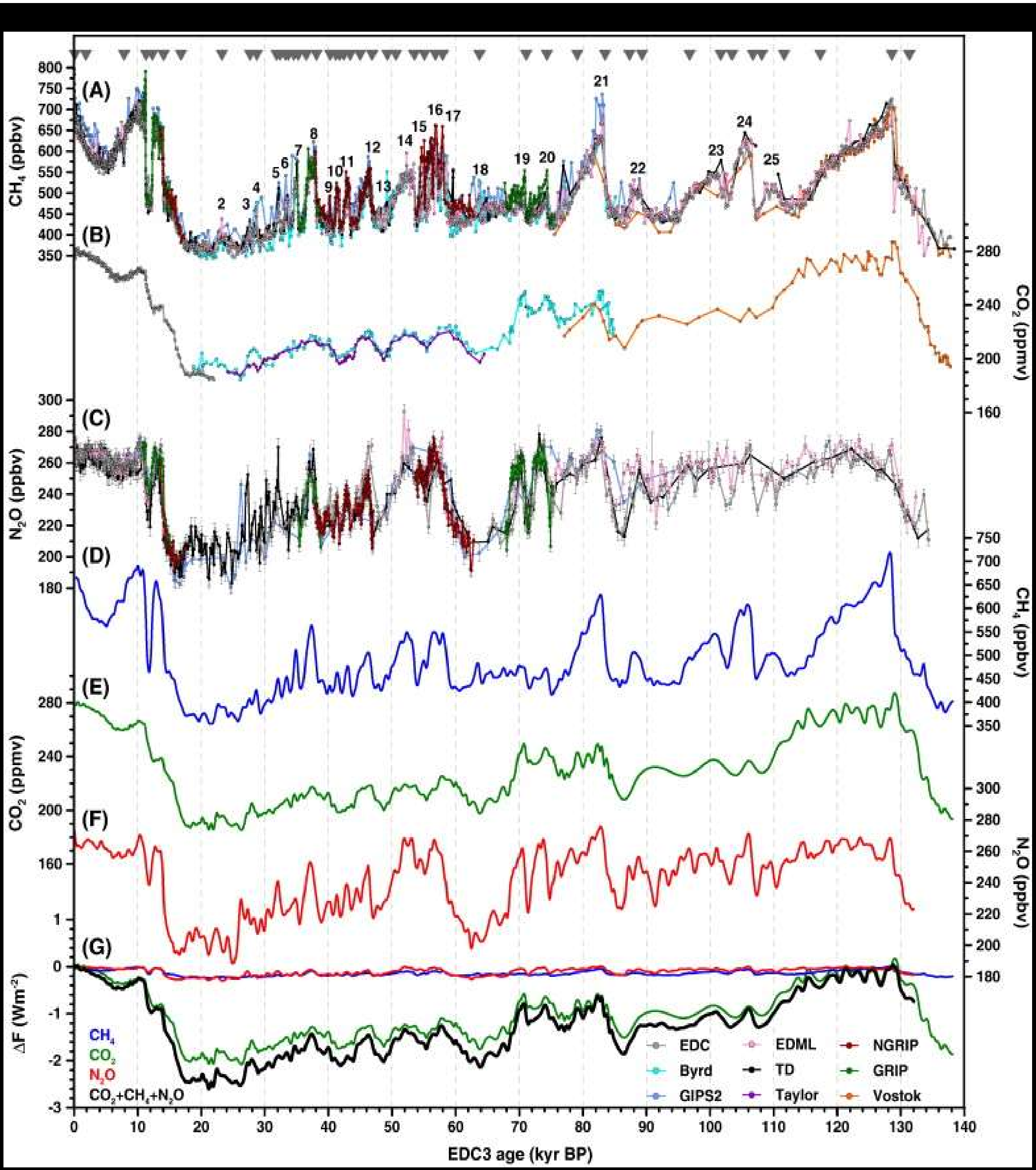
EPICA-DC CH_4



Measurement of CH_4 in the Vostok and EDC ice cores confirms the **high precision** of measurements and their **reproducibility**.

Loulergue et al., 2008

stacked high-resolution CO_2, CH_4, and N_2O records were compiled for the last glacial cycle combining different ice cores (*Schilt et al., 2010*).



Contribution from CH_4 and N_2O is of secondary importance compared to CO_2

(CH_4 + N_2O): 20% of total change in the radiative forcing of all greenhouse gases over Termination 1 (~3 W/m^2).

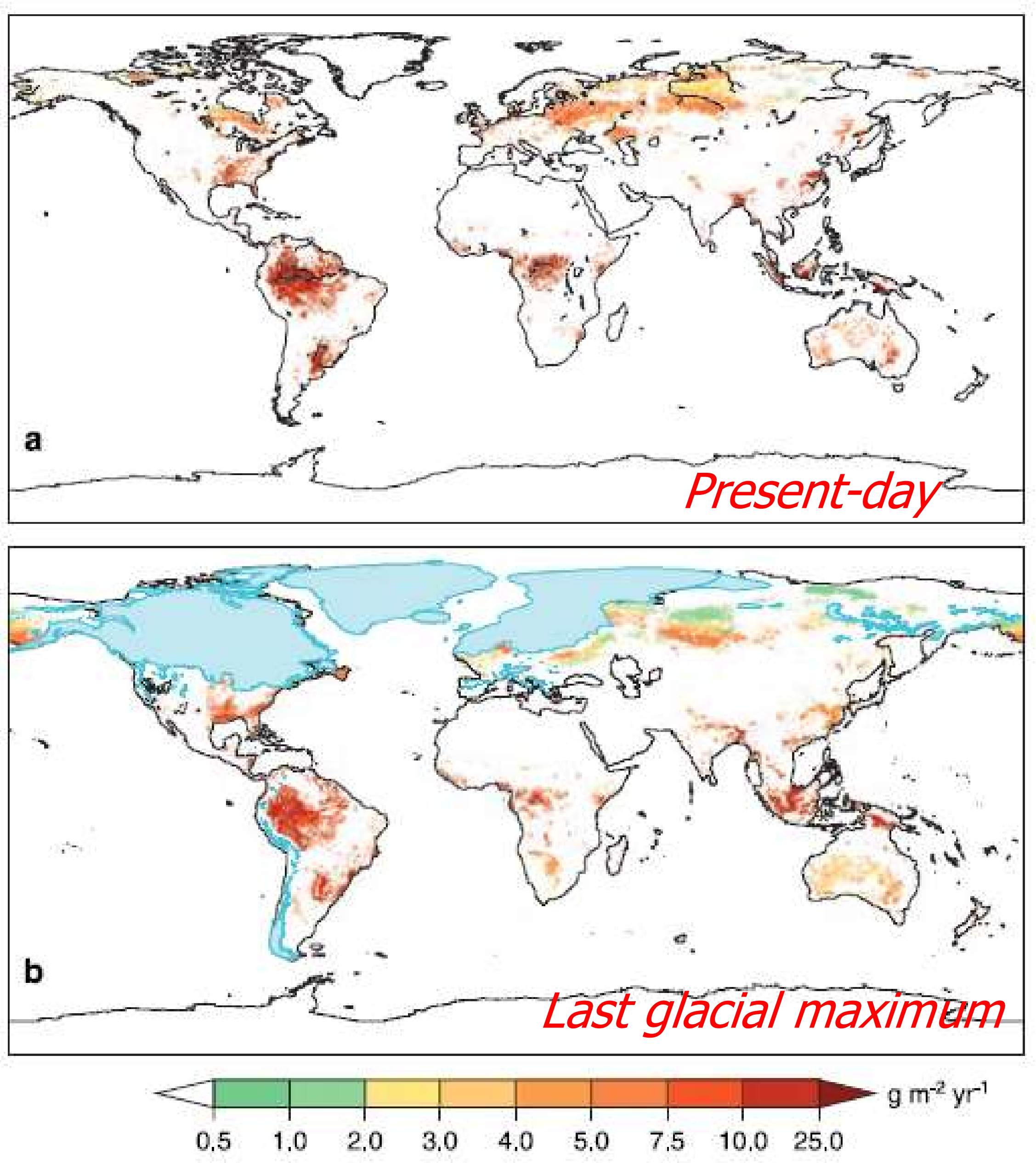
Sources of CH4

Wetlands are by far the largest natural source of methane today, and represented 85% of CH4 sources in the pre-industrial period (Loulergue et al., 2008).

The largest wetland extents are found in boreal regions, with a second latitudinal belt between the tropics.

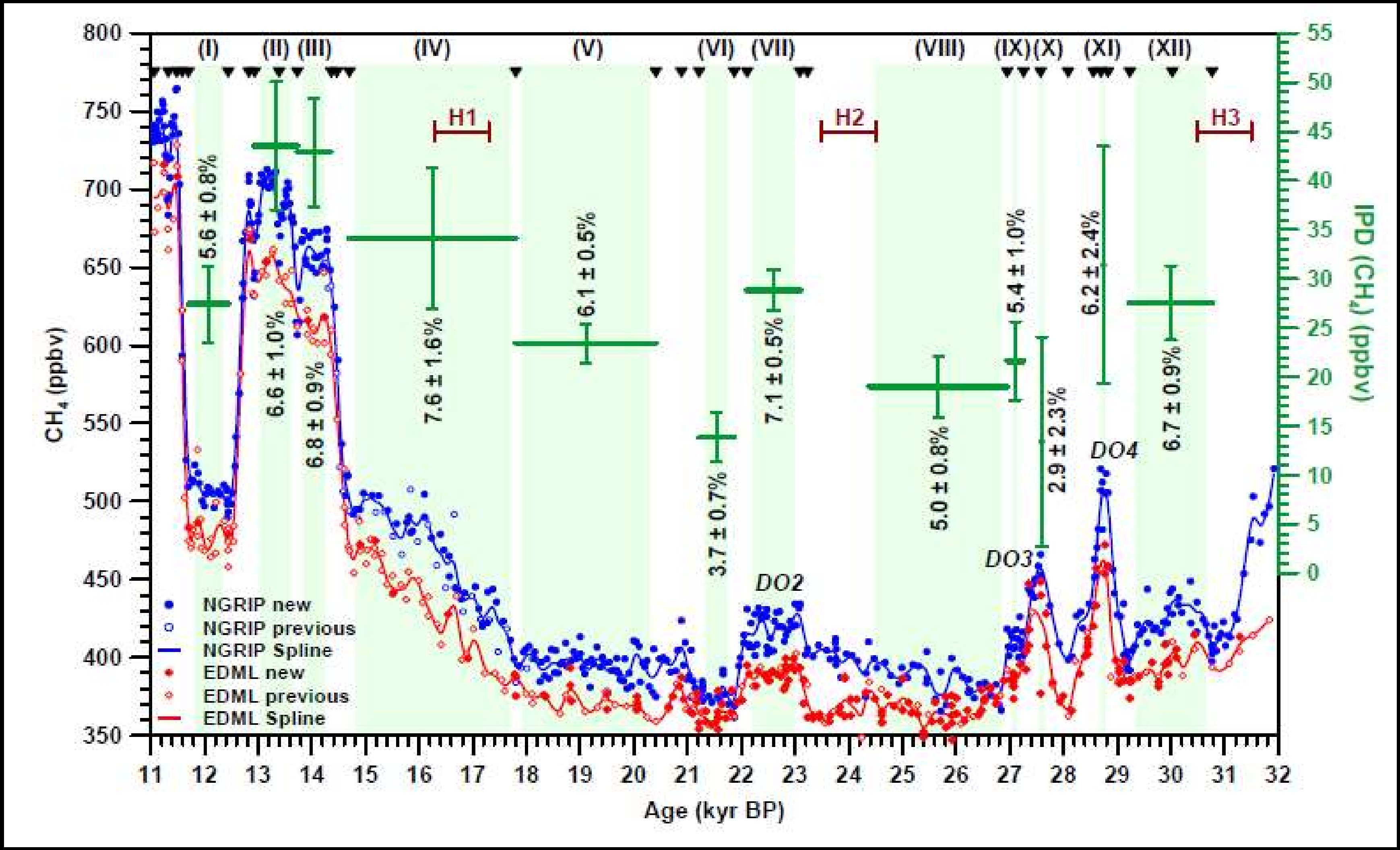
Other lesser sources such as biomass burning and clathrate degassing could also have contributed.

Sinks of methane, are tropospheric OH radicals.



Kaplan et al., 2002

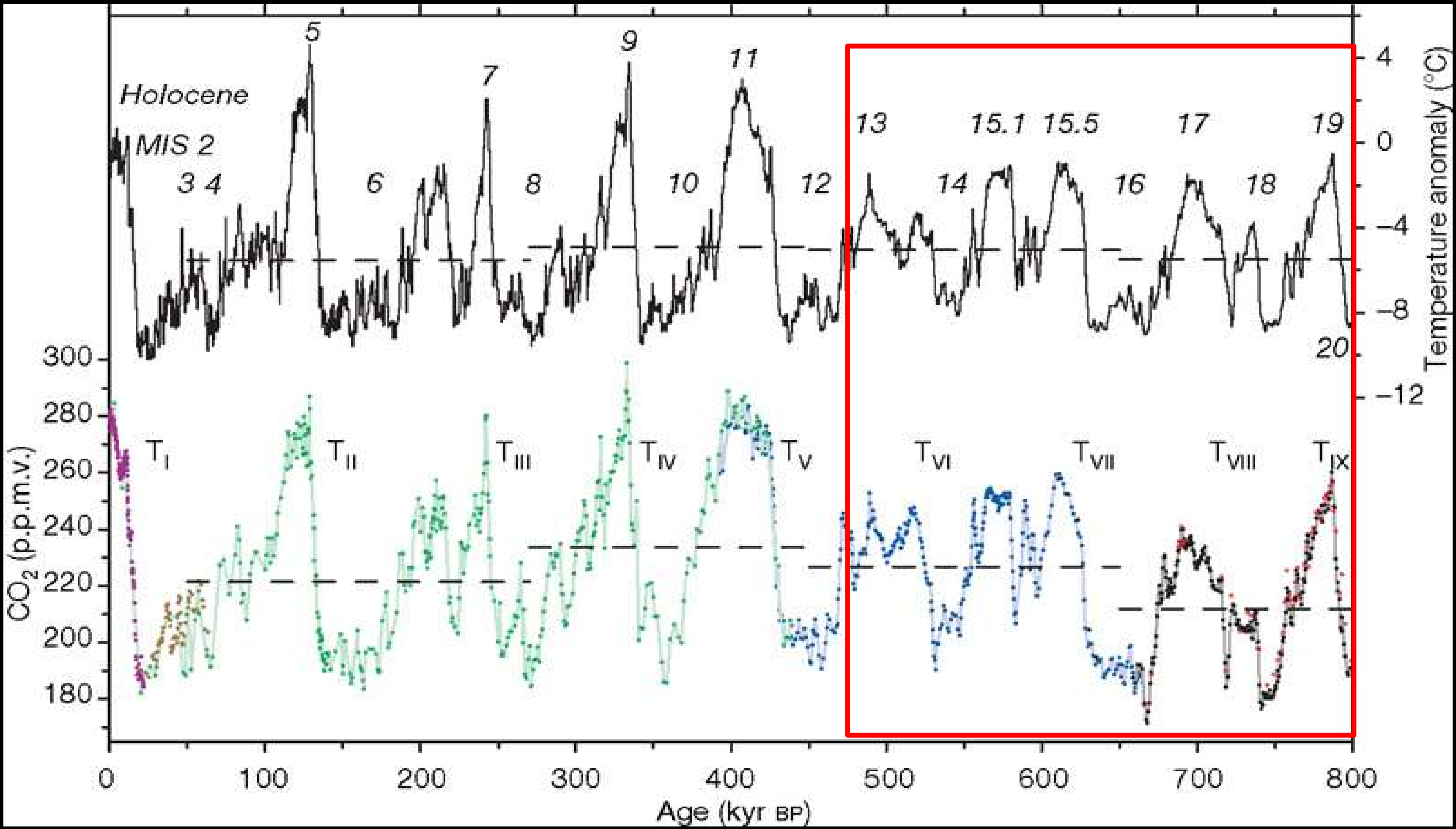
CH4 relative interpolar difference



Minimum CH_4 interpolar difference during the Last Glacial Maximum but still positive. This implies that NH boreal wetlands never completely shut off during peak glacial.

From Glacial to Holocene, methane emissions from biomass burning remained almost constant but emissions from boreal wetlands increased.

The long CO_2 record reveals long-term (>200 kyr) trends in addition to G/I variations



Lüthi et al., 2008

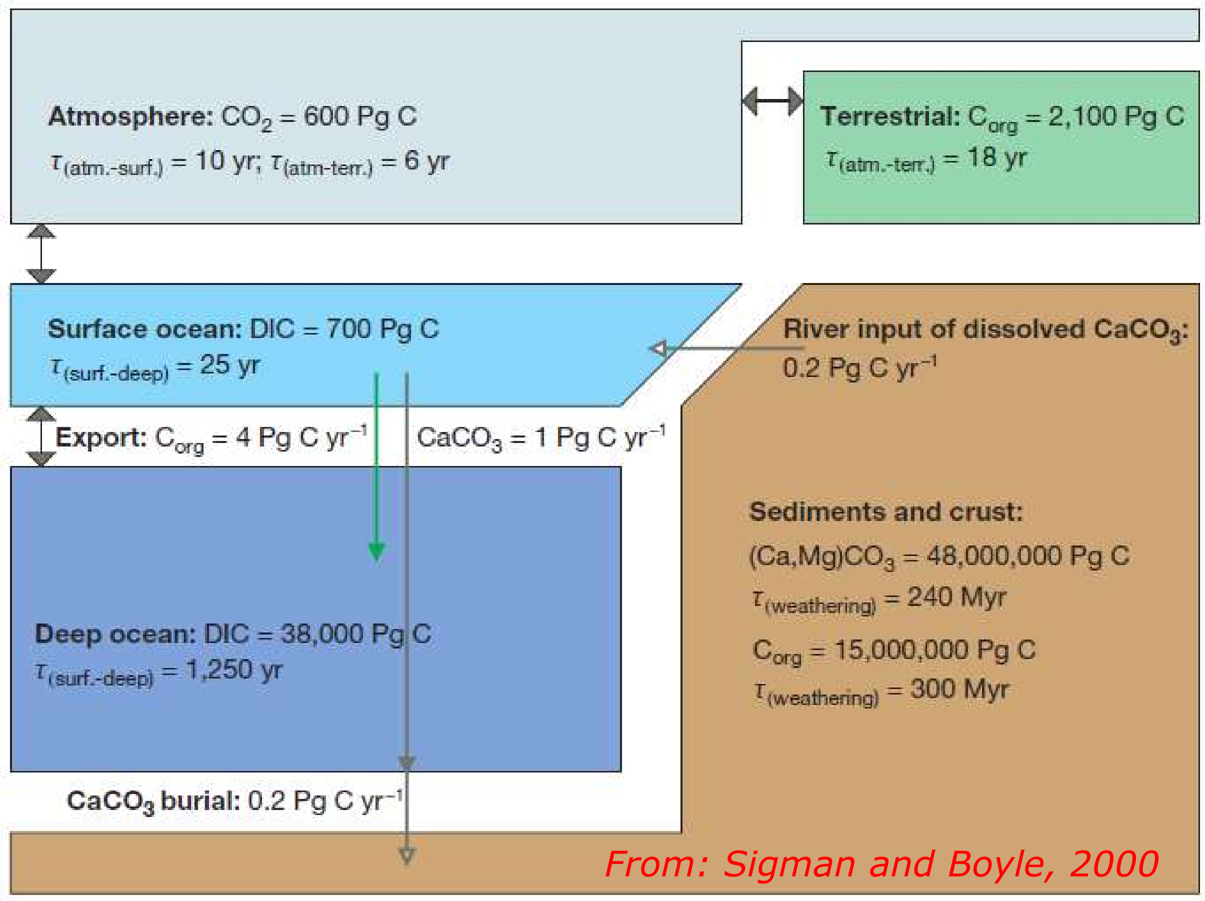
While the transition from warm to cold periods has been generally progressive, temperature and CO_2 increase during glacial terminations was relatively abrupt. lukewarm interglacials (i.e. MIS 13-19) show generally lower atmospheric CO_2 concentration

Natural CO_2 variability on G/I timescale: *unsolved questions in climate research*

- Natural CO_2 glacial/interglacial changes involve processes in the atmosphere, in the surface and deep ocean, in marine sediments and on land.

The ocean is one of the largest and fast-exchanging carbon reservoirs.

It seems inescapable that changes in ocean carbon cycle played a significant role in modulating and controlling past variations of atmospheric CO_2 (e.g. Broecker,1982; Sigman and Boyle, 2000).

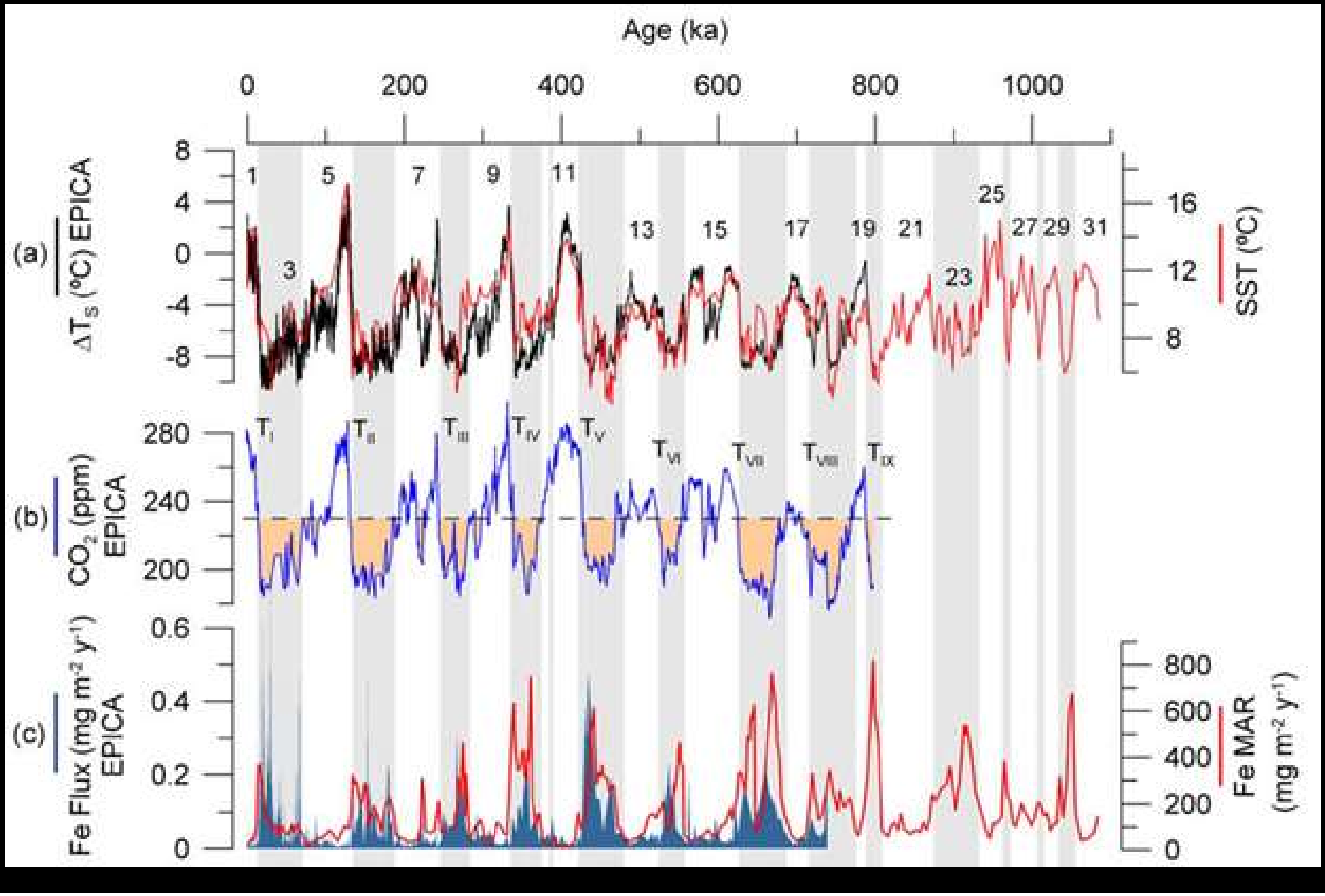


From: Sigman and Boyle, 2000

Ocean `biological pump'

- Among causes of G/I CO_2 changes, the extraction of C from the surface ocean by biological production, either at low or high latitudes, in tandem with changes in the marine calcium carbonate budget must be taken into account.

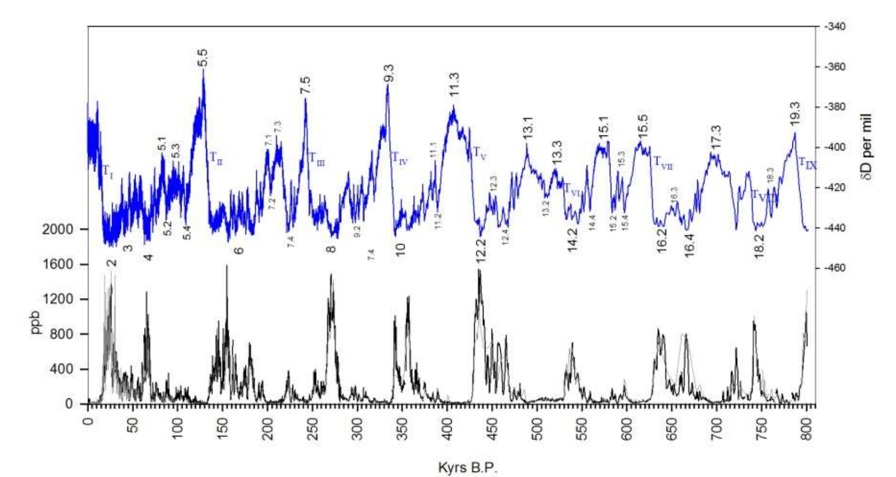
- Among other factors, fertilization of phytoplankton growth in the subantarctic zone of the Southern Ocean related to increased deposition of iron-containing dust from the atmosphere may account for CO_2 glacial drawdown of 20-40 ppm.



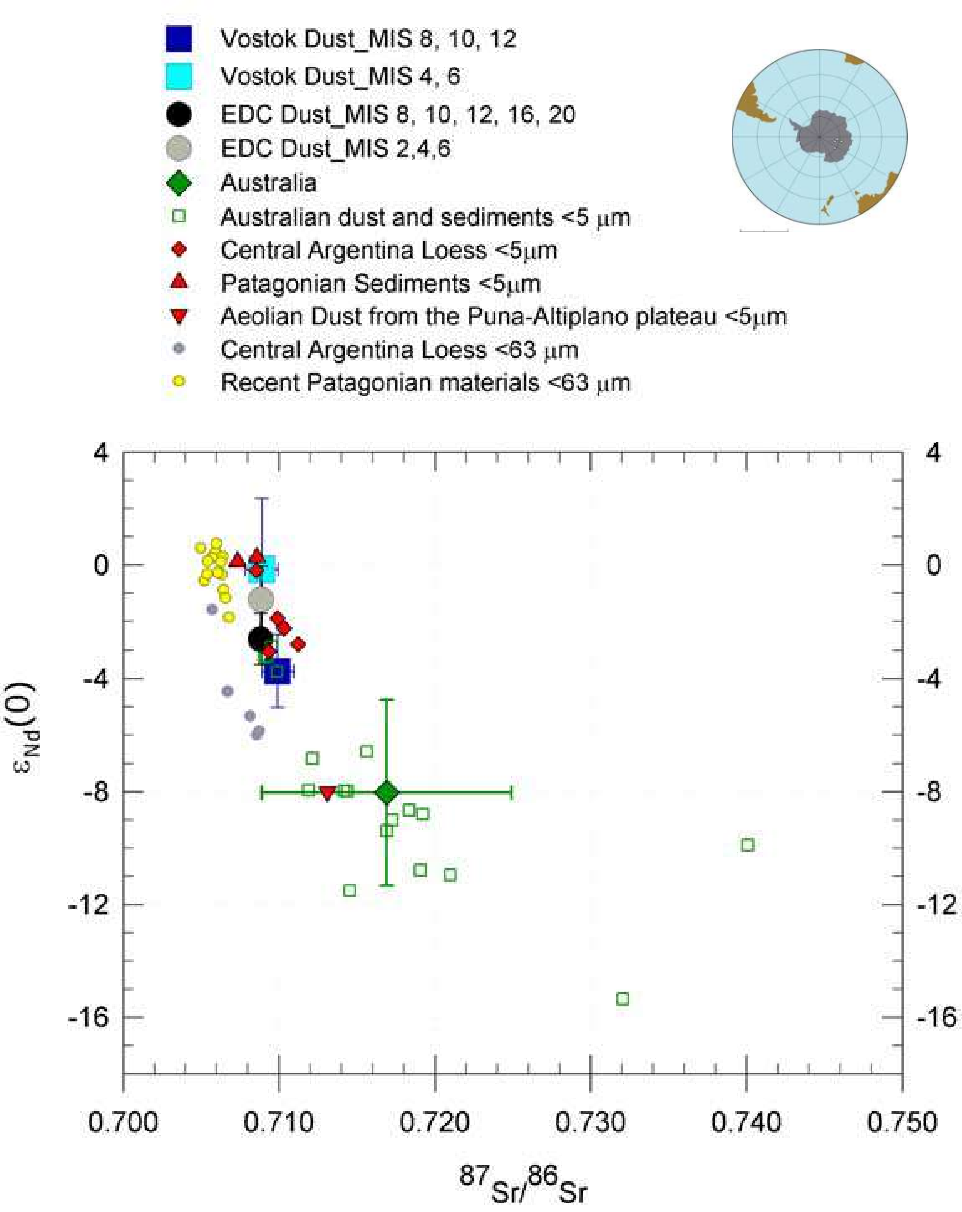
Martinez-Garcia et al., 2009

Dust-climate coupling over the last 800 kyrs

South America seems to be the dominant source area for dust in central East Antarctica during glacial periods, on the basis of geochemical data (es. radiogenic isotopes).

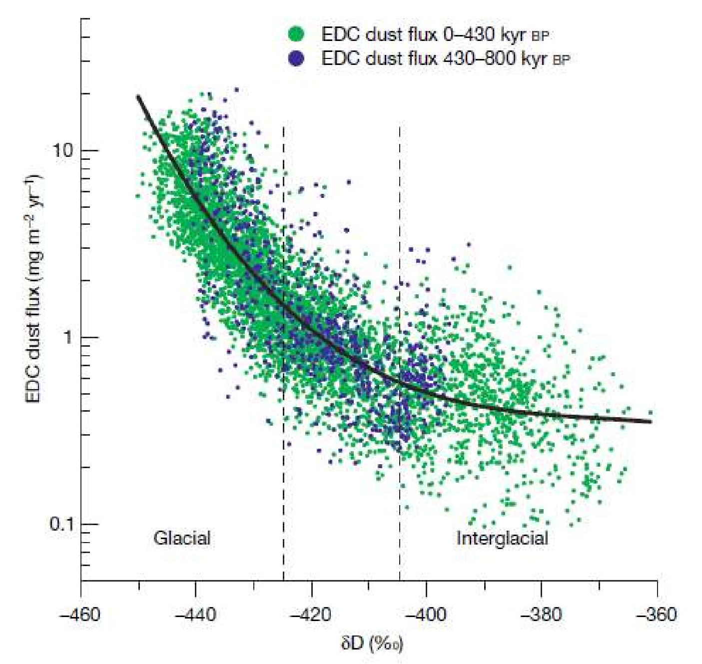


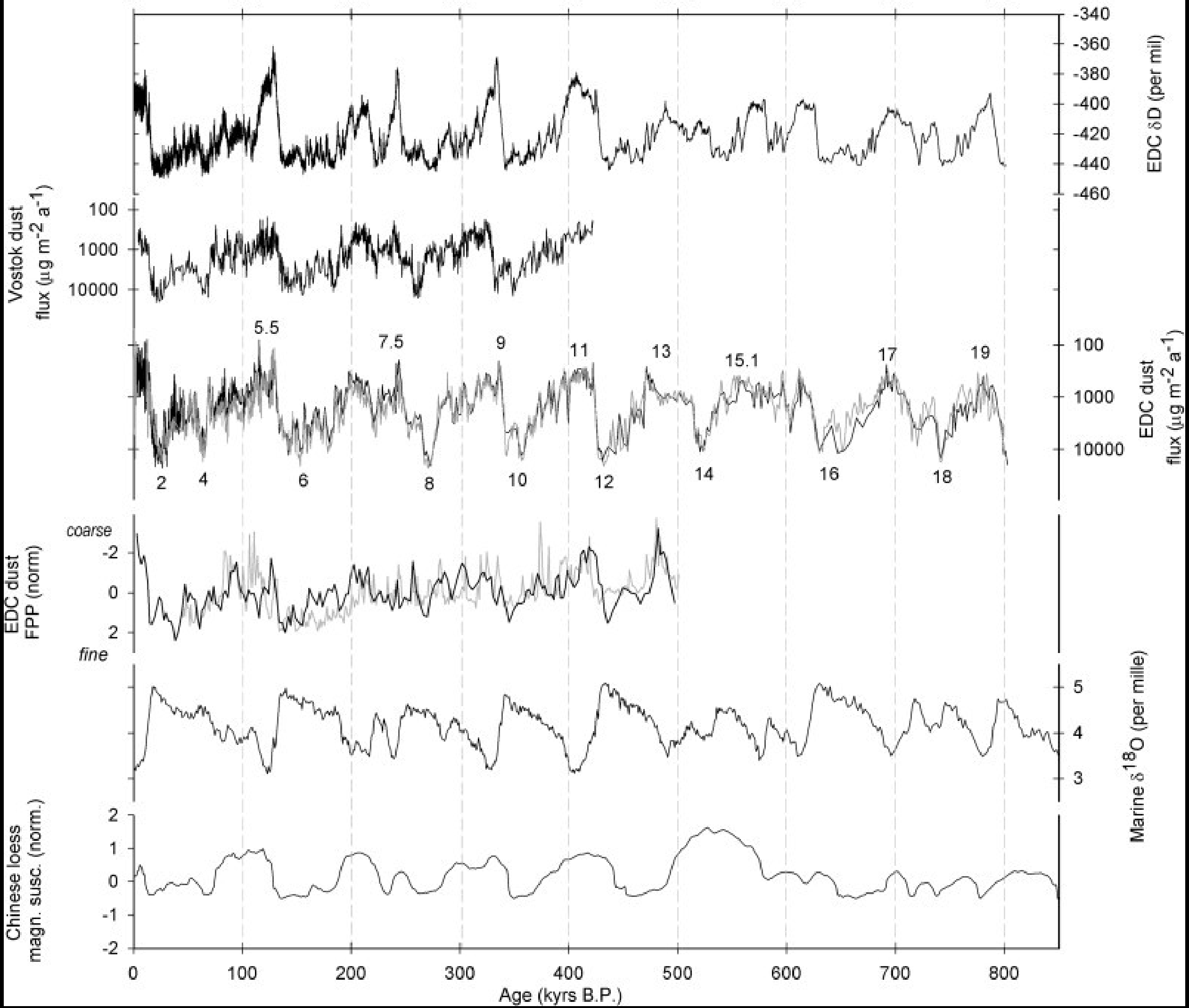
Three climatic factors (source productivity, accumulation rate, lifetime of aerosol) explain up to 80% of the dust signal variance.



Dust-climate coupling over the last 800 kyrs

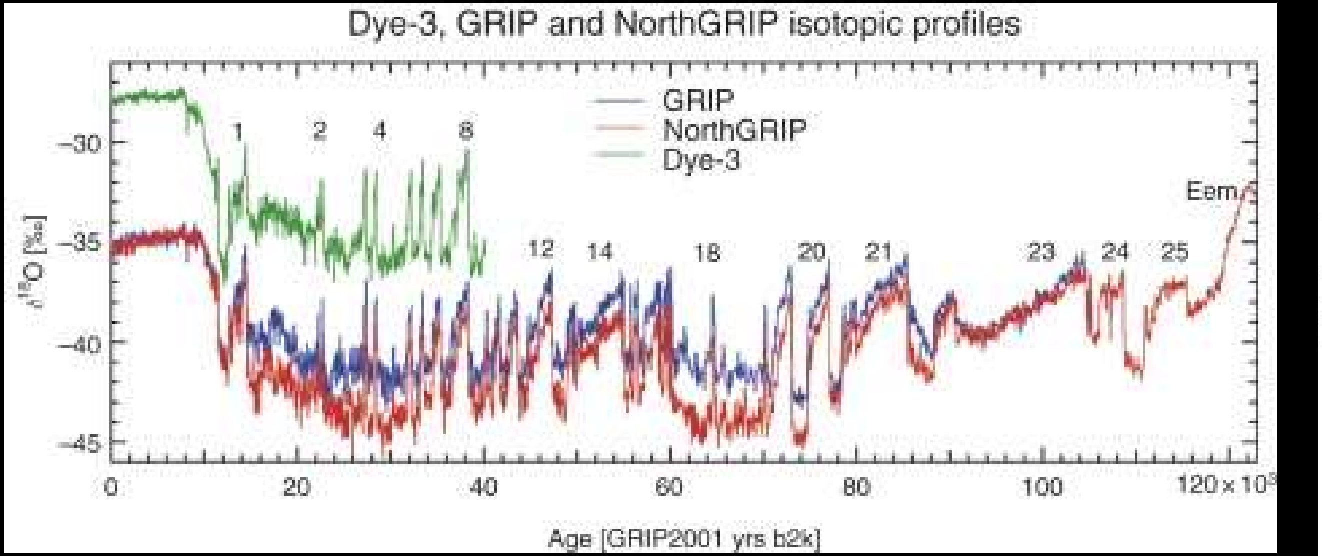
As climate becomes colder, dust flux is increasingly correlated to Antarctic temperature

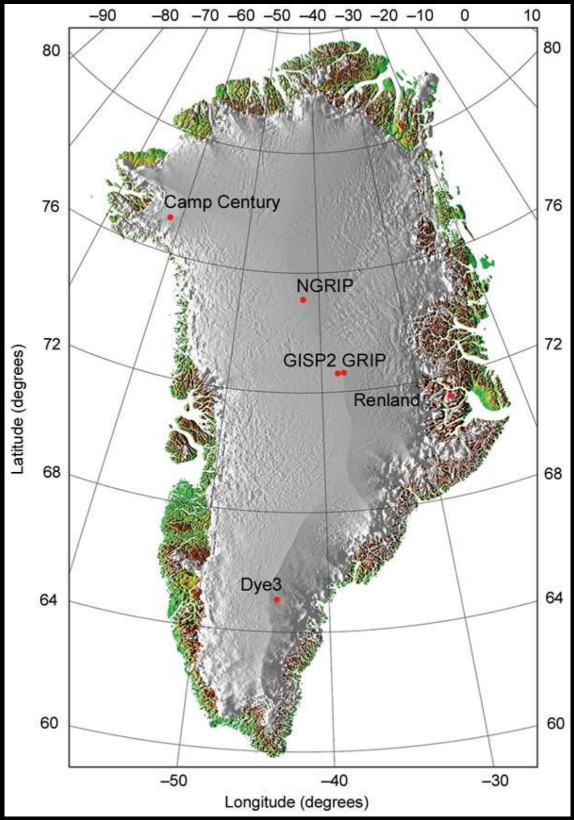




And Greenland?

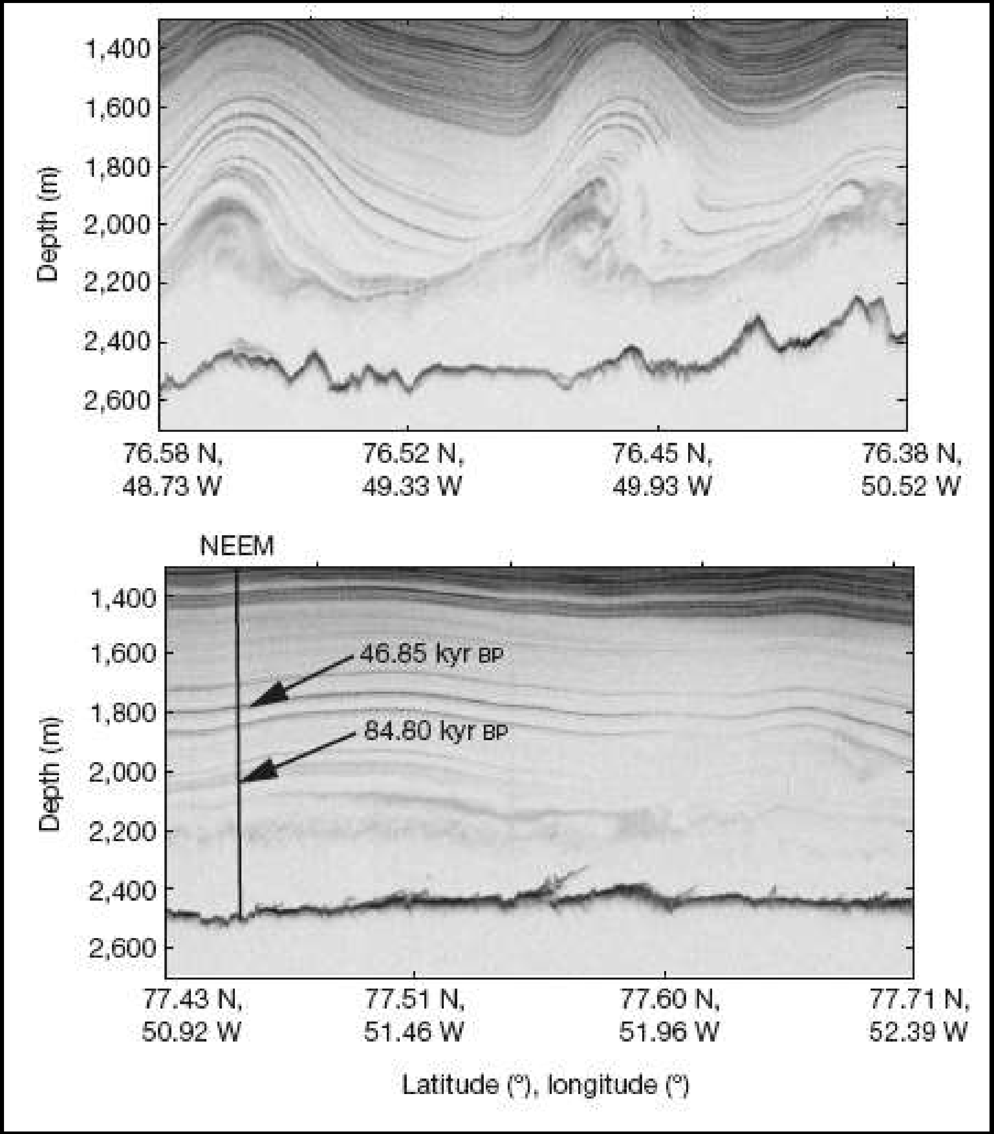
- Undisturbed Greenland ice core records are available for the last climatic cycle.
- The 123,000 years long climate history archived in the NorthGRIP ice core suggests that the end of the last interglacial period was 3–5 °C warmer than today.





Eemian interglacial reconstructed from a Greenland folded ice core

- The climate record from the Eemian interglacial (130,000 to 115,000 years ago) is perturbed everywhere in Greenland ice cores.
- This because glacial ice deforms over the harder Eemian ice.



(NEEM community, 2013)

Below 2200 m - at the interface between ice from the glacial and Eemian periods - very large differences in ice rheological properties are documented

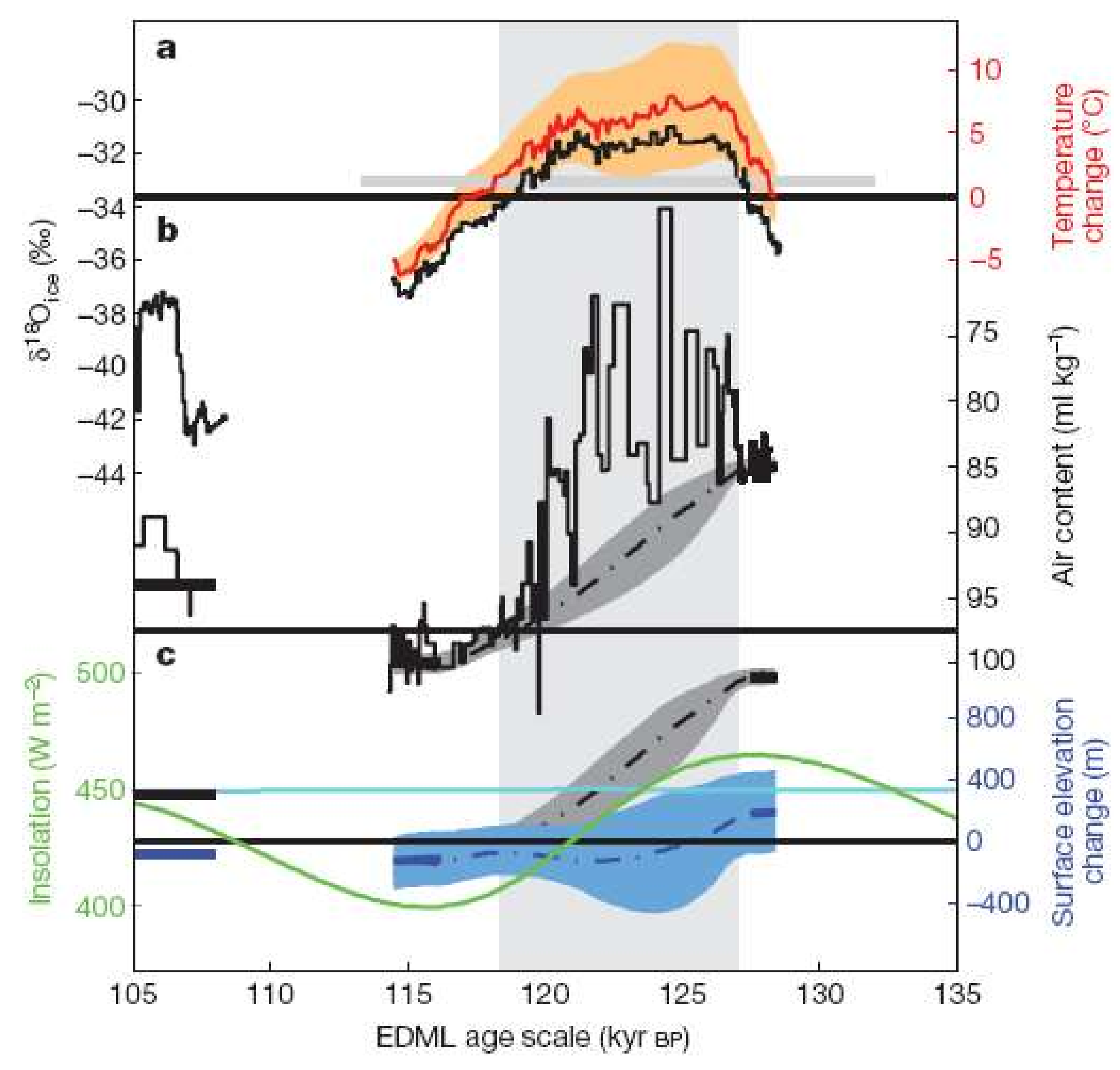
Eemian climate reconstructed

Using globally-homogeneous parameters known from dated Greenland and Antarctic ice core records, Eemian climate in NW Greenland has been reconstructed.

Surface temperatures after the onset of the Eemian (126,000 years ago) peaked at 8±4 °C above the mean of the past millennium, followed by a gradual cooling driven by decreasing summer insolation.

122-128 kyrs ago: thickness of the NW Greenland ice sheet decreased by **400±250** metres,

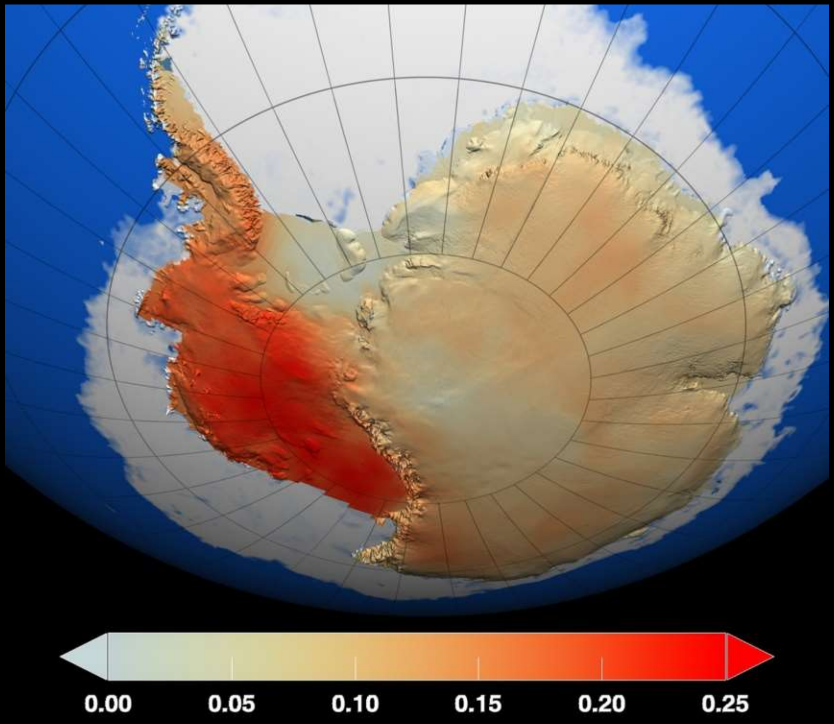
surface elevations 130±300 m lower than present.



Greenland NEEM tells lessons about Antarctica

1- Greenland is not as sensitive to climate warming as thought

2- If Greenland's ice sheet only slightly thinned during the Eemian, and contributed only to about 2 m of the 4-8 m sea level rise at that time, then Antarctica must have been responsible for a significant part of the sea-level rise.

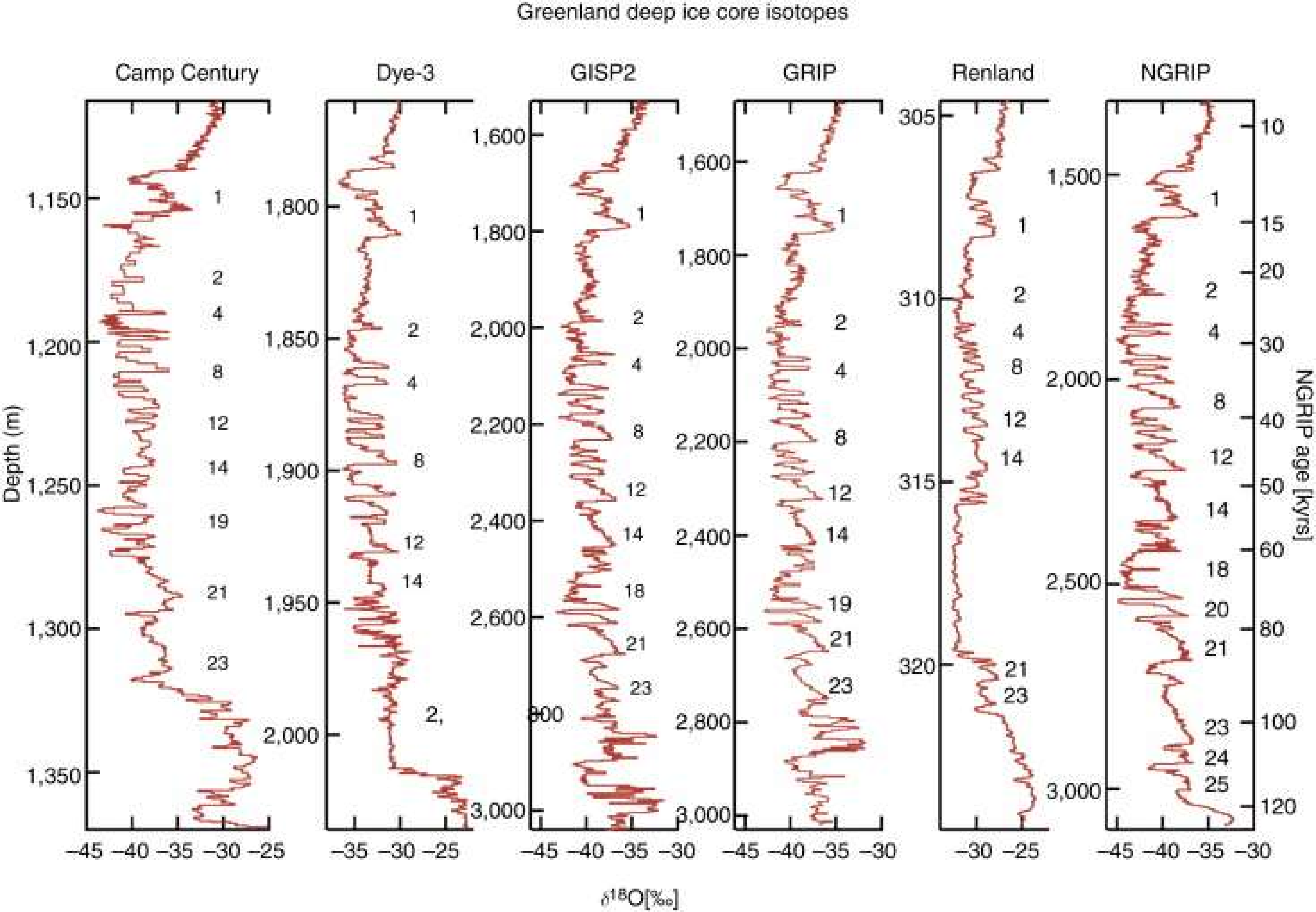


Scientists long believed that ice on Antarctica was stable. But growing evidence suggests that the ice sheet covering West Antarctica may be prone to collapse during periods of warmth. The first look at the Eemian ice in Greenland seems to support this idea.

Abrupt climate variability

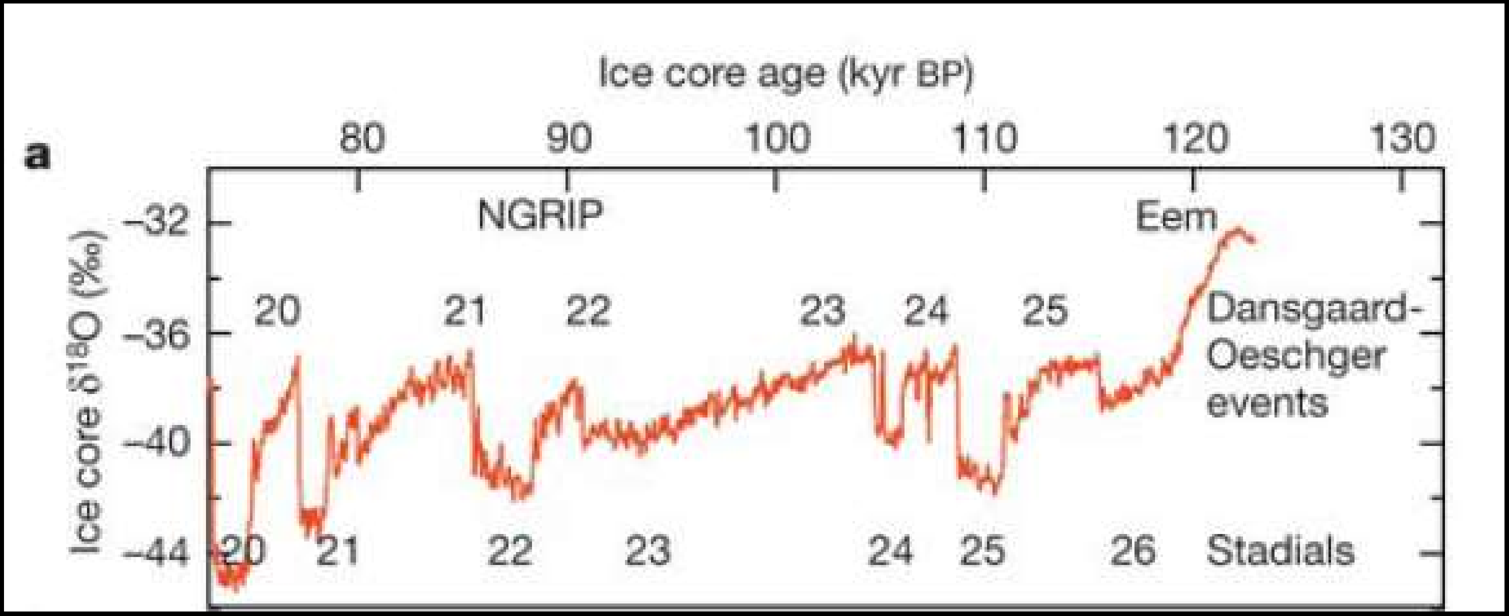
“Abrupt” climate changes

The Greenland ice core records are marked by a succession of 25 *abrupt* climate events (*Dansgaard–Oeschger events, D/O*) punctuating the last glacial period and the last deglaciation.



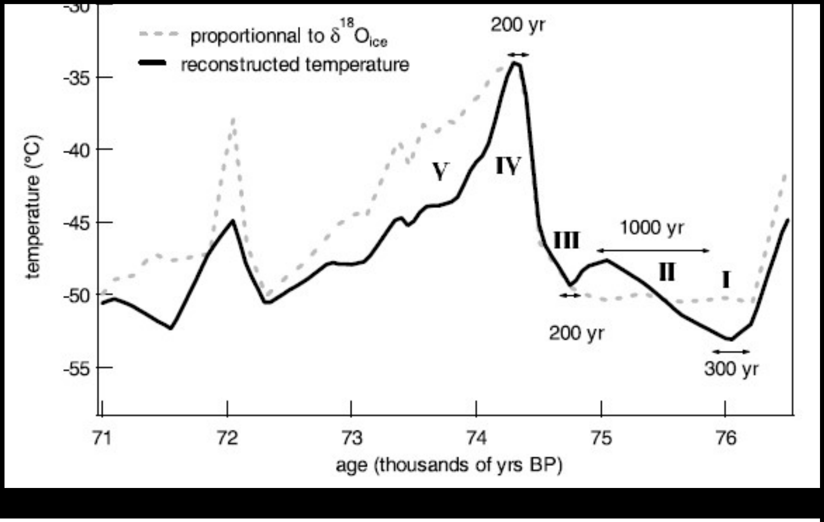
Johnsen & Vinther, 2007

The D/O events are formed by a cold and rather stable phase ('stadial') which can last for several thousand years followed by an abrupt warming, and a progressive cooling from this warm transient interstadial back to glacial conditions (*NGRIP Community Members, 2004*)

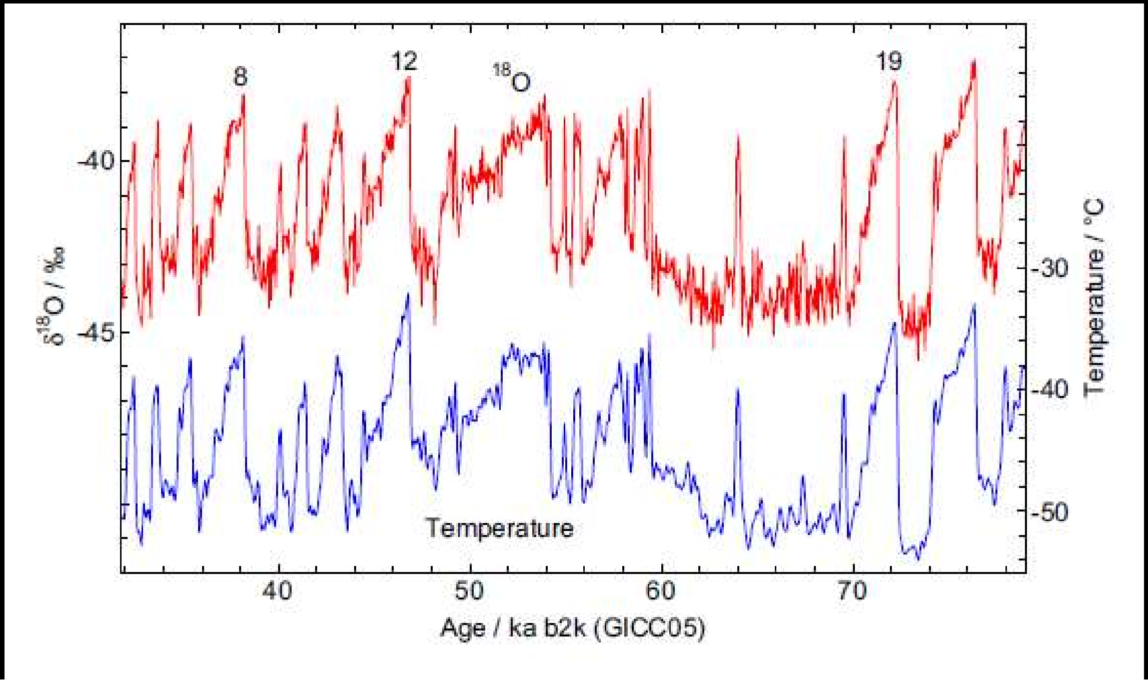


During D/O events , quantitative estimation of temperature changes based on water stable isotopes (δD and δ^{18}O) are problematic because of changes in precipitation seasonality and moisture origin.

Water isotopes paleothermometer +
air isotopic measurements (δ^{15}N and δ^{40}Ar) +
firn densification model and a heat diffusion model



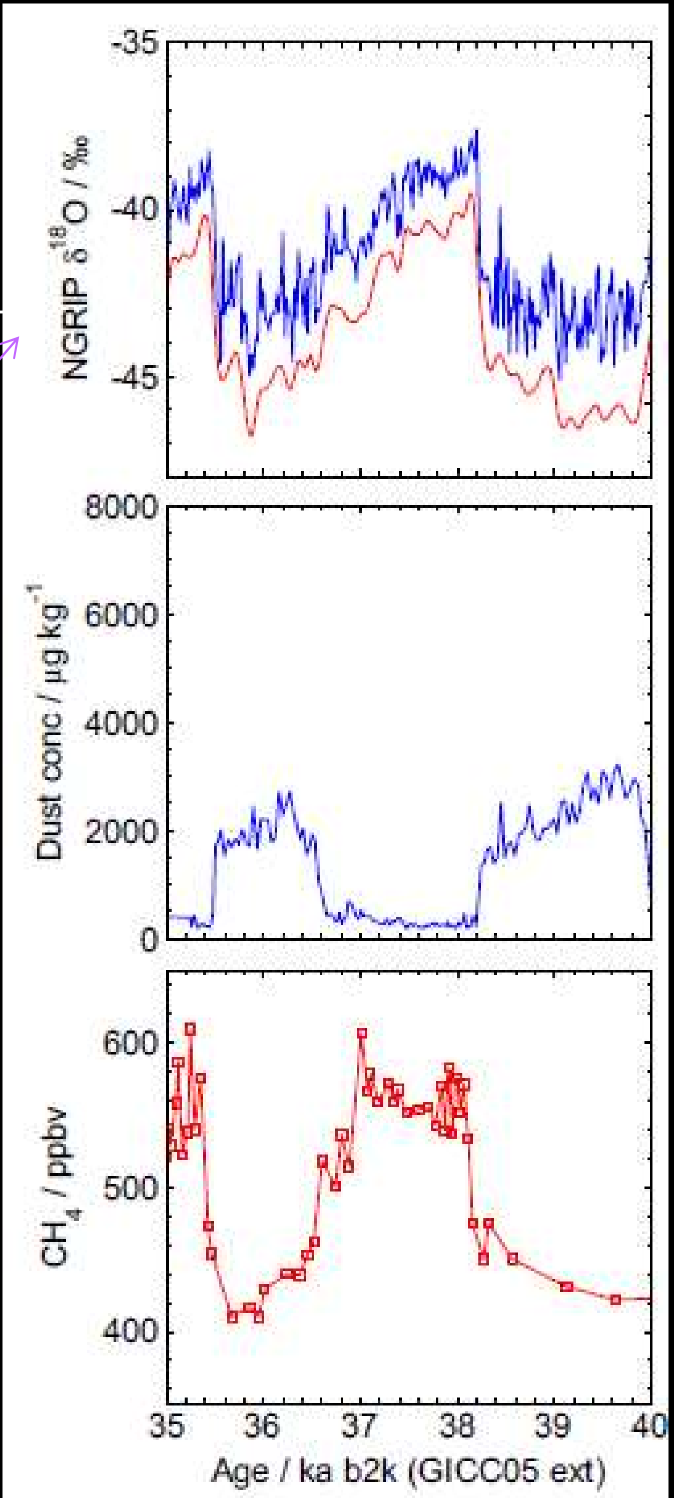
Abrupt warmings reached magnitudes of **8 to 16 ± 3°C** within decades to centuries!



(Huber et al., 2006; Landais et al., 2004).

CH_4 during rapid D/O events

D/O temperature changes: sawtoothed in shape with highest values at the start, and ramping down during the warming event

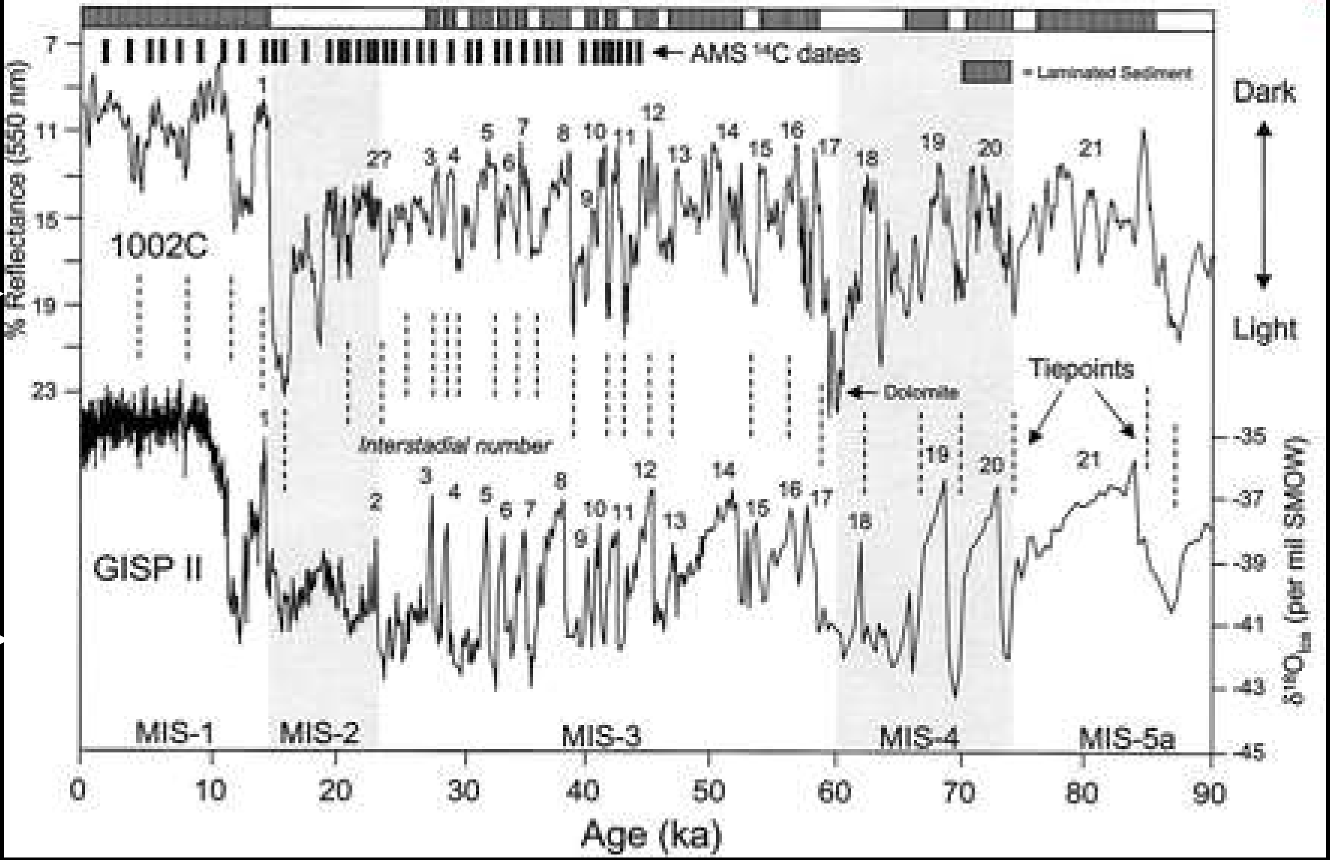


CH_4 changes shows a variety of patterns, with events in which concentration increase during the warm period.

This means that the source of CH4 can be enhanced as long as the temperature remains high, event if it is decreasing.

The very abrupt, millennial-scale, climatic flips of the last glacial period were not restricted to Greenland
but had a global imprint.

They coincide with large-scale northern hemisphere warming, changes in the ITCZ position
and in the northern hemisphere monsoons.



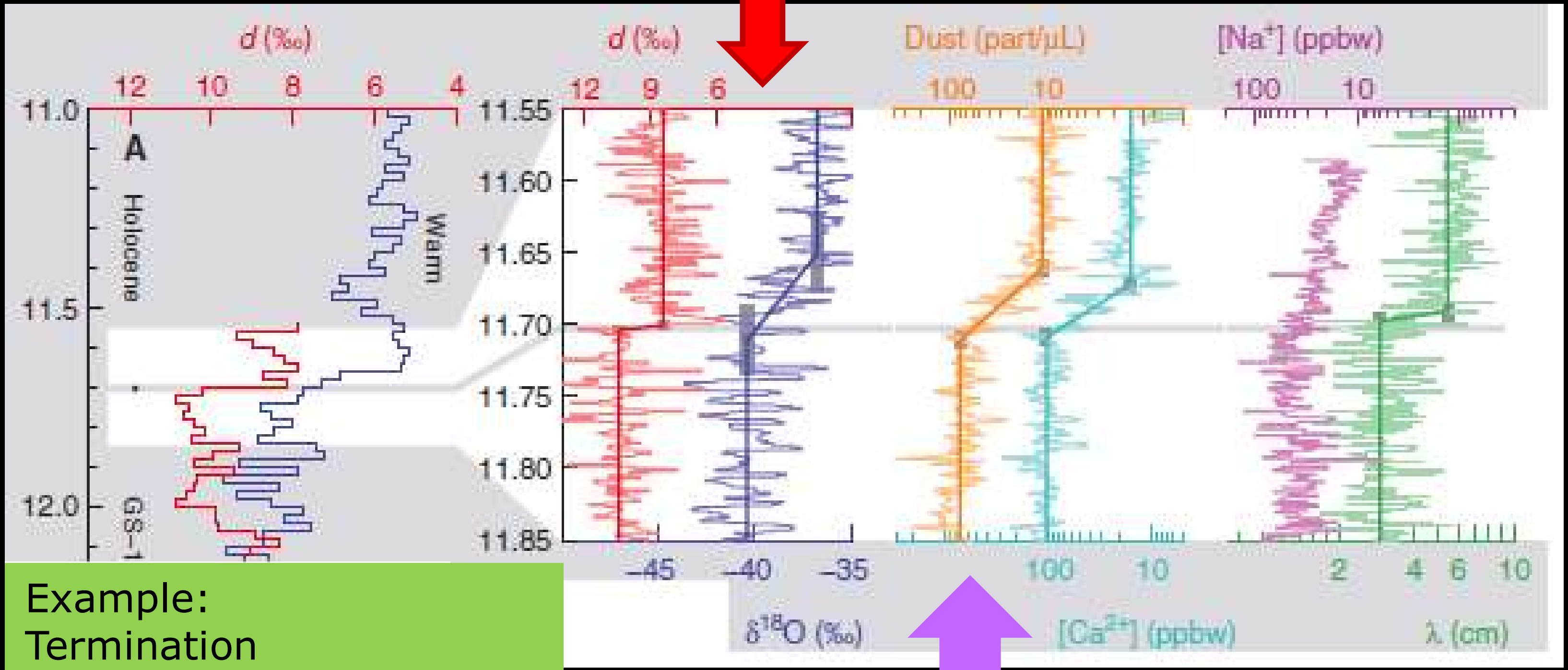
CARIACO BASIN
Venezuela

GREENLAND

Peterson et al.,2000

The SEQUENCE OF EVENTS recorded on the same core allows investigating the phasing of these events.

The most abrupt transitions are those of the deuterium excess – switching mode within 1 to 3 years over rapid climate swings.
This initiated a more gradual change, over about 50 yrs, of Greenland air temperature.

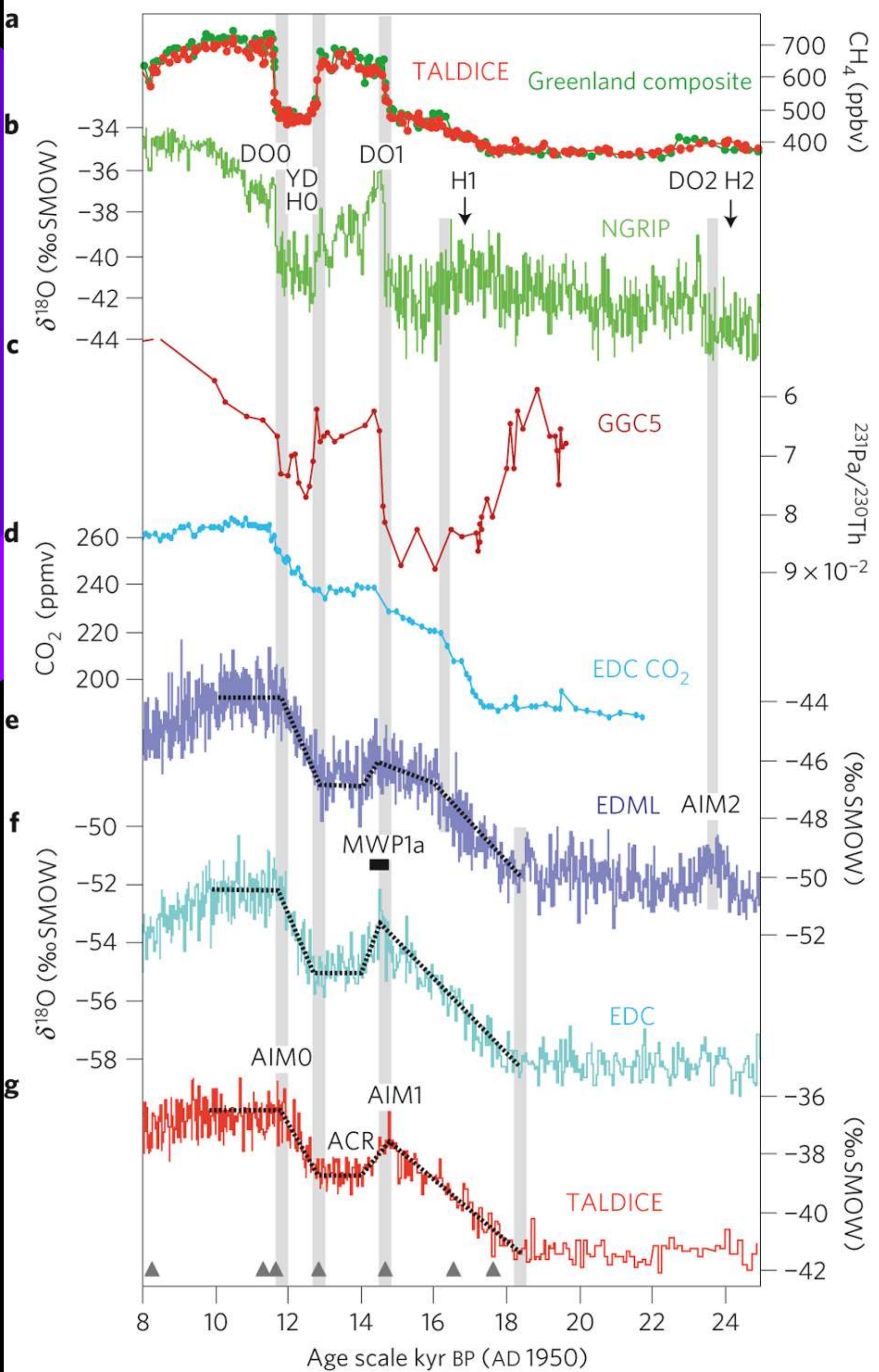


Example:
Termination
of the YD cold period

Interestingly, Greenland warming seem to be *preceded* by decreasing dust deposition, which originates from Asia. This suggests wetting of Asian deserts related to northward shift of the ITCZ, which could trigger Northern Hemisphere abrupt climate events.

Rapid change is not the whole story from Greenland

- The phasing of D/O events recorded in Greenland ice cores suggest that the first sign of climatic change may originate from ***outside the North Atlantic region.***
- Not only dust from Asia, but also N_2O concentration starts to rise a few centuries before the Greenland warming during D/O events (Fluckinger et al., 2004).
- Also marine records (intermediate-water-temperature tracers measured along a marine core from the Santa Barbara Basin) indicate that parts of the climate system started to move toward a new state before the abrupt transition in the North Atlantic (Hendy and Kennett, 2003).



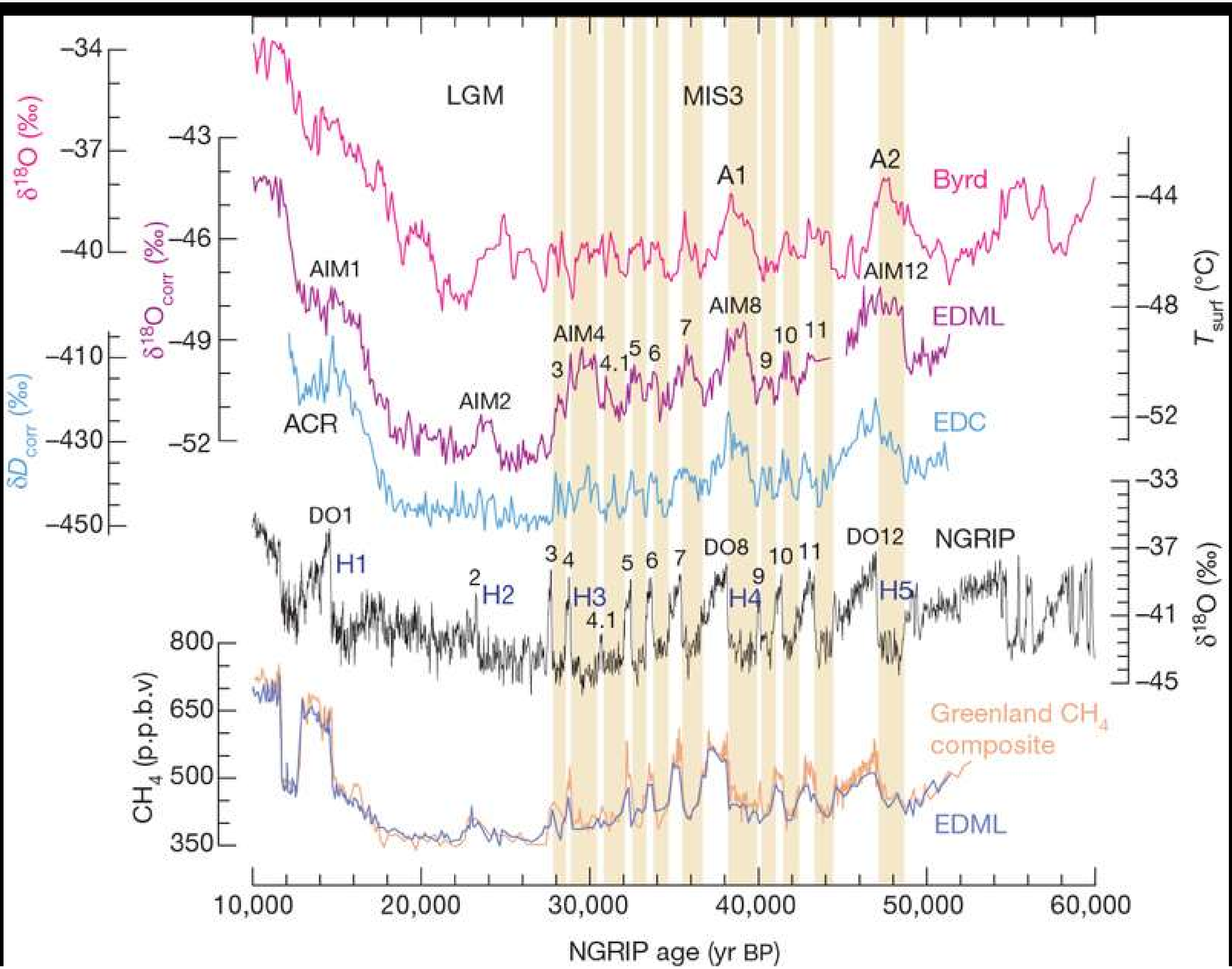
A bipolar seesaw between the poles

- A prerequisite for studying the sequence and possible links between climate events in Greenland and Antarctica is the determination of their relative timing with sufficient accuracy

- High-resolution CH_4 records have been used to place the EPICA Dronning Maud Land (EDML), and by extension the EPICA-Dome C (EDC) , Vostok, and Talos Dome Antarctic ice cores, on the layer-counted GICC05 timescale.

Stenni et al., 2010

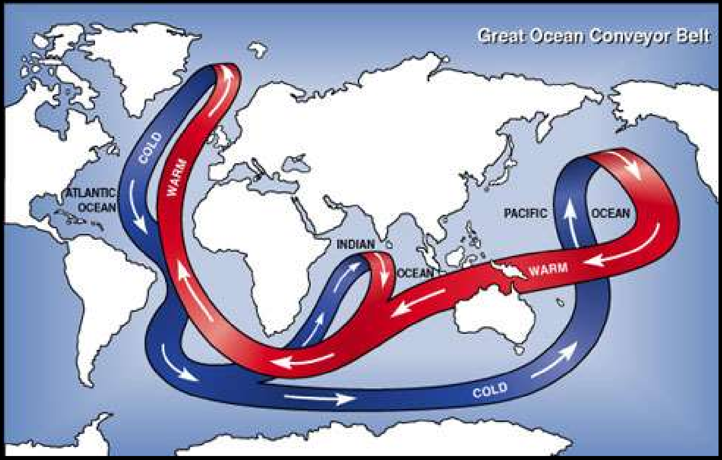
Greenland stadials are marked by a slow Antarctic warming, reaching a typical amplitude of ~2°C. Abrupt Greenland warmings end the Antarctic optima and Greenland interstadials coincide with slow Antarctic cooling.

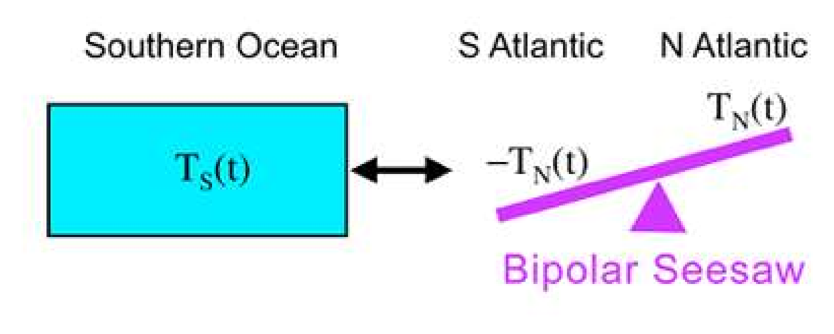


Southern and Northern Hemispheres “climate see-saw”

The usual explanation for the millennial-scale variability is that it is due to changes in the deep meridional overturning circulation (MOC) in the Atlantic Ocean. Put simply, a vigorous MOC is thought to deliver heat to the North Atlantic at the expense of the Southern Ocean.

Increases and decreases in MOC strength should thus result in a in a climate 'see-saw' between the Southern and Northern hemispheres (Crowley, 1992)





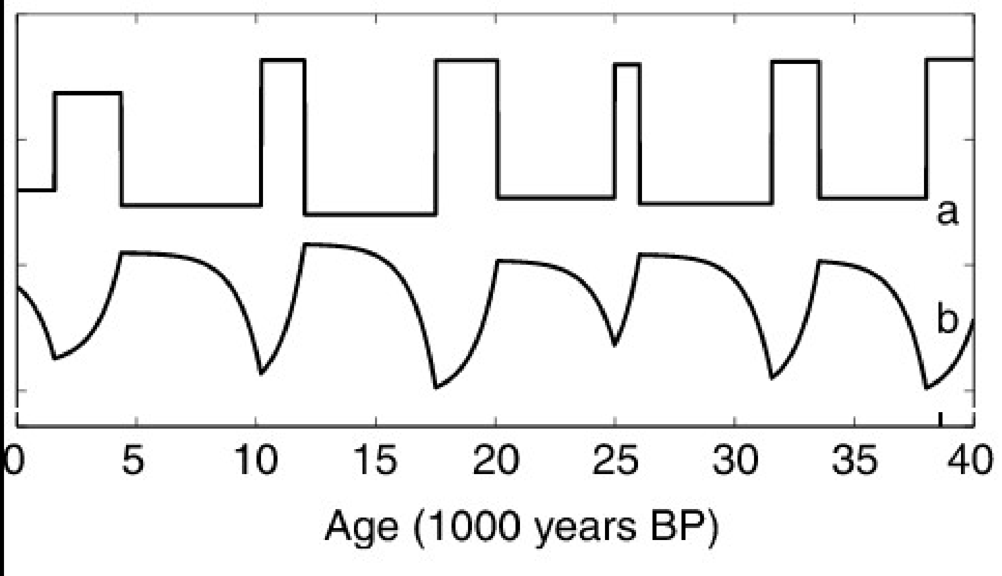
North Atlantic temperature changes are mirrored by equal amplitude South Atlantic changes of opposite sign.

Southern Ocean temperatures are relaxed toward this South Atlantic temperature.

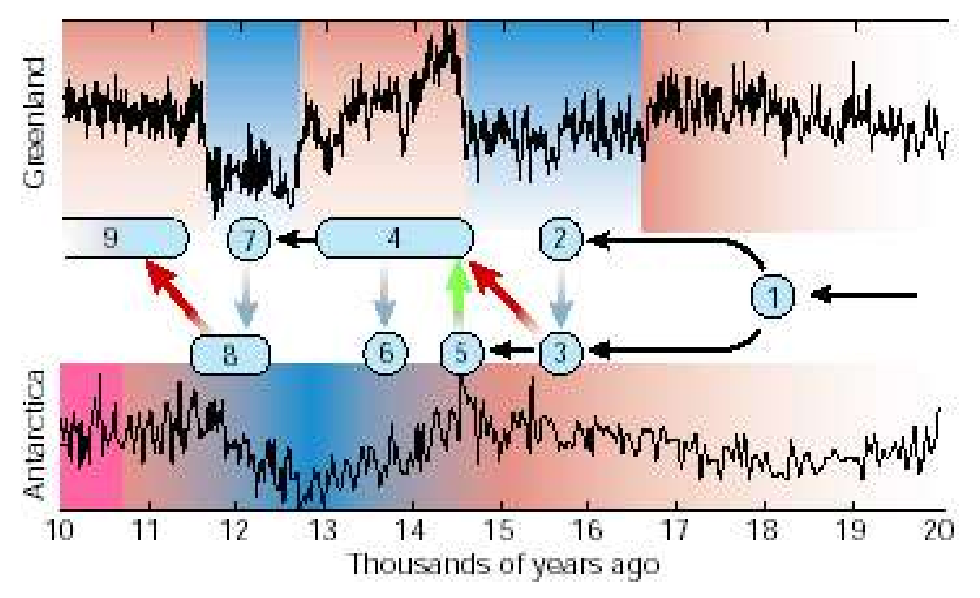
A simple model of the thermal bipolar seesaw

Stocker and Johnsen (2003)

The heat reservoir convolves northern time signals with a characteristic timescale (1000–1500 years). In its cleanest form, and without any other climate processes at work, the model would produce a step-shaped Northern Atlantic climate curve (a) and a softer Southern Ocean response (b)

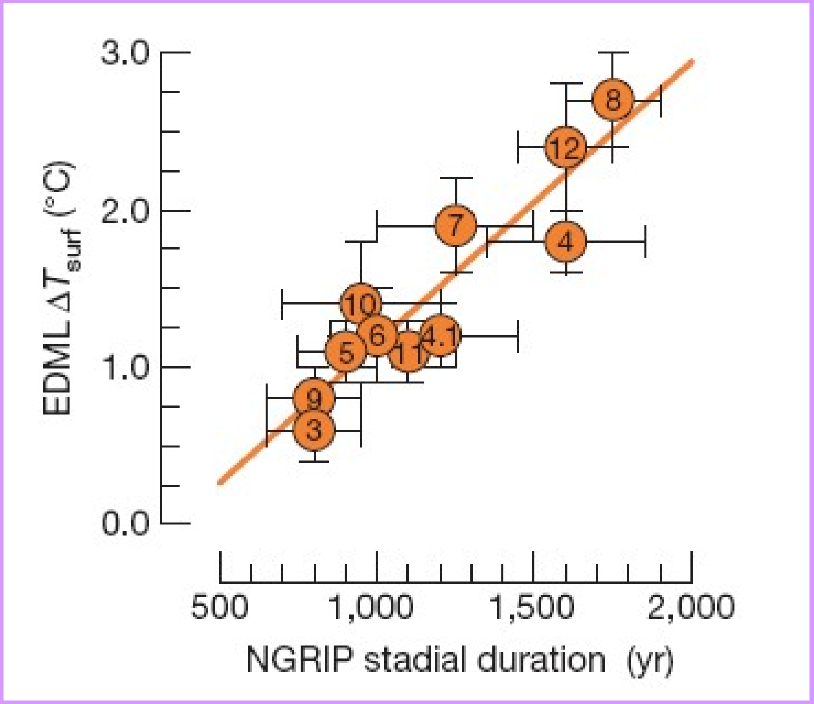


This simple seesaw model accounts for both the phasing and the shape of the events



The response of the Southern Ocean is slow compared to the Atlantic temperature seesaw, reflecting the relatively strong separation of the Antarctic Southern Ocean from the remaining global circulation system.

Magnitude of warming in Antarctica & duration of the warm period that follows each abrupt event in Greenland.



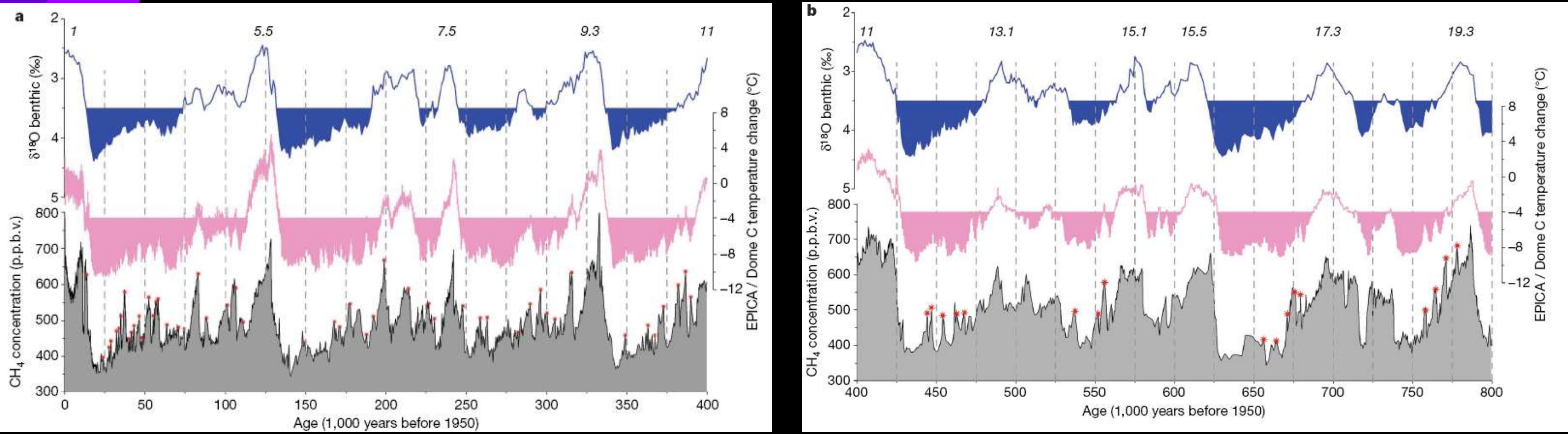
EPICA Community, 2006

The duration of the warm periods in Greenland reflects the duration of reduced MOC hence the amount of heat retained in the Southern Ocean.

The magnitude of Antarctic temperature change is controlled by the effective size of the Southern Ocean heat reservoir

Southern counterpart of D/O events

In Antarctica, maxima in water stable isotopes (Antarctic Isotopic Maxima) and abrupt changes in methane concentration represent the counterpart of D/O events.

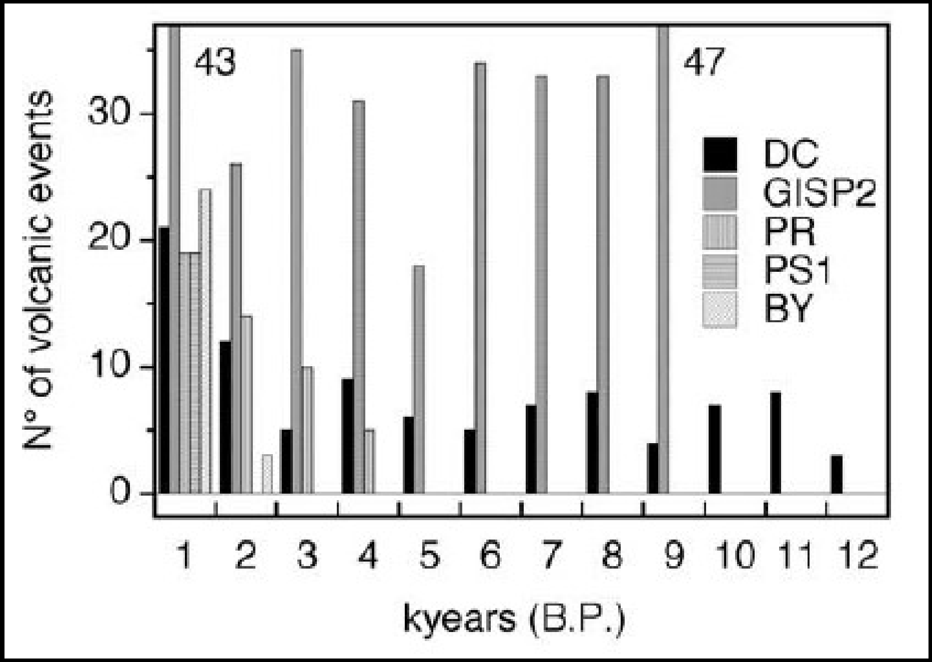


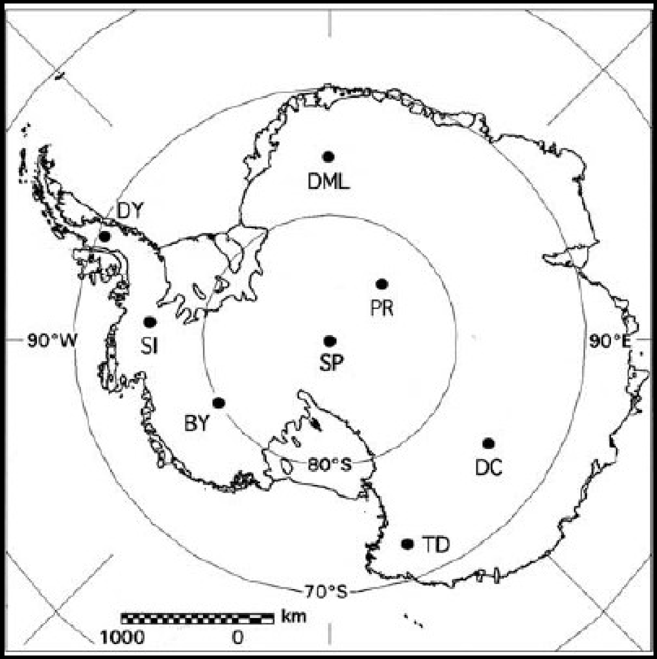
Over the last 800.000 years, 74 D/O-like events were identified in the EPICA-Dome C deuterium and methane record (Loulergue et al., 2008)

The Holocene

Holocene changes in volcanic activity based on sulphate fluxes from ice cores

Volcanic forcing amplitude and occurrence varied significantly during the Holocene, the last 2000 years being a period of enhanced volcanic activity (Castellano et al., 2005).



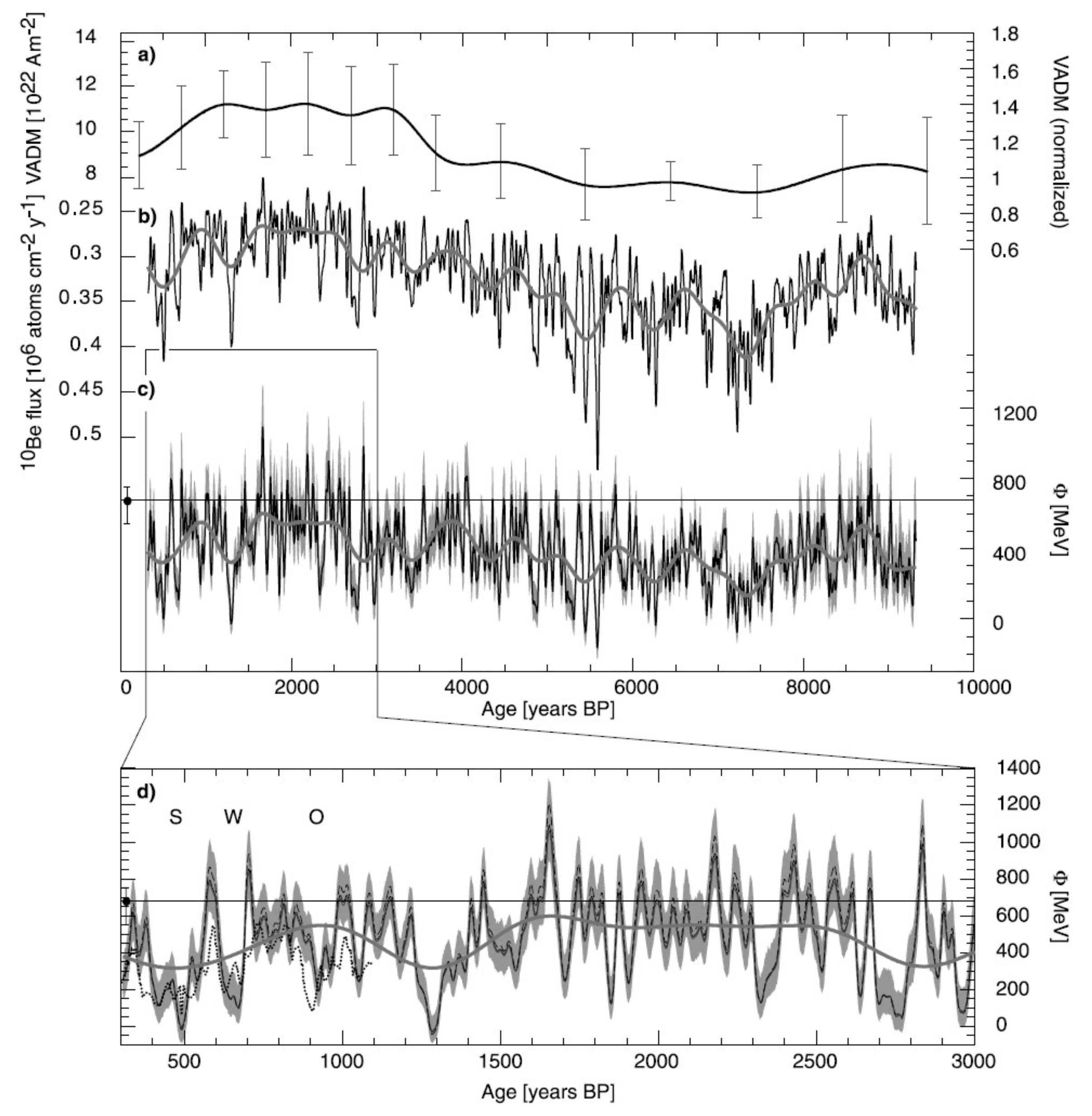


Holocene changes in solar activity based on ^{10}Be from ice cores

- The solar modulation function has been derived from the filtered ^{10}Be and lowpass filtered geomagnetic dipole moment.

- Further work is needed to disentangle solar from non-solar influences on these proxies over the full Holocene

Vonmoos et al., 2006



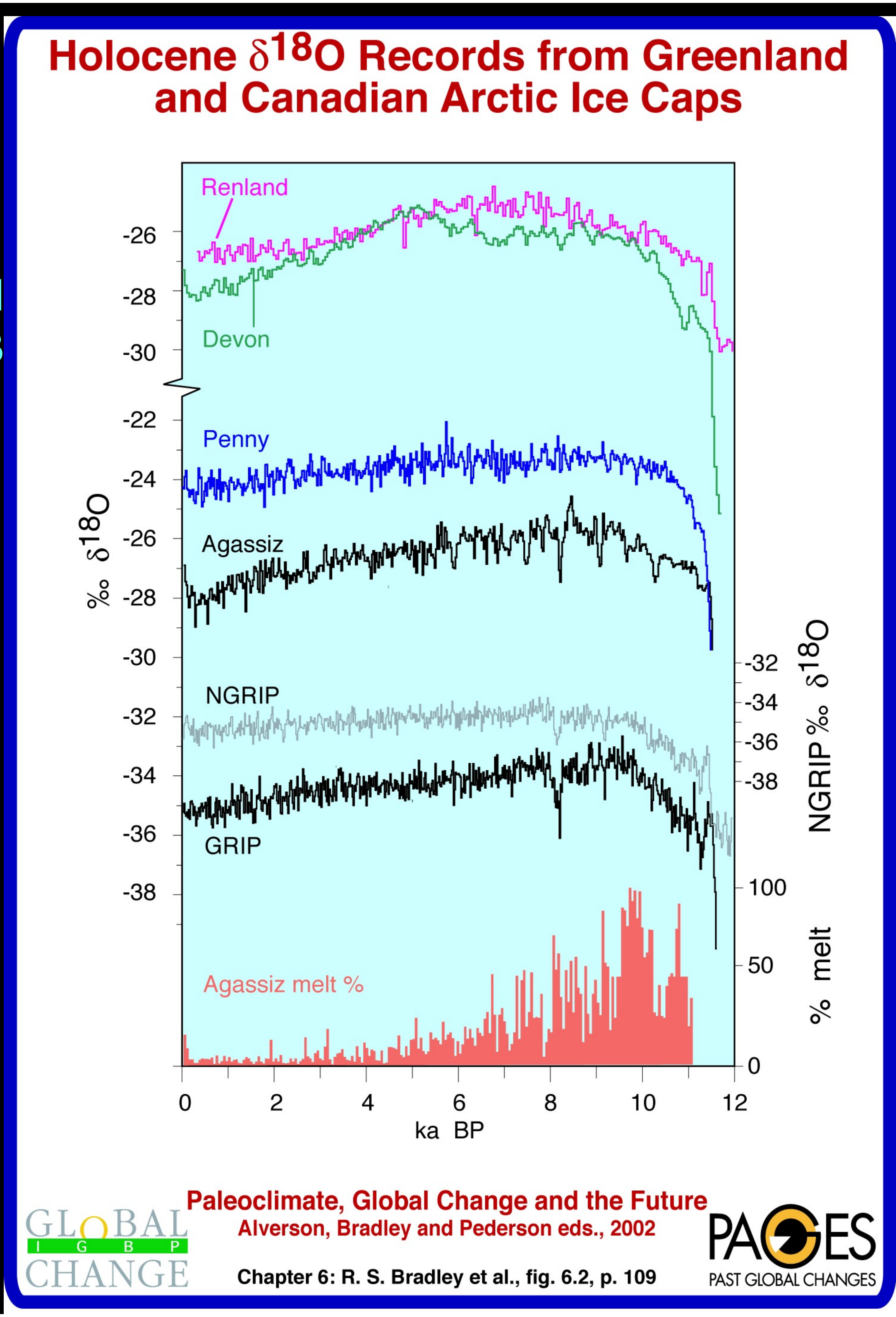
Apparent temperature stability in Greenland

Alverson, Bradley and Pedersen, 2003

Holocene δ^{18}O records from Greenland (Renland, GRIP) and Canadian Arctic ice caps (Devon, Penny, Agassiz).

Also shown is the record of melt in cores from the Agassiz Ice Cap, Ellesmere Island, Arctic Canada

(% of core sections showing evidence of melting and percolation of meltwater into the firn) (after Fisher and Koerner 2002).



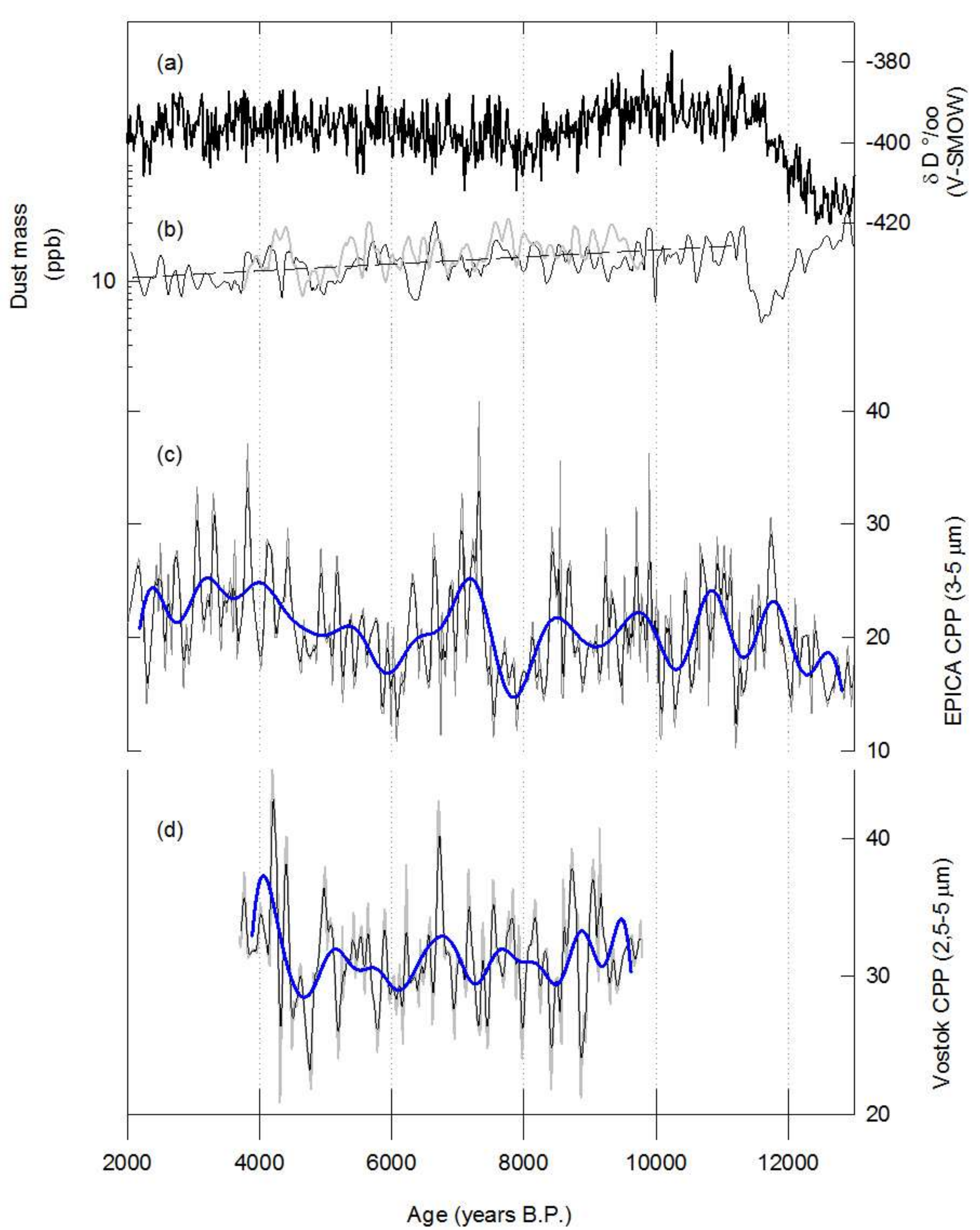
Holocene δ^{18}O Records from Greenland and Canadian Arctic Ice Caps

Paleoclimate, Global Change and the Future

Alverson, Bradley and Pederson eds., 2002

Chapter 6: R. S. Bradley et al., fig. 6.2, p. 109

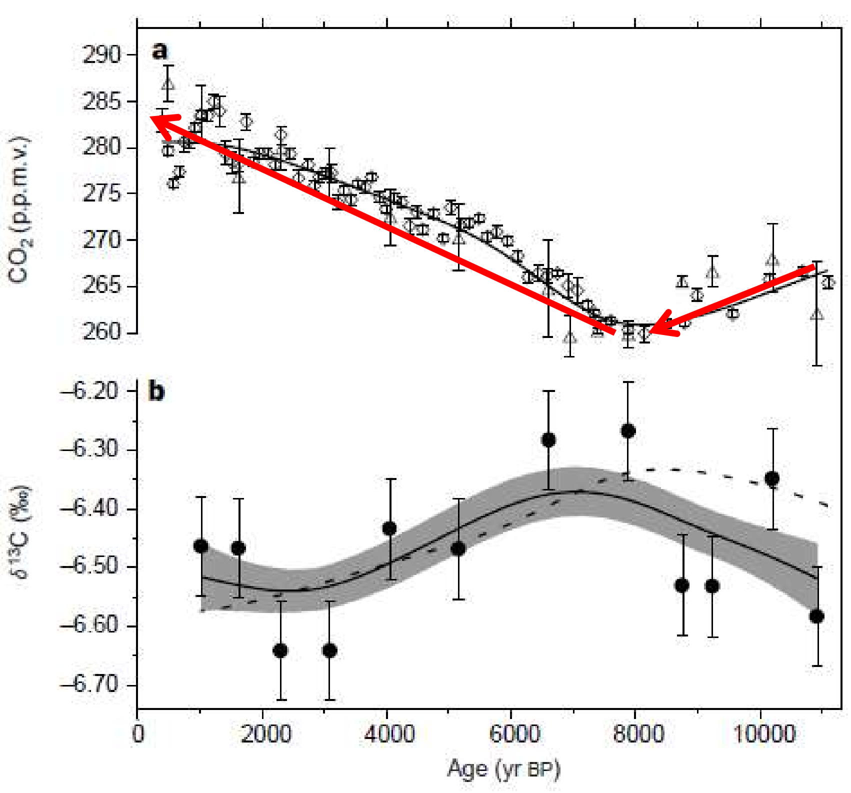
Small temperature trends in Antarctica but significant atmospheric circulation variability through the Holocene



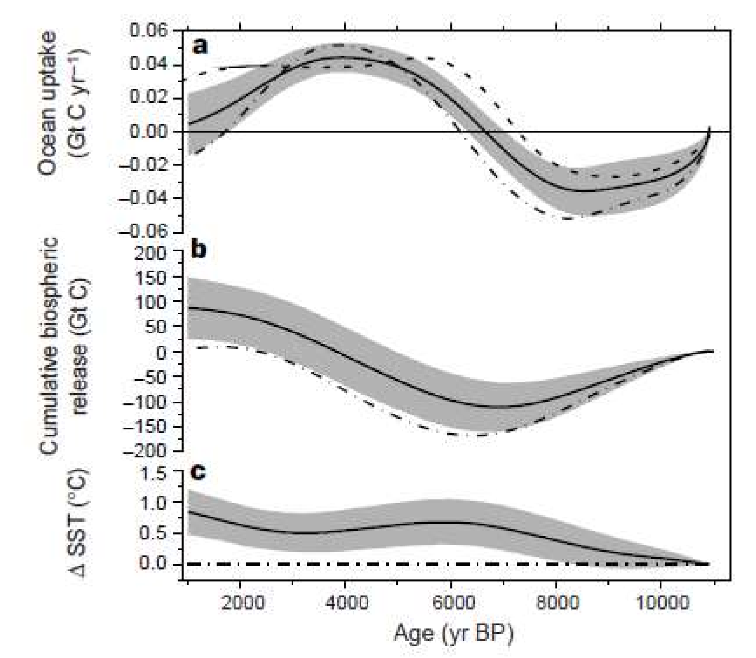
(Masson-Delmotte, 2000)

(Delmonte, 2005)

Holocene pre-industrial CO_2 changes from Antarctic ice cores



11-7 kyrs BP:
Biospheric uptake of C observed in ice cores is consistent with expectations based on vegetation regrowth and soil build-up on areas initially covered by ice sheets, and with a climatic gradual development towards a Holocene optimum.



7 -1 kyrs BP:
biospheric release of C related to the change from warm and wet mid-Holocene conditions to colder and drier conditions.

Holocene GHG change from polar ice cores

The mid- Holocene CH4 minimum is associated with a high interpolar gradient, indicating relatively larger northern sources and smaller tropical sources.

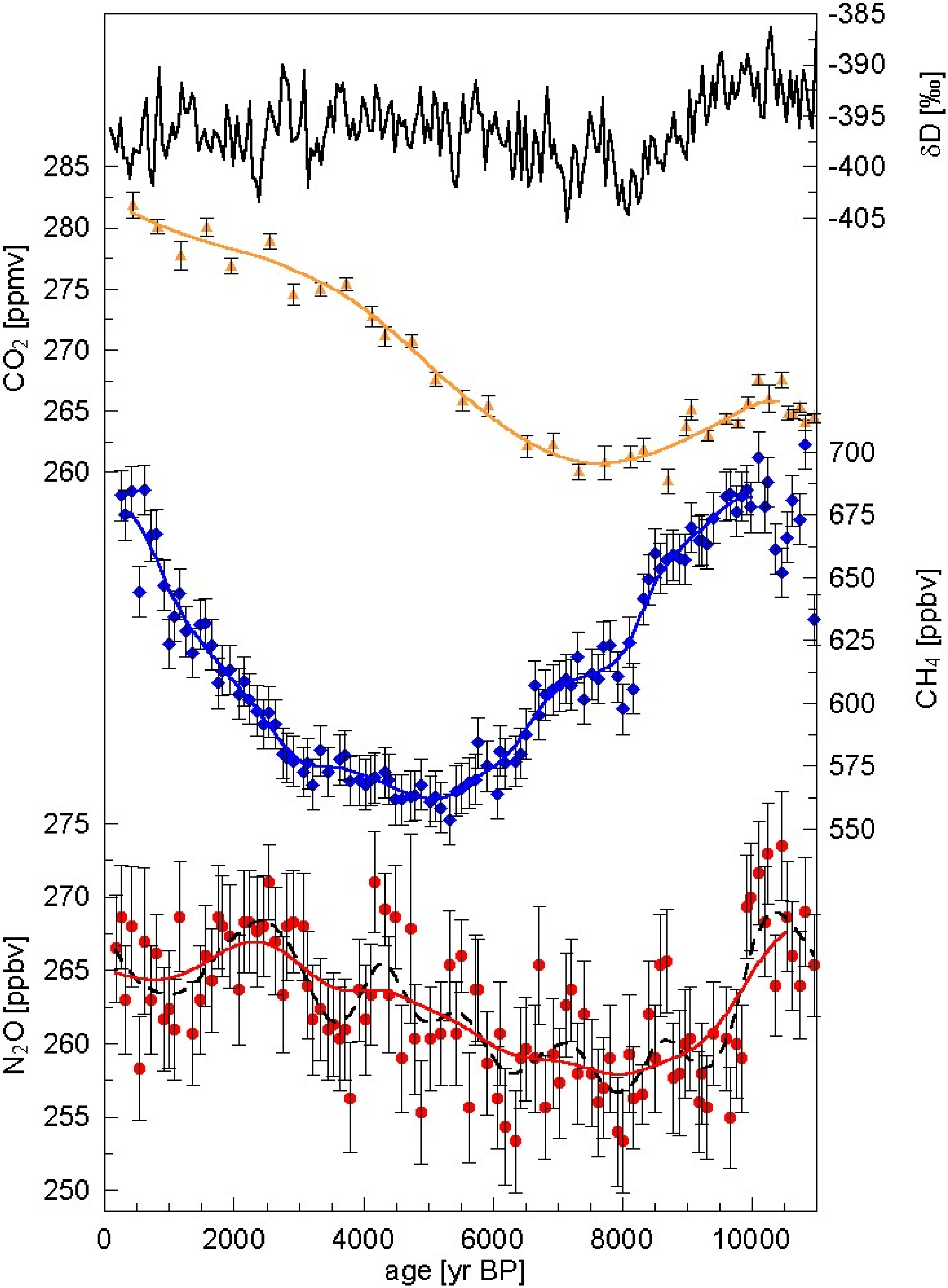
This probably reflects the drying of a tropical region, perhaps in Africa (which is also consistent with the atmospheric oxygen isotope data), and increase in boreal emissions as the Laurentide ice sheet disappeared.

After 5 kyr B.P., progressive drying of the tropical regions combined with a period of massive peat growth in the boreal regions occurred.

(Monnin et al., 2004)

(Chappellaz et al., 1997)

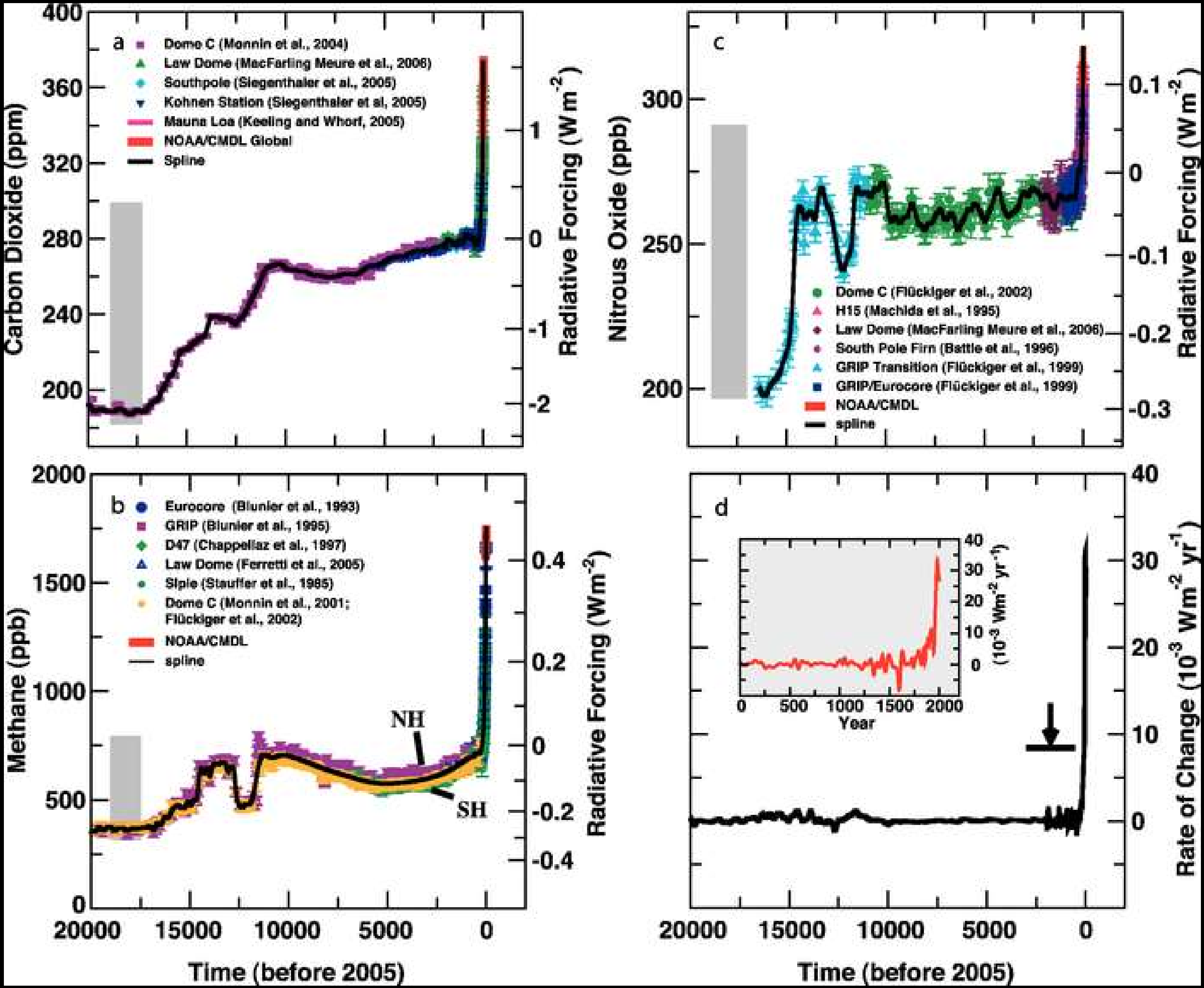
(Fluckinger et al., 2002)



Ice core relevance to understand the “anthropocene”

Ice core information on past climates is essential to place the anthropogenic perturbation in the context of the natural variability of atmospheric circulation and polar climate.

Polar ice cores demonstrate that both the current level and the rate of GHG concentration change of in the atmosphere are unprecedented over the last 800.000 years


a
Dome C (Monnin et al., 2004)
Law Dome (MacFarling Meure et al., 2006)
Southpole (Siegenthaler et al., 2005)
Kohnen Station (Siegenthaler et al, 2005)
Mauna Loa (Keeling and Whorf, 2005)
NOAA/CMDL Global
Spline
Carbon Dioxide (ppm)
Radiative Forcing (W m^{-2})
400
360
320
280
240
200
1
0
-1
-2
c
Nitrous Oxide (ppb)
Radiative Forcing (W m^{-2})
300
250
200
0.1
0
-0.1
-0.2
-0.3
Dome C (Flückiger et al., 2002)
H15 (Machida et al., 1995)
Law Dome (MacFarling Meure et al., 2006)
South Pole Firn (Battle et al., 1996)
GRIP Transition (Flückiger et al., 1999)
GRIP/Eurocore (Flückiger et al., 1999)
NOAA/CMDL
spline
b
Eurocore (Blunier et al., 1993)
GRIP (Blunier et al., 1995)
D47 (Chappellaz et al., 1997)
Law Dome (Ferretti et al., 2005)
Siple (Stauffer et al., 1985)
Dome C (Monnin et al., 2001; Flückiger et al., 2002)
NOAA/CMDL
spline
Methane (ppb)
Radiative Forcing (W m^{-2})
2000
1500
1000
500
0
0.4
0.2
0
-0.2
-0.4
NH
SH
20000
15000
10000
5000
0
Time (before 2005)
d
40
30
20
10
0
(10^{-3} Wm^{-2} yr^{-1})
0
500
1000
1500
2000
Year
Rate of Change (10^{-3} Wm^{-2} yr^{-1})
40
30
20
10
0
20000
15000
10000
5000
0
Time (before 2005)

EPICA-Dome C Atmospheric carbon dioxide over the last 800.000 years

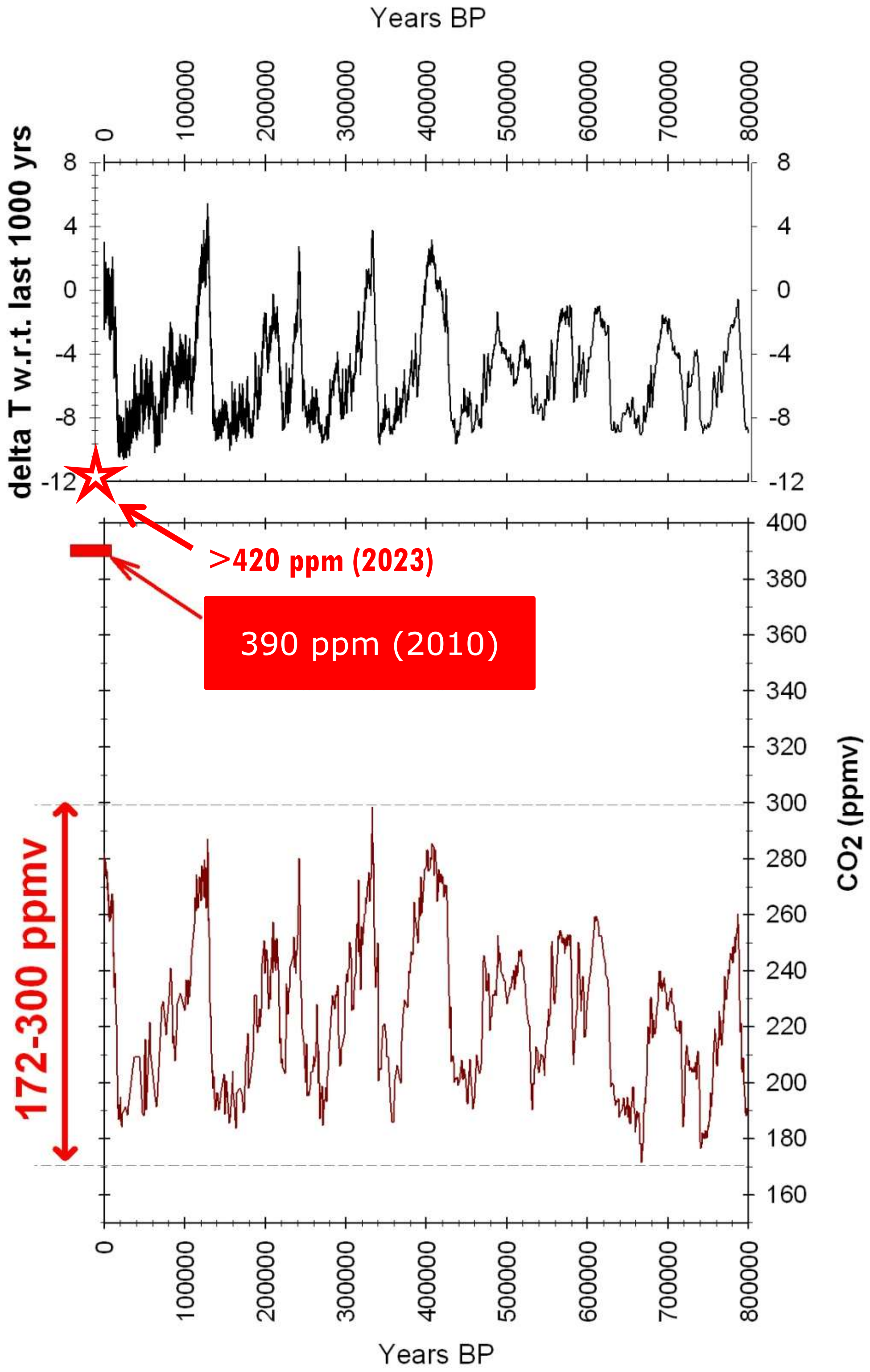
Luthi et al., 2008

Pre-industrial range of CO_2: 172-300 ppmv

Carbon dioxide has increased from fossil fuel use in transportation, building heating/cooling and the manufacture of cement and other goods.

Deforestation releases CO_2 and reduces its uptake by plants.

Carbon dioxide is also released in natural processes such as the decay of plant matter.



>420 ppm (2023)

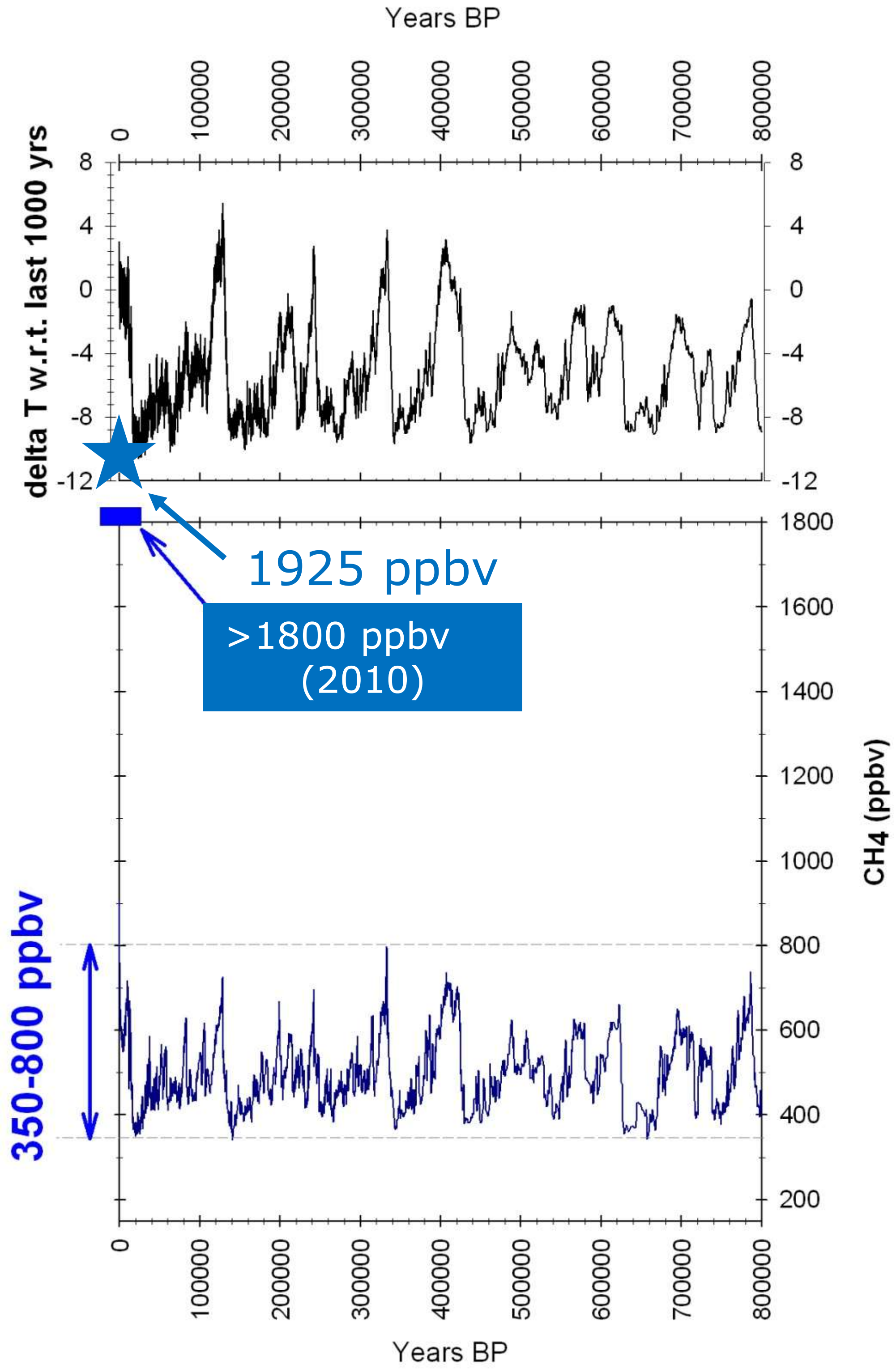
390 ppm (2010)

172-300 ppmv

EPICA-Dome C Atmospheric methane over the last 800.000 years

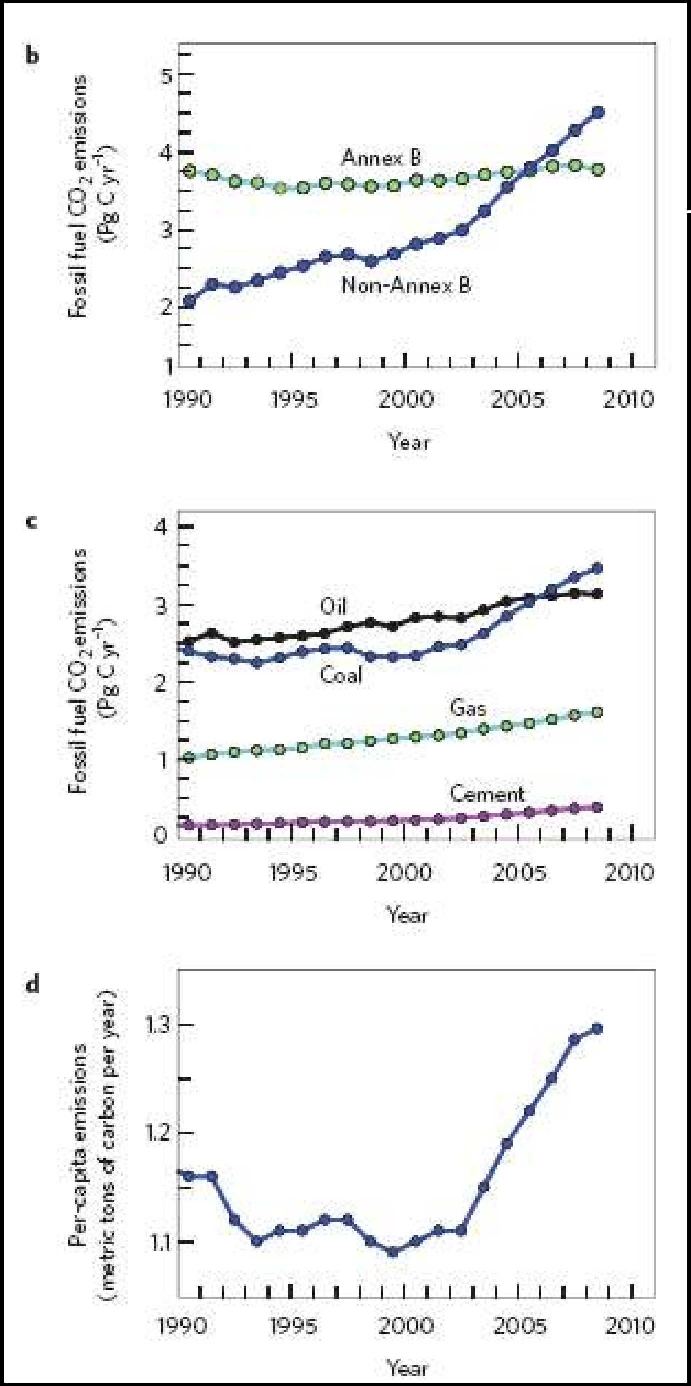
Loulergue et al., 2008

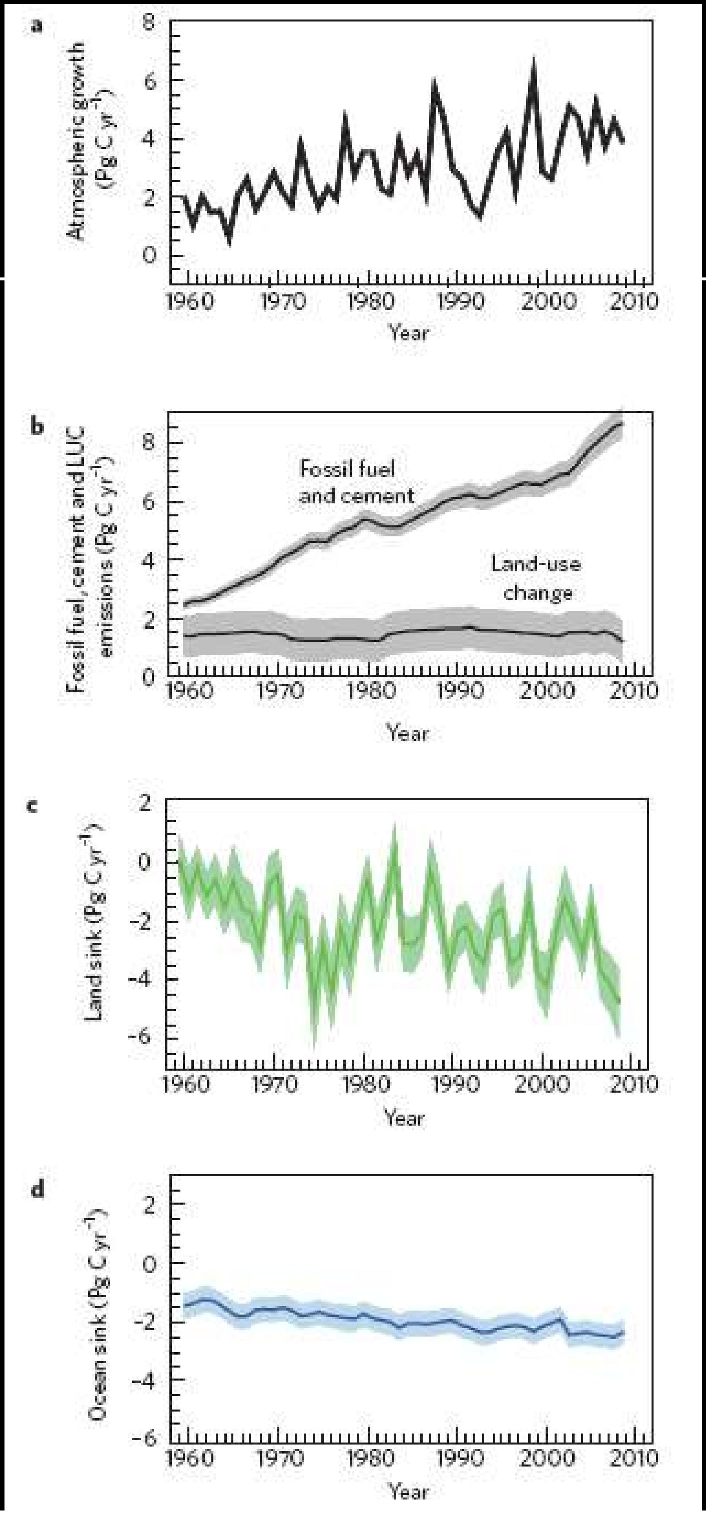
Pre-industrial range of CH_4

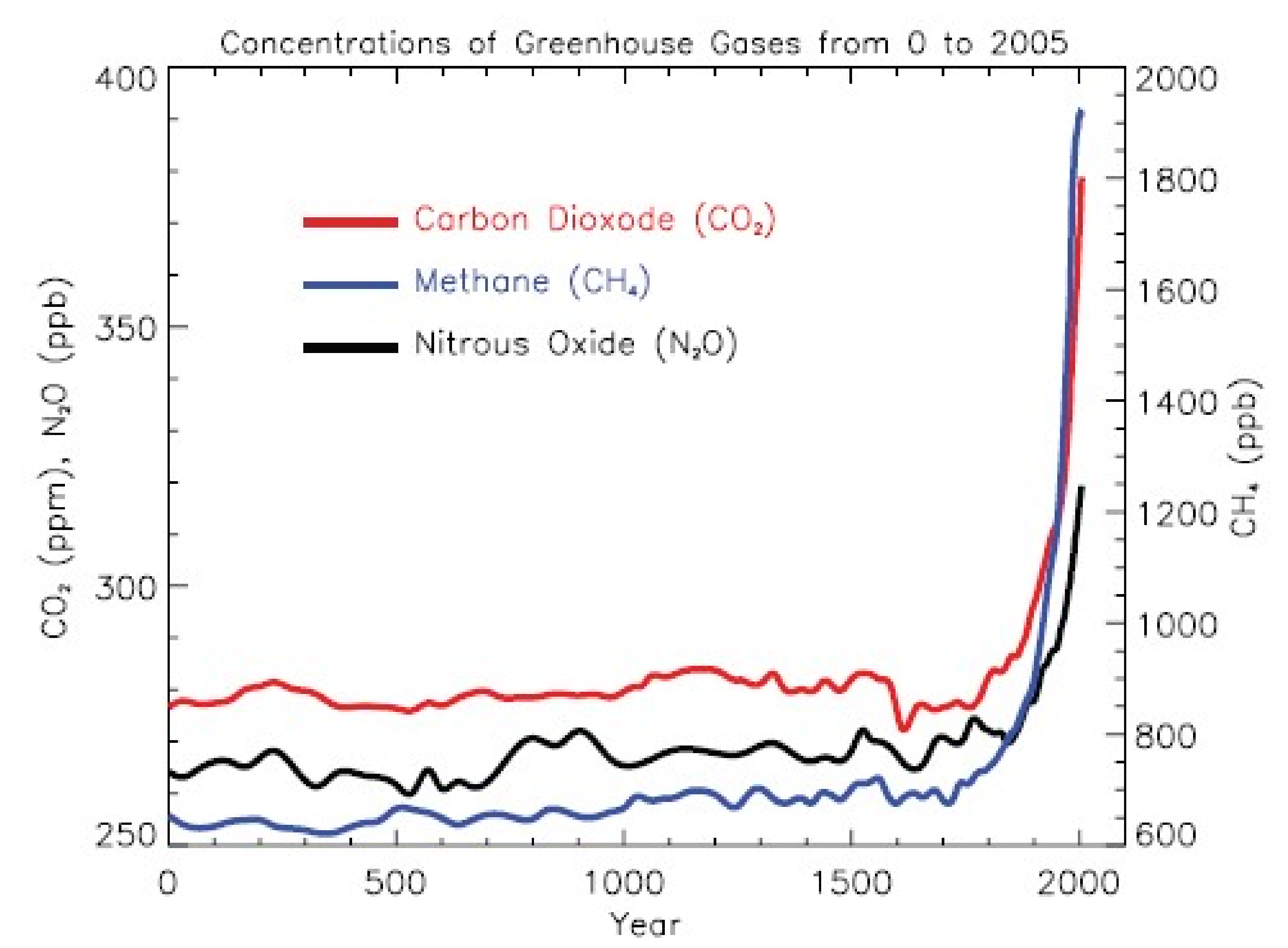


- Methane has increased as a result of human activities related to agriculture, natural gas distribution and landfills. Methane is also released from natural processes that occur, for example, in wetlands.

Le Quéré et al., 2009





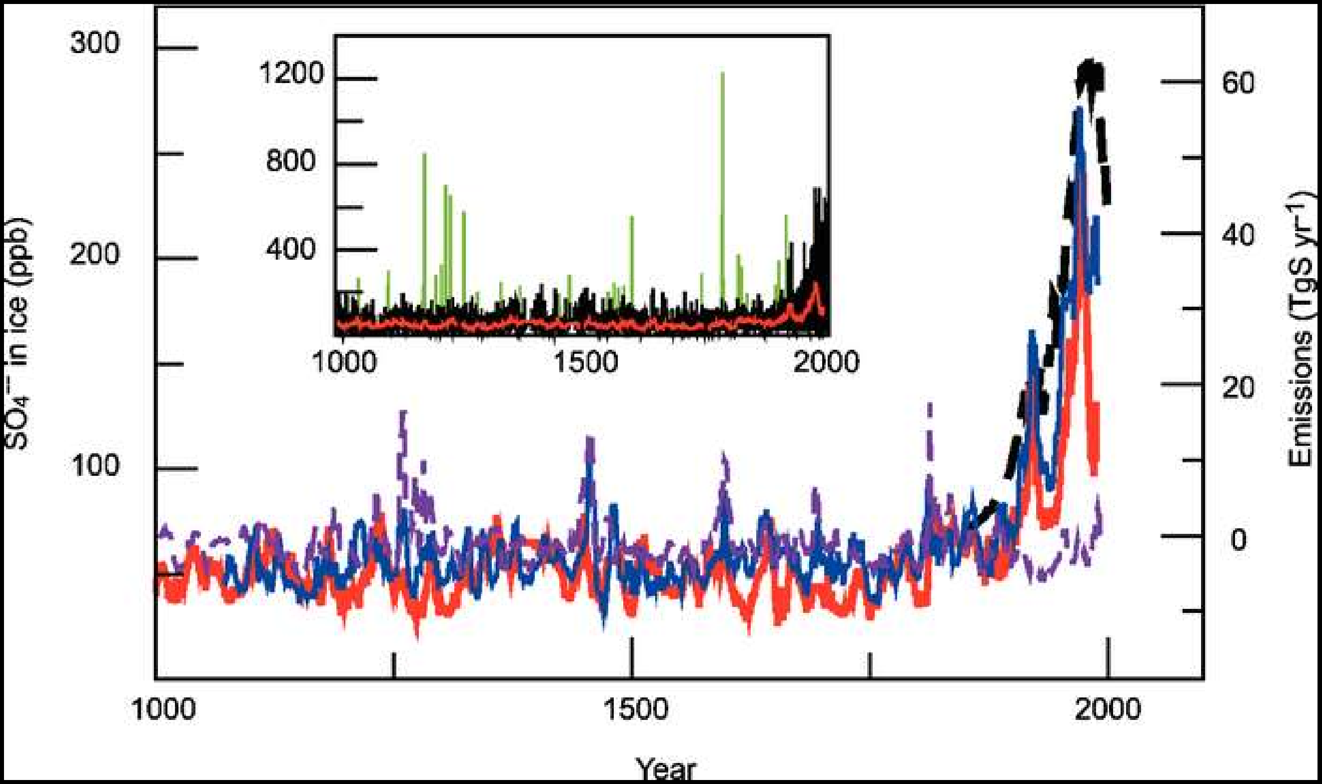


- Nitrous oxide is also emitted by human activities such as fertilizer use and fossil fuel burning. Natural processes in soils and the oceans also release N_2O.

Preindustrial levels: 270 ppbv
Present-day (2008): 322 ppbv

7: Natural and anthropogenic aerosols

Ice core data from Greenland (Bigler et al., 2002) document changes in sulphur dioxide emissions and tropospheric sulphate aerosol loading above the pre-industrial background during the modern industrial era. They also show a very recent decline in these emissions.

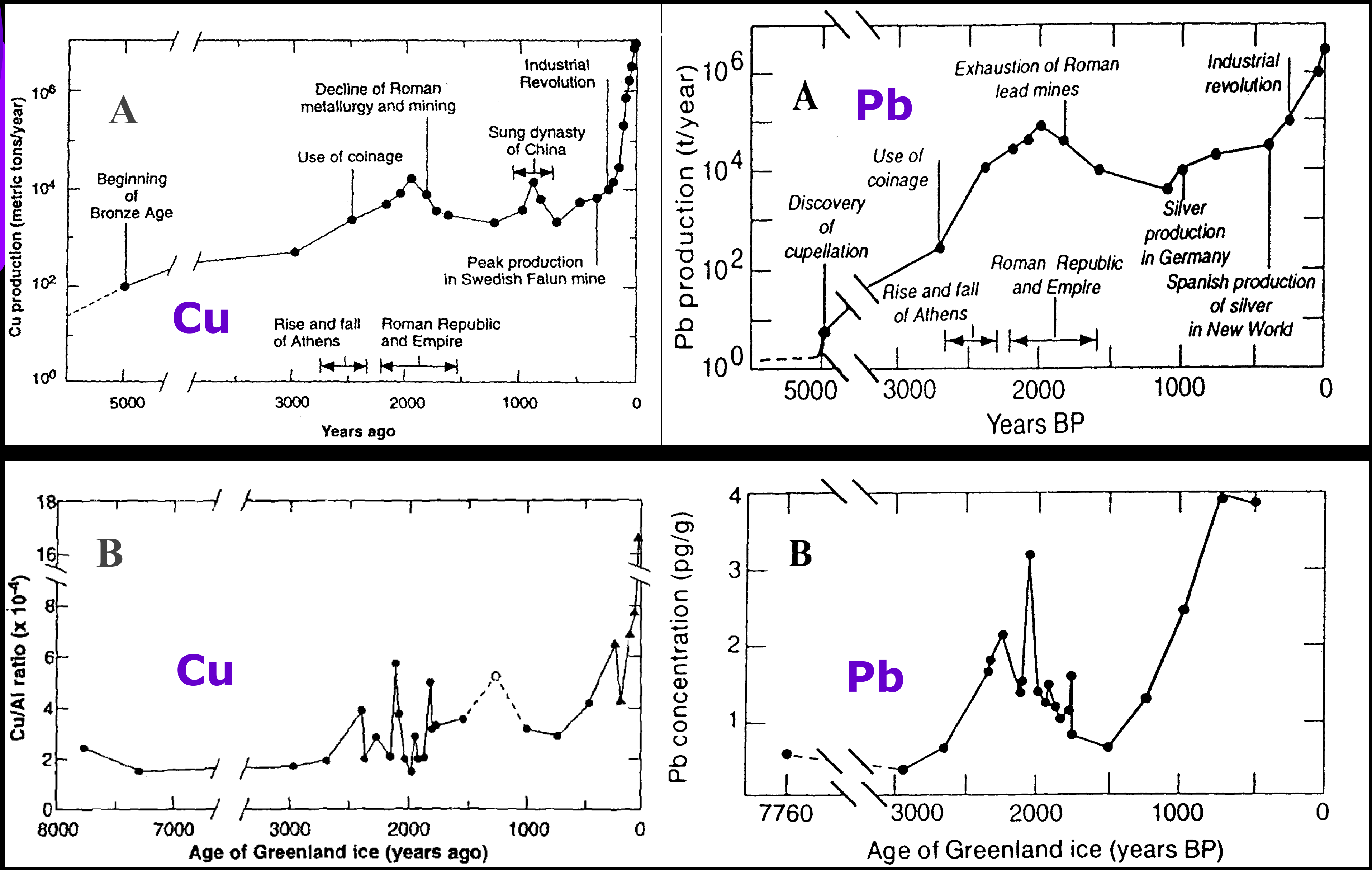


1940s -1970s
Rising background level of sulphate because of the use of sulphur-rich fossils fuels

Initiatives to cut emissions and clean the sulphate from exhaust gasses were initiated, and by 2000, the sulphate level in Greenland precipitation dropped.

7: Natural and anthropogenic aerosols

Cu and Pb production (A) and (B) concentration in Greenland



Boutron et al., 1995,1996

Continuous CH_4 measurements have been performed on the TALDICE ice core with a new on-line melting technique associated to the Continuous Flow Analysis (CFA) system.

Schüpbach et al., 2011

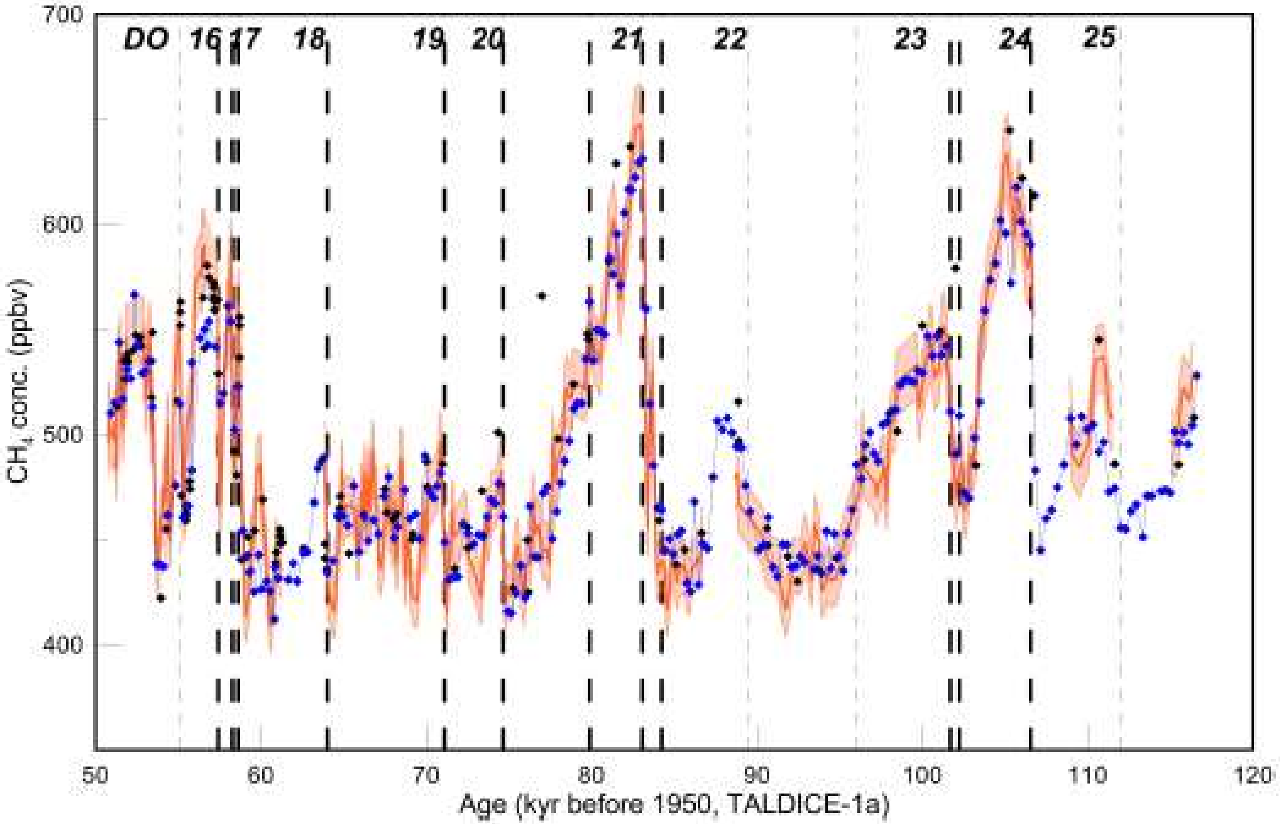
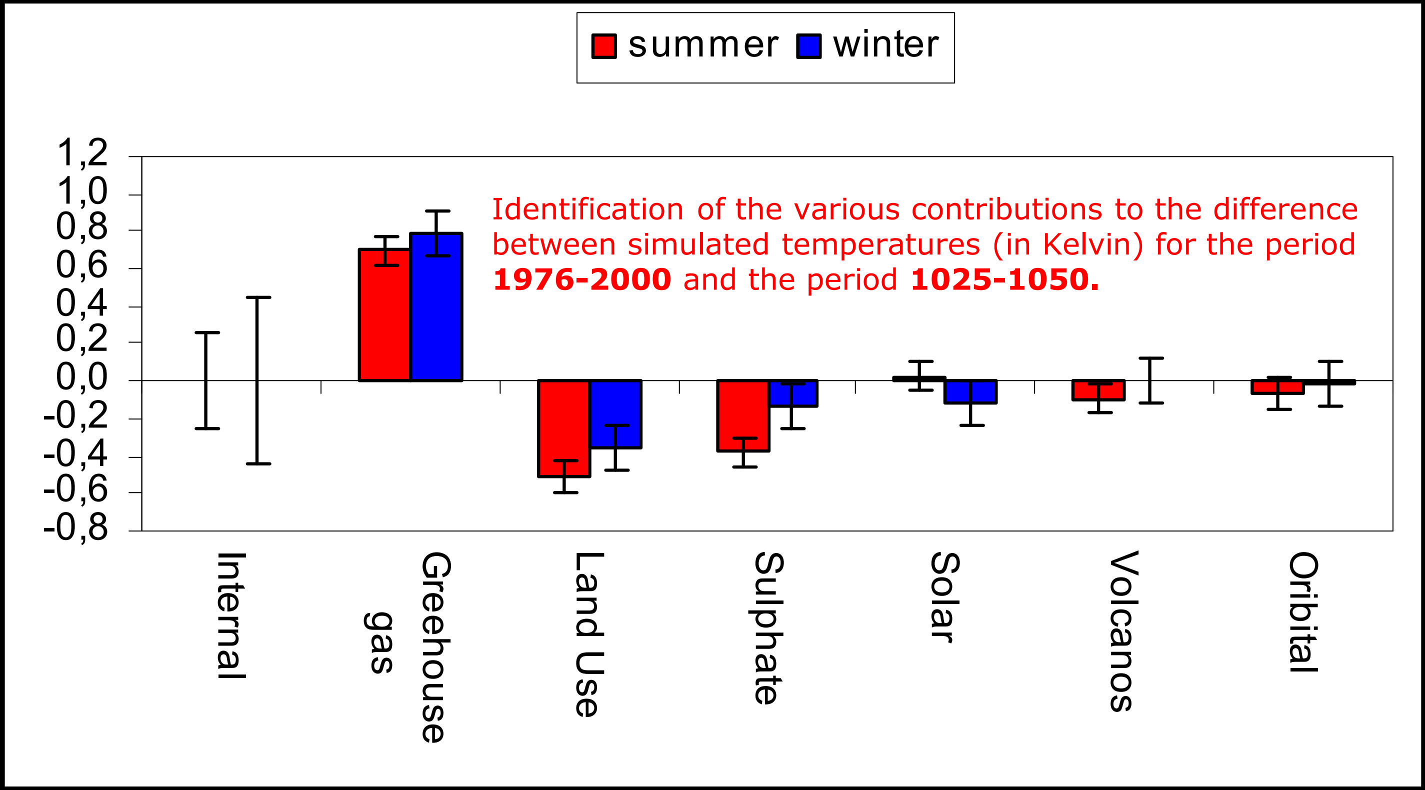


Fig. 3. The CH_4 records (EDC: blue diamonds, discrete TALDICE data: black diamonds, new high resolution TALDICE data: orange line) on the whole interval from 55–112 ka BP where the TALDICE-1 age scale has been refined. Bold dashed lines indicate the new tie point; fine dashed lines indicate tie points adopted from the TALDICE-1 age scale; bold italic numbers indicate Dansgaard-Oeschger (DO) events.

This is mainly caused by the warming effect of the increase in greenhouse gas concentrations, which is only partly compensated by the cooling effect associated with the increase in sulphate aerosol load.



Identification of the various contributions to the difference between simulated temperatures (in Kelvin) for the period **1976-2000** and the period **1025-1050.**

Goosse et al., 2006

The range associated with the contribution of internal variability is given by two standard deviations of the ensemble of simulations around the ensemble mean. The contributions of the individual forcings are obtained by performing an ensemble of 10 experiments with only one of the 6 forcing studied.

Ice core research today

- Today, good-quality cores can be recovered in key glaciological settings.
- Ice core research is carried out in the framework of international collaboration for logistics, drilling techniques, ice core analyses and data depositaries.
- Ice core analysis has reached a high detail of resolution and accuracy.
- Application of cut-edge technologies in parallel with classical ones.