AstroBio 2015, Santiago, Chile, 28 sept. – 2 oct. 2015

The history of Earth's climate

a short story of carbon and climate

Didier PAILLARD

LSCE - IPSL
Laboratoire des Sciences du Climat et de l'Environnement
Institut Pierre-Simon Laplace

1. Climate change and ice ages

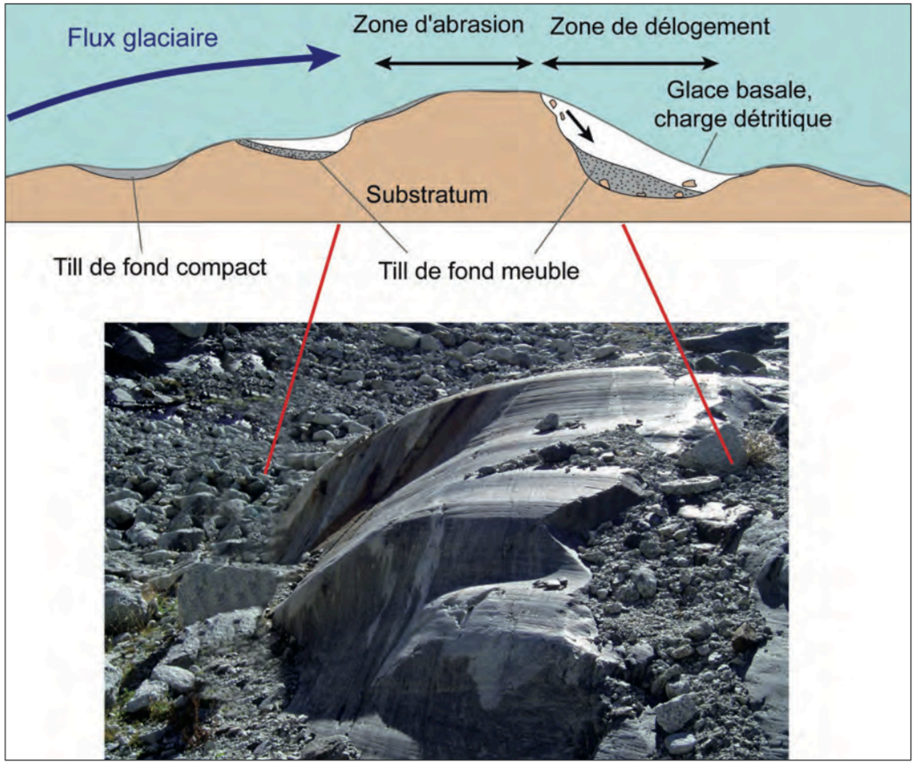
2. Carbon dynamics : the Earth's thermostat

3. Some remarks

Ice ages : the first evidence of climate change

Striations

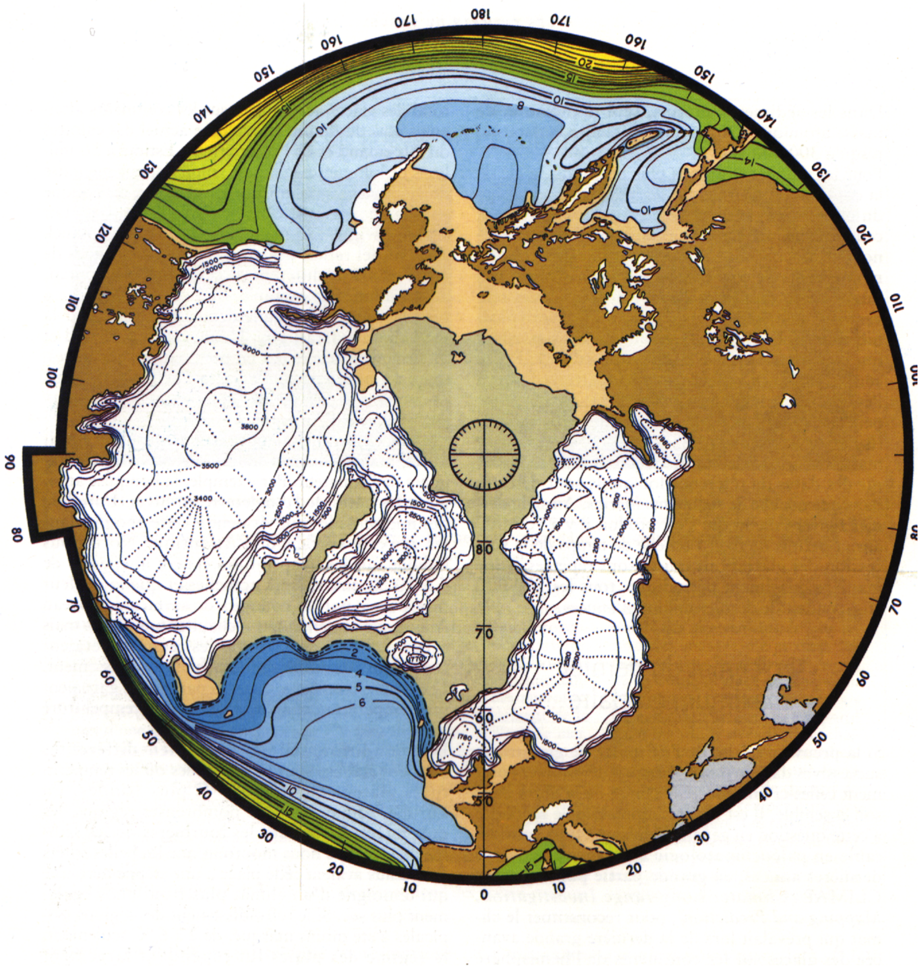
« Roches moutonnées »
(de Saussure, 18th century)



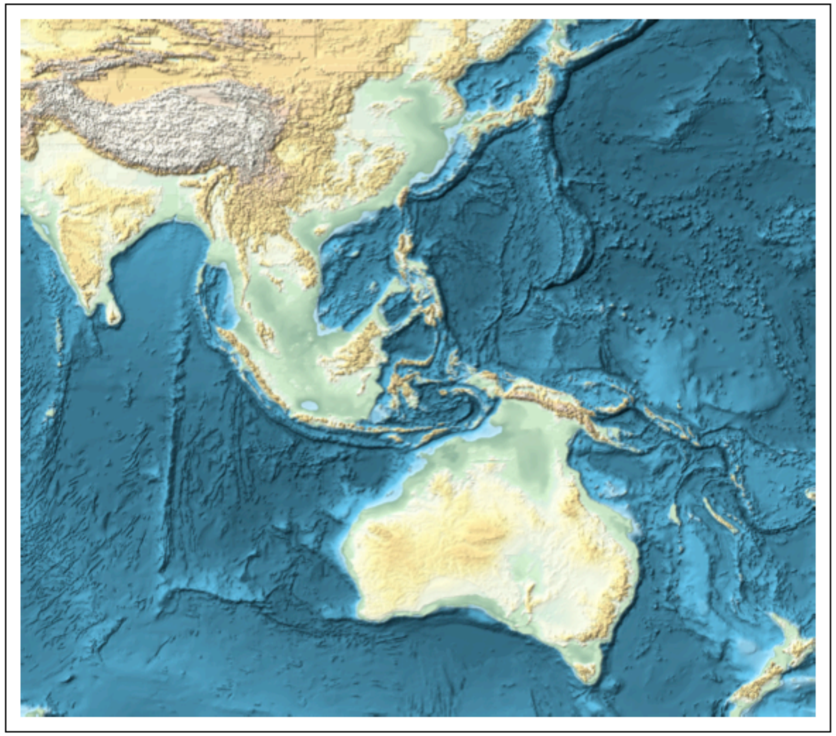
(from S. Couteran, PhD thesis)

Ice ages : the first evidence of climate change

Northern hemisphere ice sheets



Lower sea level (~ -120 m)

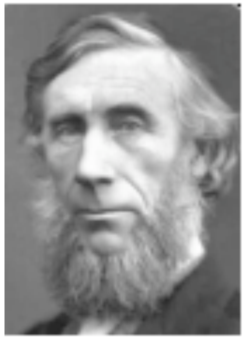


Two « physically based » theories

(physics: cf. Fourier, 1824)

CO_2

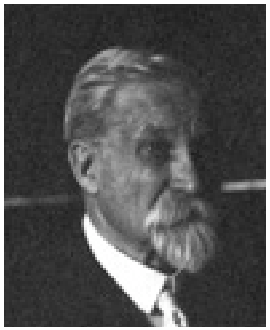
Ebelmen, 1845



Tyndall, 1861, 1863

Arrhenius, 1896

Ekholm, 1901



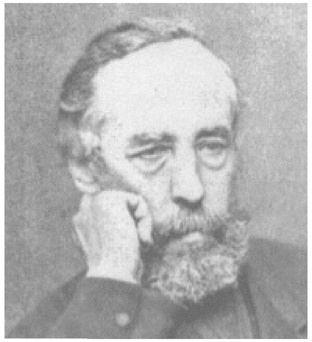
Chamberlin, 1897,1899

Astronomy

(analogy: 3rd movement of Earth, Hipparchus, 127 BC)

Adhémar, 1842

Croll, 1864,1867



Milankoviç, 1920, 1941

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

Arrhenius, 1896

I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them. In the Physical Society of Stockholm there have been occasionally very lively discussions on the probable causes of the Ice Age; and these discussions have, in my opinion, led to the conclusion that there exists as yet no satisfactory hypothesis that could explain how the climatic conditions for an ice age could be realized in so short a time as that which

0.67xCO_2 2.0xCO_2

Latitude.	Carbonic Acid=0·67.					Carbonic Acid=1·5.					Carbonic Acid=2·0.					Carbonic Acid=2·5.					Carbonic Acid=3·0.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	3·52	6·0	6·1	6·0	6·1	6·05	7·9	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
60–50	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	3·62	6·1	6·1	5·8	6·1	6·02	8·0	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
50–40	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	3·65	6·1	6·1	5·5	6·0	5·92	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
40–30	−3·4	−3·4	−3·2	−3·3	−3·32	3·7	3·6	3·3	3·5	3·52	6·0	5·8	5·4	5·6	5·7	7·9	7·6	6·9	7·3	7·42	9·3	9·0	8·2	8·8	8·82
30–20	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	3·47	5·6	5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
20–10	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	3·25	5·2	5·0	4·9	5·0	5·02	6·7	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
10–0	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	3·15	5·0	5·0	4·9	4·9	4·95	6·6	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
0–−10	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	3·15	4·9	4·9	5·0	5·0	4·95	6·4	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
−10–−20	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	3·2	5·0	5·0	5·2	5·1	5·07	6·6	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
−20–−30	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	3·27	5·2	5·3	5·5	5·4	5·35	6·7	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
−30–−40	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	3·52	5·5	5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
−40–−50	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	3·7	5·8	6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
−50–−60	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—	6·0	6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—

-3°C +5°C

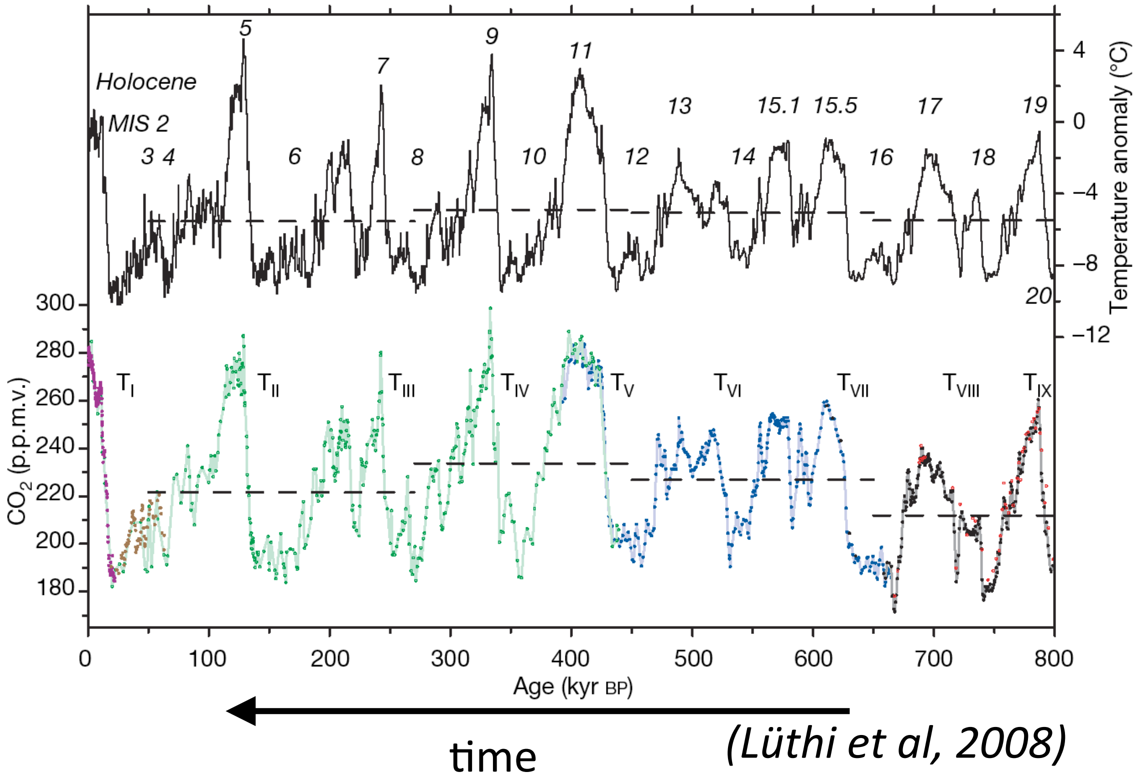
CO_2 does change ! …

- CO_2 was lower during glacial times

(Delmas et al, 1980; Neftel et al. 1982; Barnola et al, 1983)

- CO_2 variations correspond to glacial-interglacial cycles

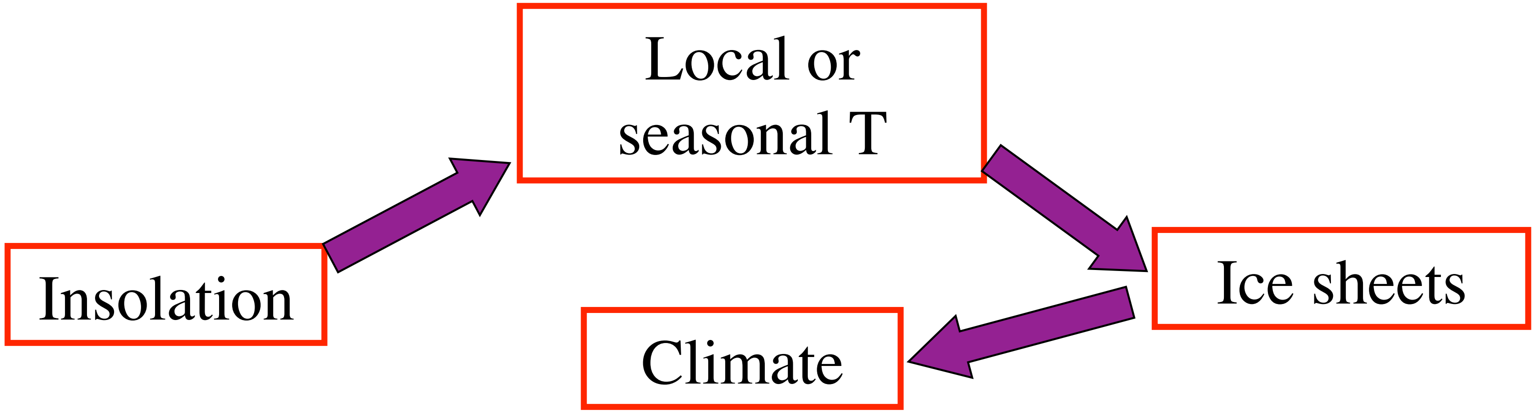
(Barnola et al, 1987; Petit et al. 1999; Lüthi et al, 2008)



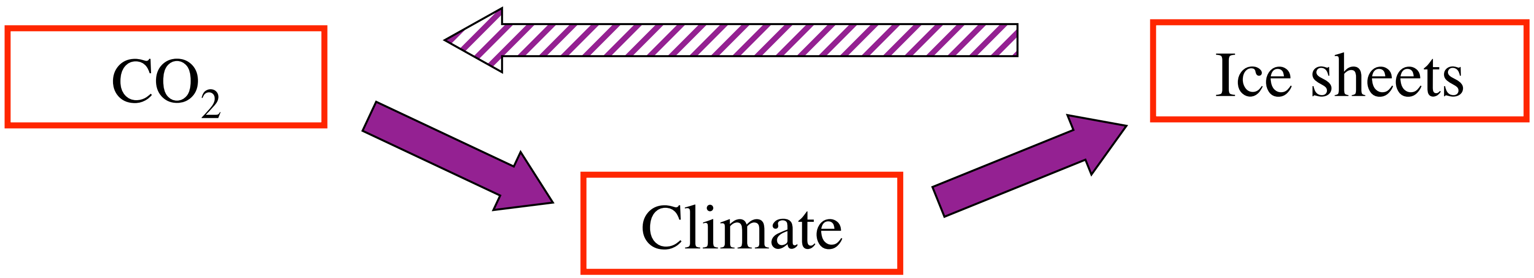
(Lüthi et al, 2008)

!! The important message !!

Astronomical theory

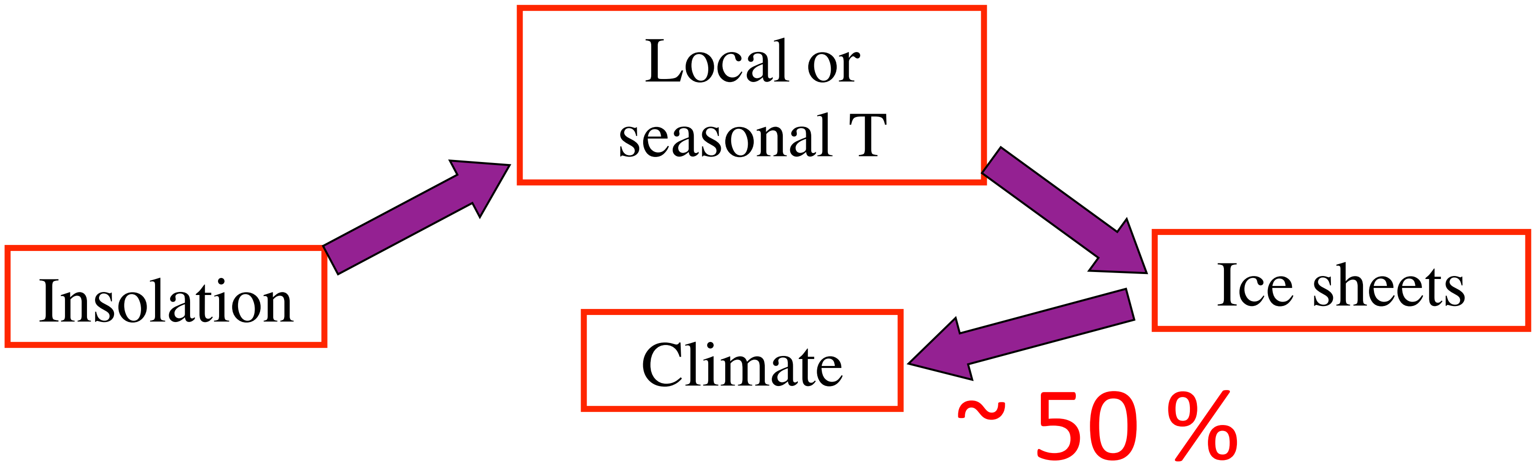


CO_2 theory

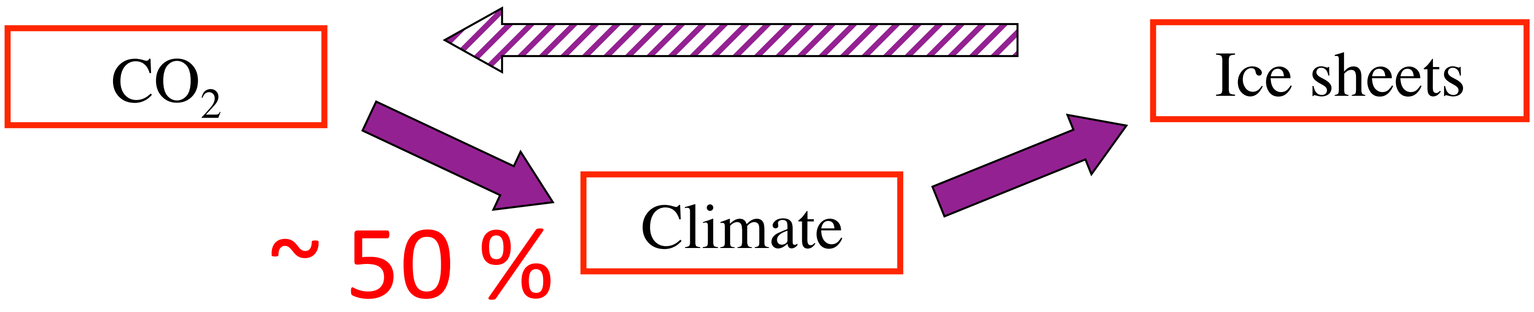


!! The important message !!

Astronomical theory



CO_2 theory



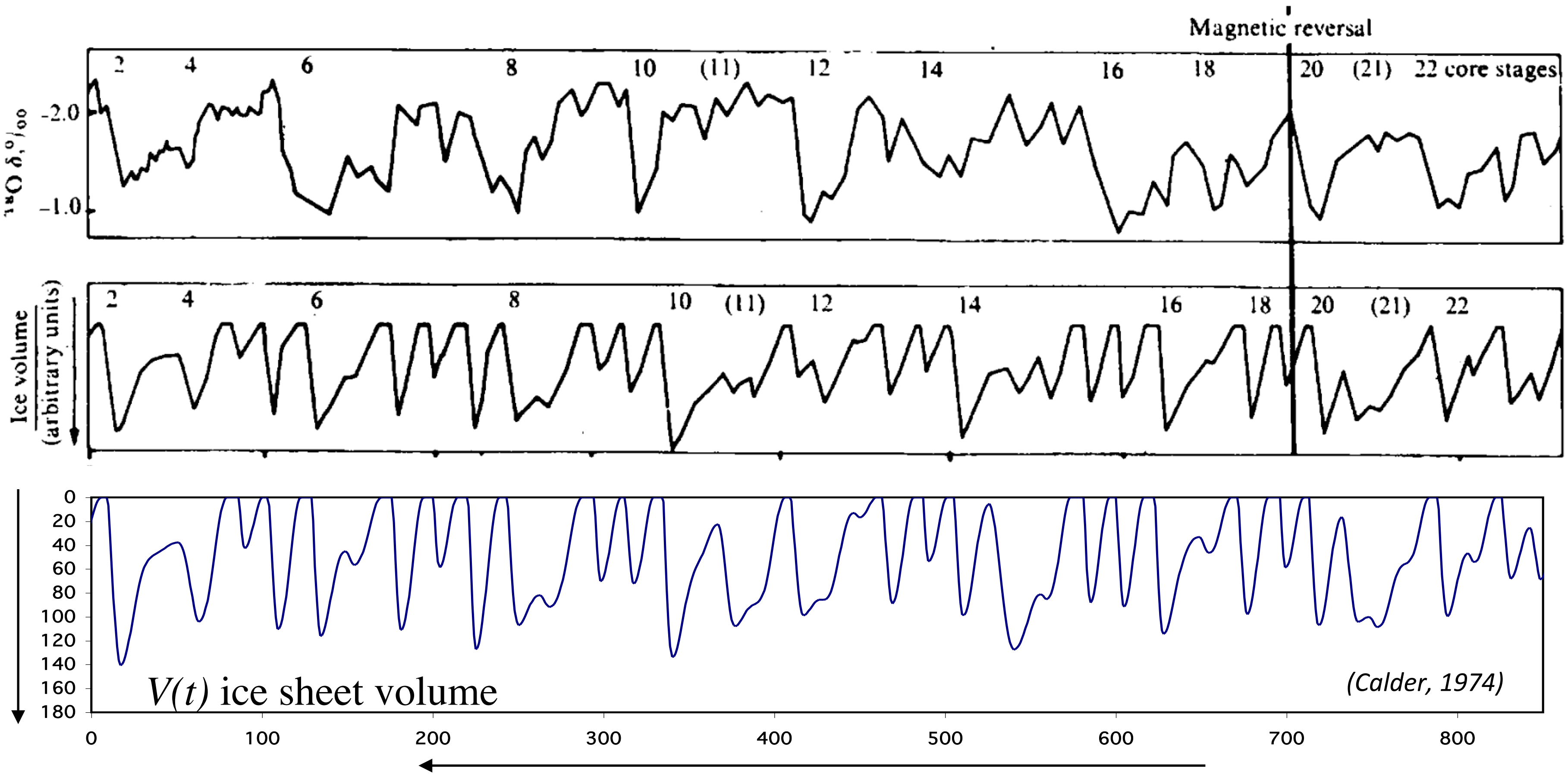
Calder's Model *(Nature, 1974)*

$$\frac{dV}{dt} = -k(i(t) - i_0)$$

$$V(t) \geq 0$$

$$k = \begin{cases} k_M \ , \text{ if } i(t) > i_0 \\ k_A \ , \text{ if } i(t) < i_0 \end{cases}$$

$$\begin{cases} i_0 = 502\,\mathrm{W.m^{-2}} \\ \dfrac{k_A}{k_M} = 0,22 \end{cases}$$



Time (thousands of years before present)

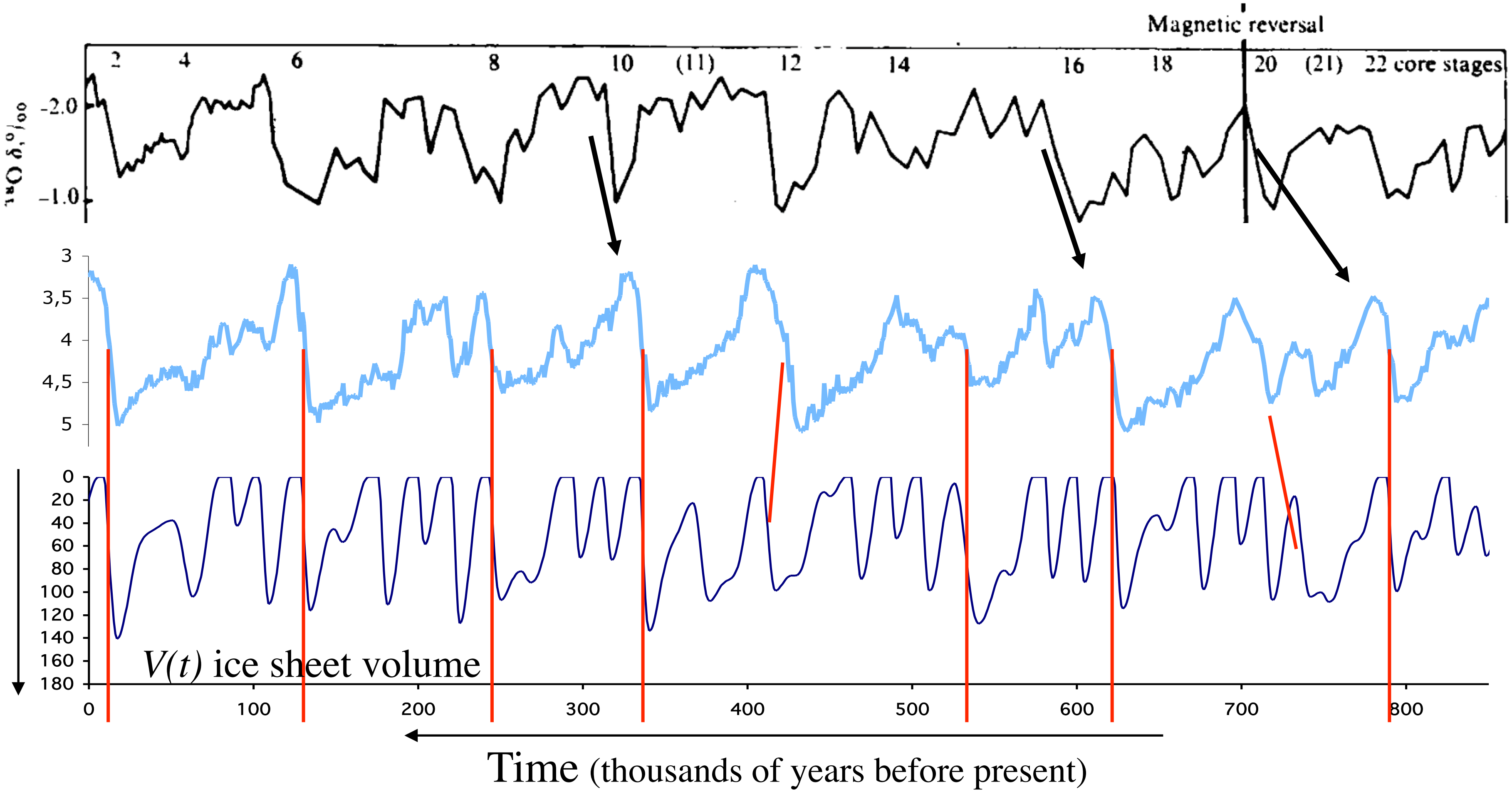
Calder's Model *(Nature, 1974)*

$$\frac{dV}{dt} = -k(i(t) - i_0)$$

$$V(t) \geq 0$$

$$k = \begin{cases} k_M \ , \text{ if } i(t) > i_0 \\ k_A \ , \text{ if } i(t) < i_0 \end{cases}$$

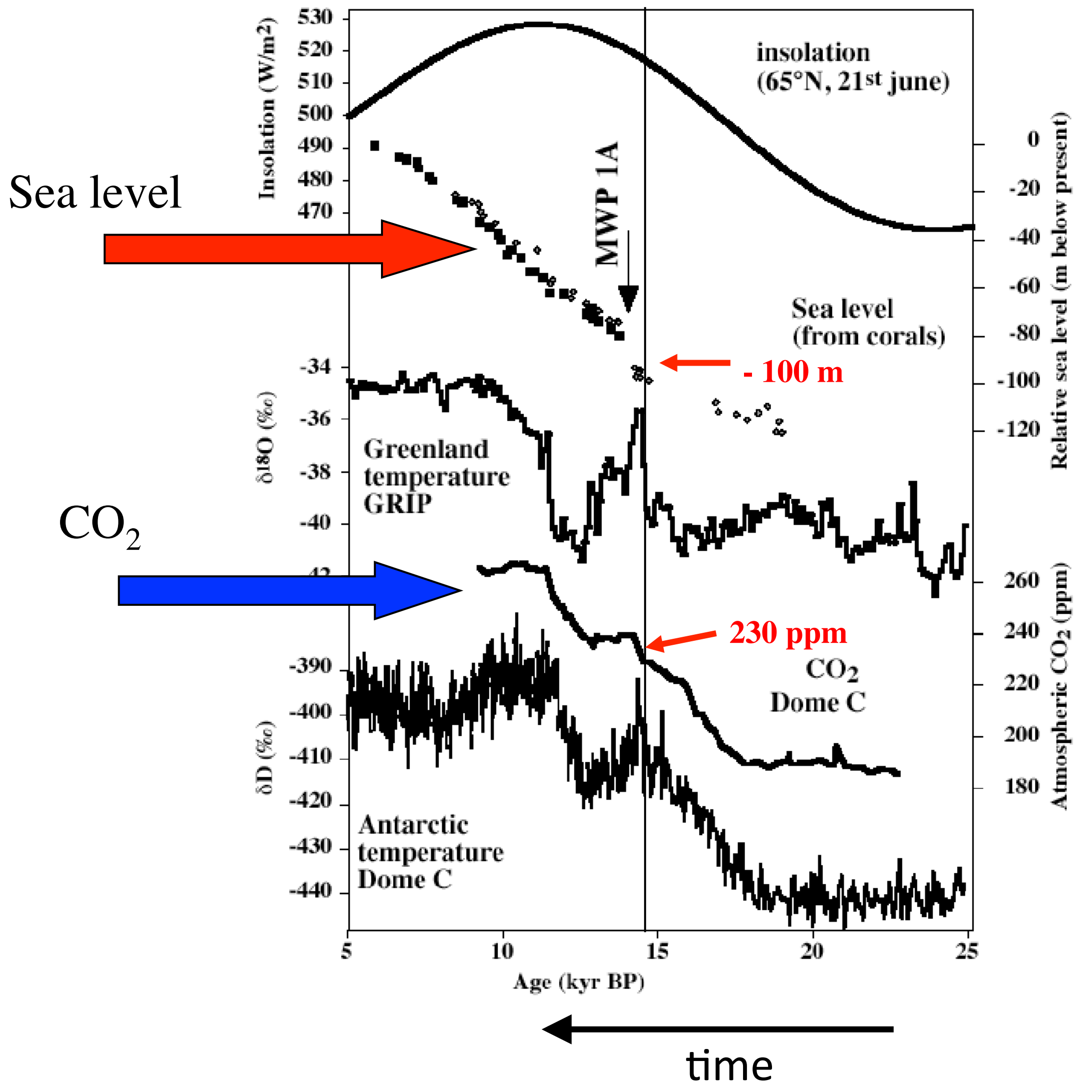
$$\begin{cases} i_0 = 502 \text{W.m}^{-2} \\ \dfrac{k_A}{k_M} = 0{,}22 \end{cases}$$



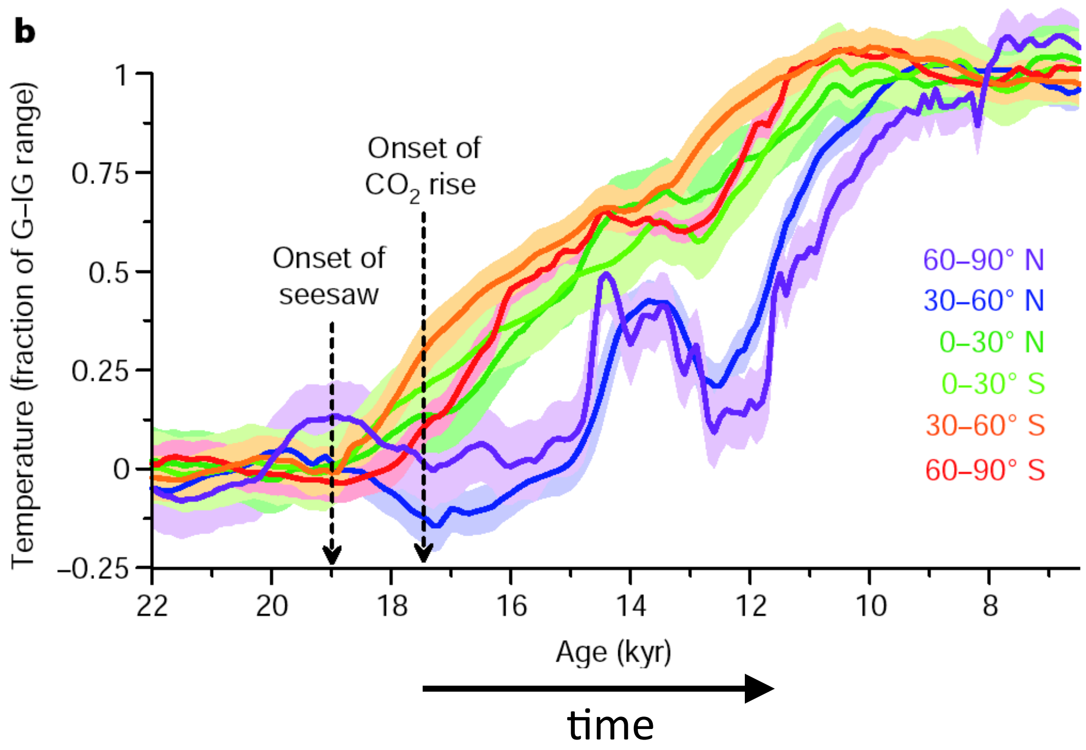
Terminations…

The Southern hemisphere and atmospheric CO_2 are leading the deglaciation

(known since Pichon et al. 1992; Sowers 1993)



Terminations…



(Shakun et al, 2012)

Who is the winner ?

Astronomical theory

+ Hays et al. (1976), Variations in the earth's orbit: pacemakers of the ice ages

+ A sound physical basis for the Milankovitch theory

- Predicted periodicity (41 ka) is not the dominant one « today » (100 ka)

- Leads and lags during terminations

CO_2 theory

+ CO_2 does changes in parallel with ice ages

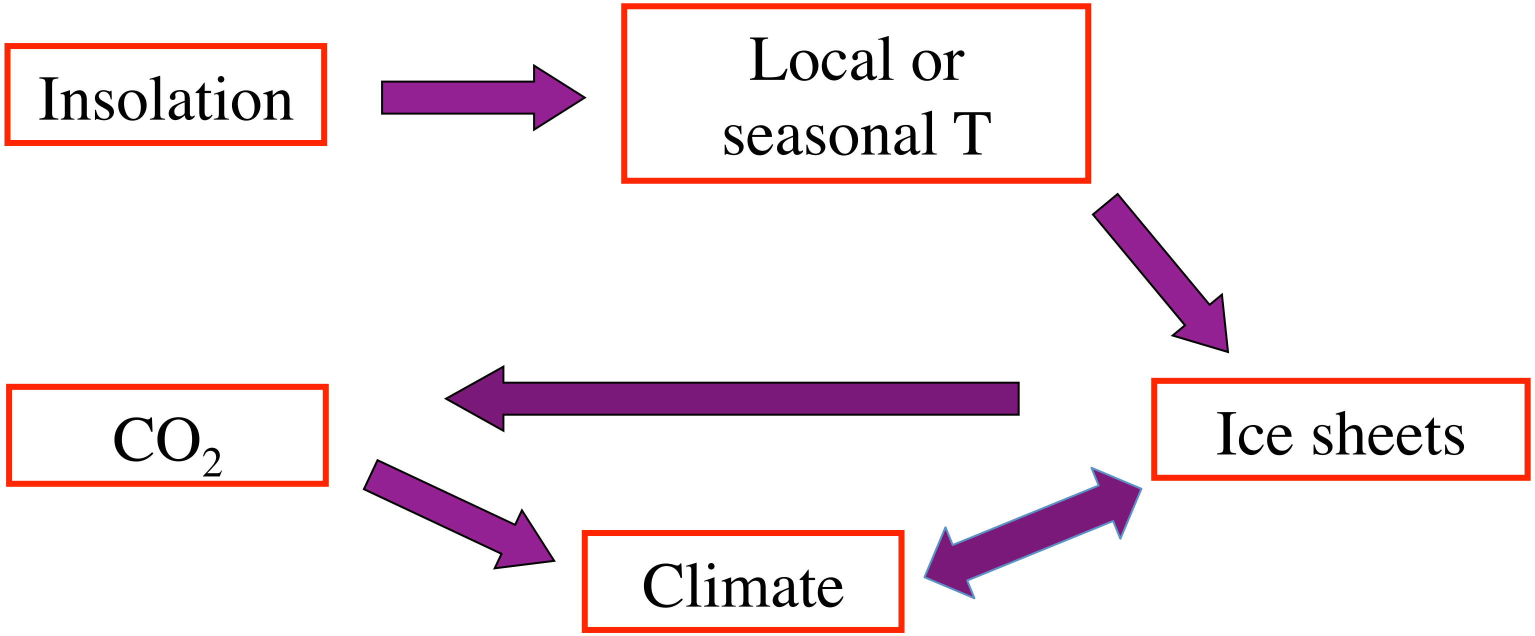
+ A sound physical basis for the greenhouse effect

+ CO_2 leads during terminations

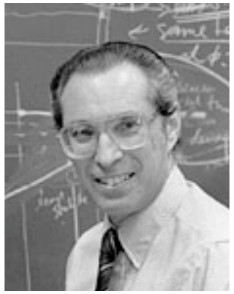
- No defined periodicity, CO_2 needs initial causes to change, unknown dynamics

Building a synthesis

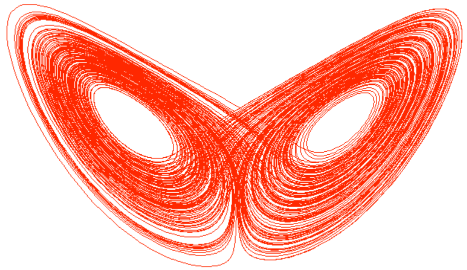
Astronomical/geochemical theory



Coupled ice sheet - carbon cycle models



B. Saltzman



The Saltzman-Lorenz attractor

(Saltzman, 1962; Lorenz, 1963)

The first conceptual model trying to understand the role of CO_2

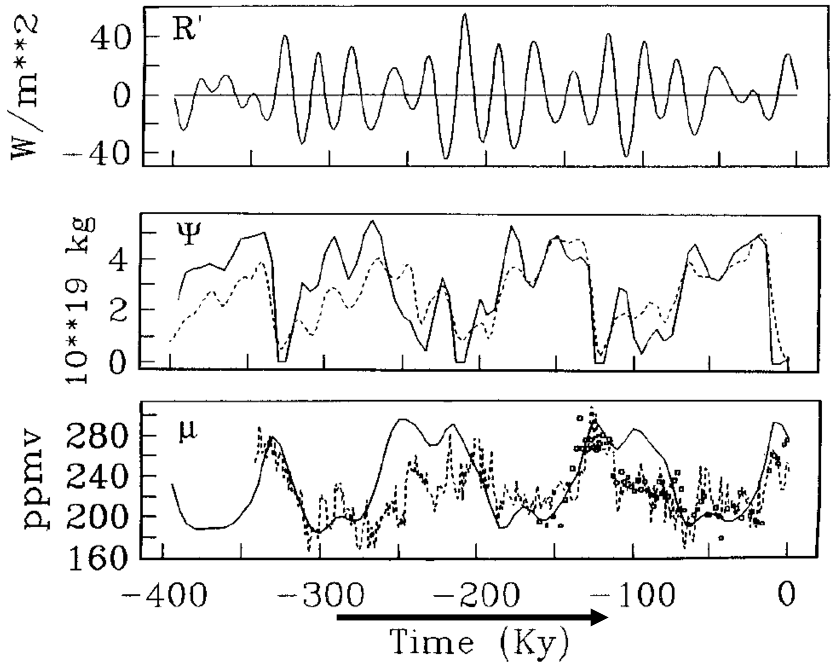
$$\frac{dV}{dt} = \alpha_1 - \alpha_2\left(cC + k_1\theta + k_2 F_V(t)\right) - \alpha_3 V$$

$$\frac{dC}{dt} = \beta_1 - \left(\beta_2 - \beta_3 C + \beta_4 C^2\right)C - \beta_5\theta + F_C(t)$$

$$\frac{d\theta}{dt} = \gamma_1 - \gamma_2 V - \gamma_3\theta$$

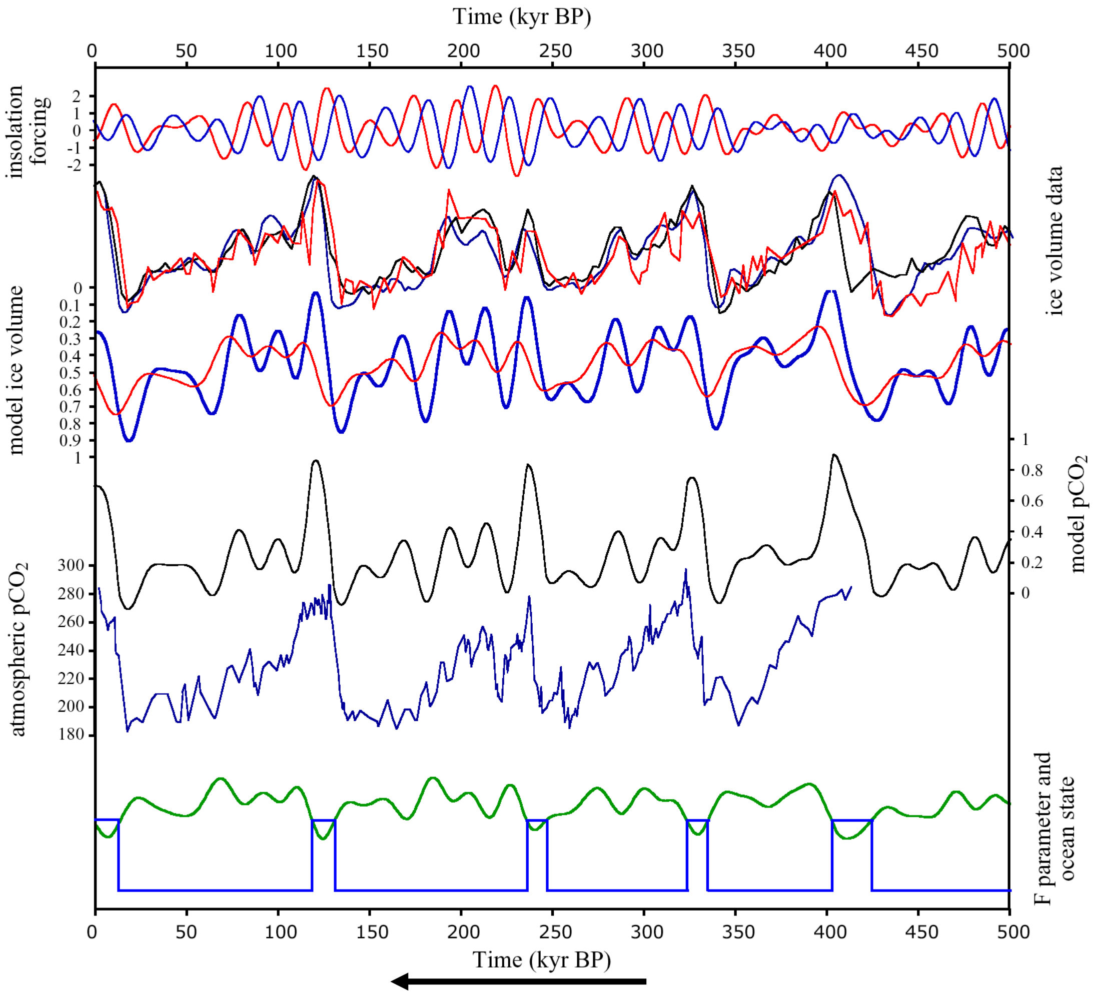
V : ice sheet volume
C : atmospheric CO_2
θ : deep ocean temperature or thermohaline circulation

(Saltzman, 1977; …2001)



(Saltzman et al, 1993)

Conceptual model for ice sheet volume and CO_2



(Paillard and Parrenin, EPSL, 2004)

V = ice volume

A = Antarctic ice sheet area

C = atmospheric CO_2

$$F = a V - b A - c I_{60} + d$$

$$C_R = \alpha I_{65} - \beta V + \gamma H(-F) + \delta$$

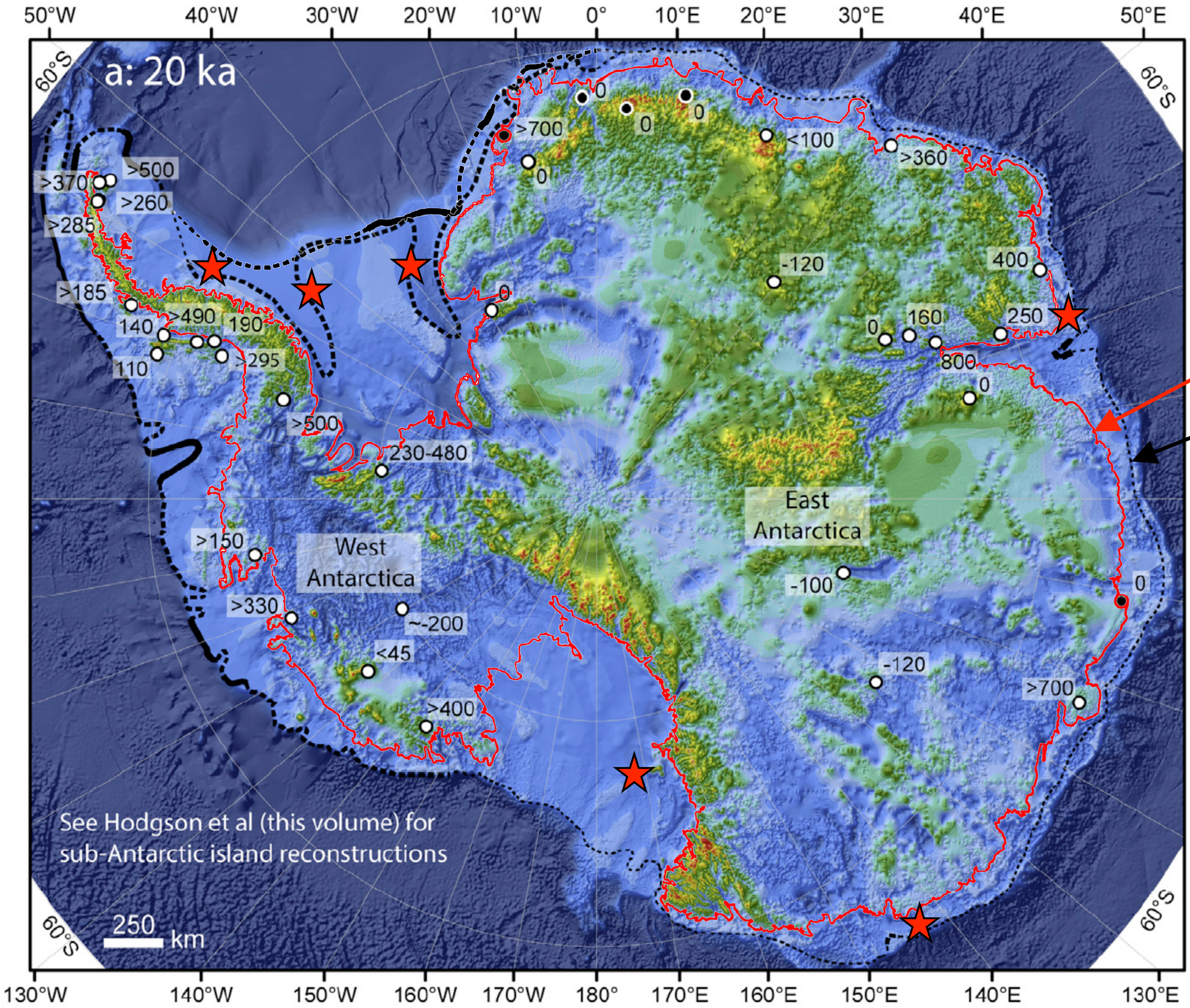
$$V_R = - x C - y I_{65} + z$$

$$\frac{dV}{dt} = \frac{V_R - V}{\tau_V}$$

$$\frac{dA}{dt} = \frac{V - A}{\tau_A}$$

$$\frac{dC}{dt} = \frac{C_R - C}{\tau_C}$$

The ice sheet - CO_2 link



Bottom water formation

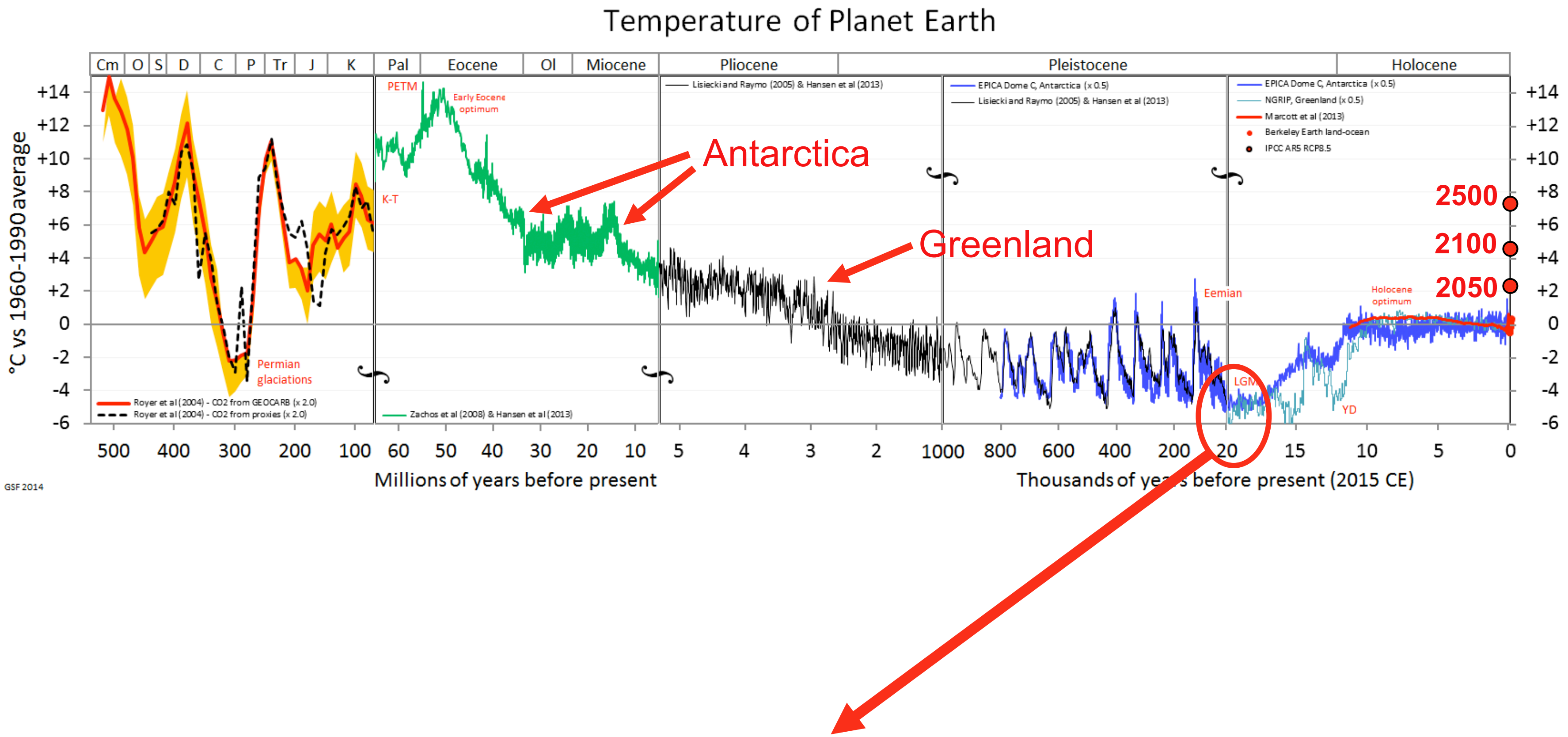
Ice-sheet grounding line

today

LGM

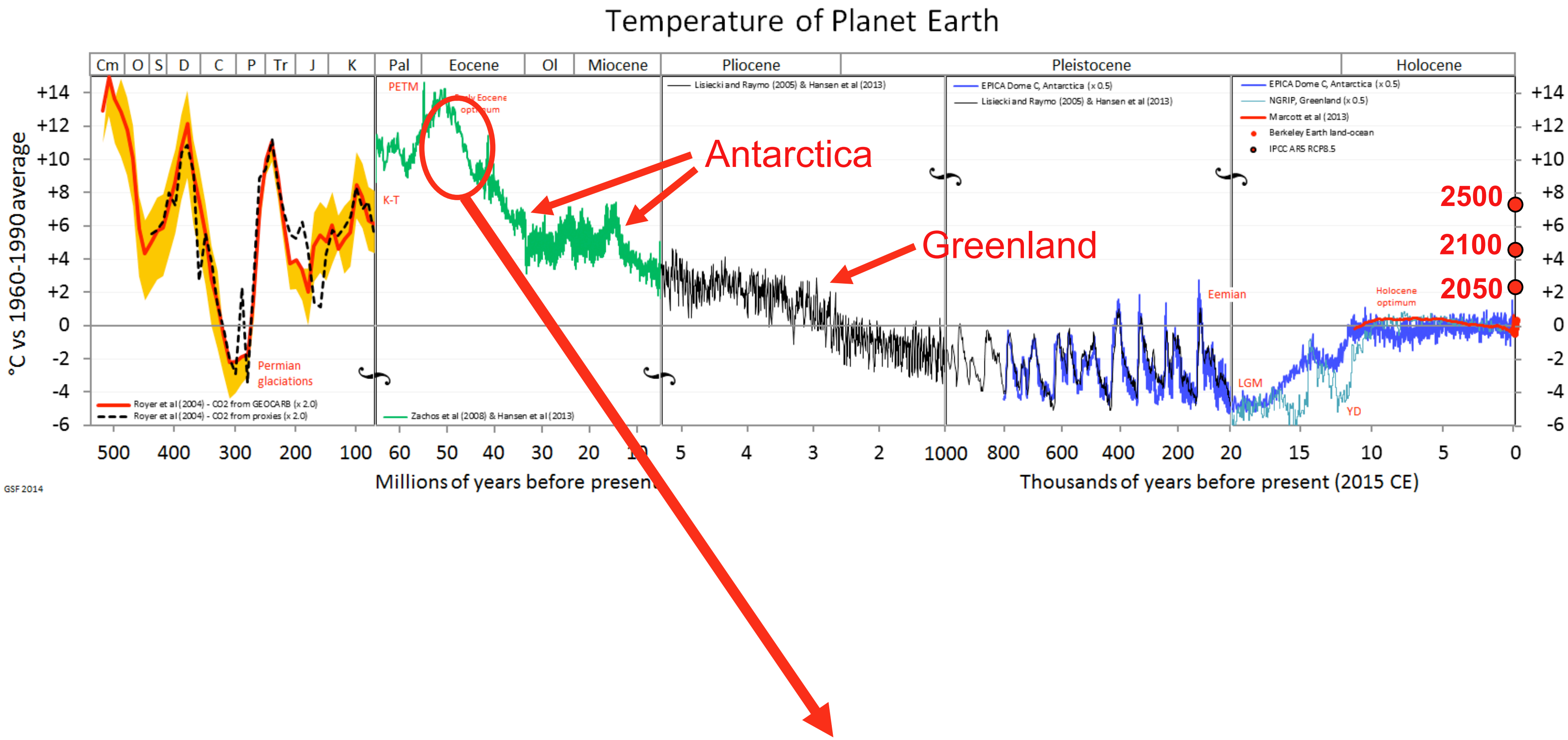
The RAISED consortium et al, QSR, 2014)

A short history of climate



Last glacial maximum : - 5°C

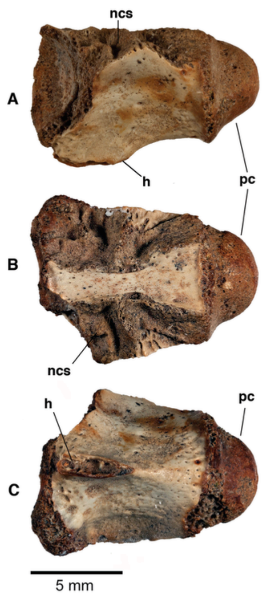
A short history of climate



Eocene : + 8 - 10°C

Eocene : + 8 - 10°C


Metasequoia occidentalis



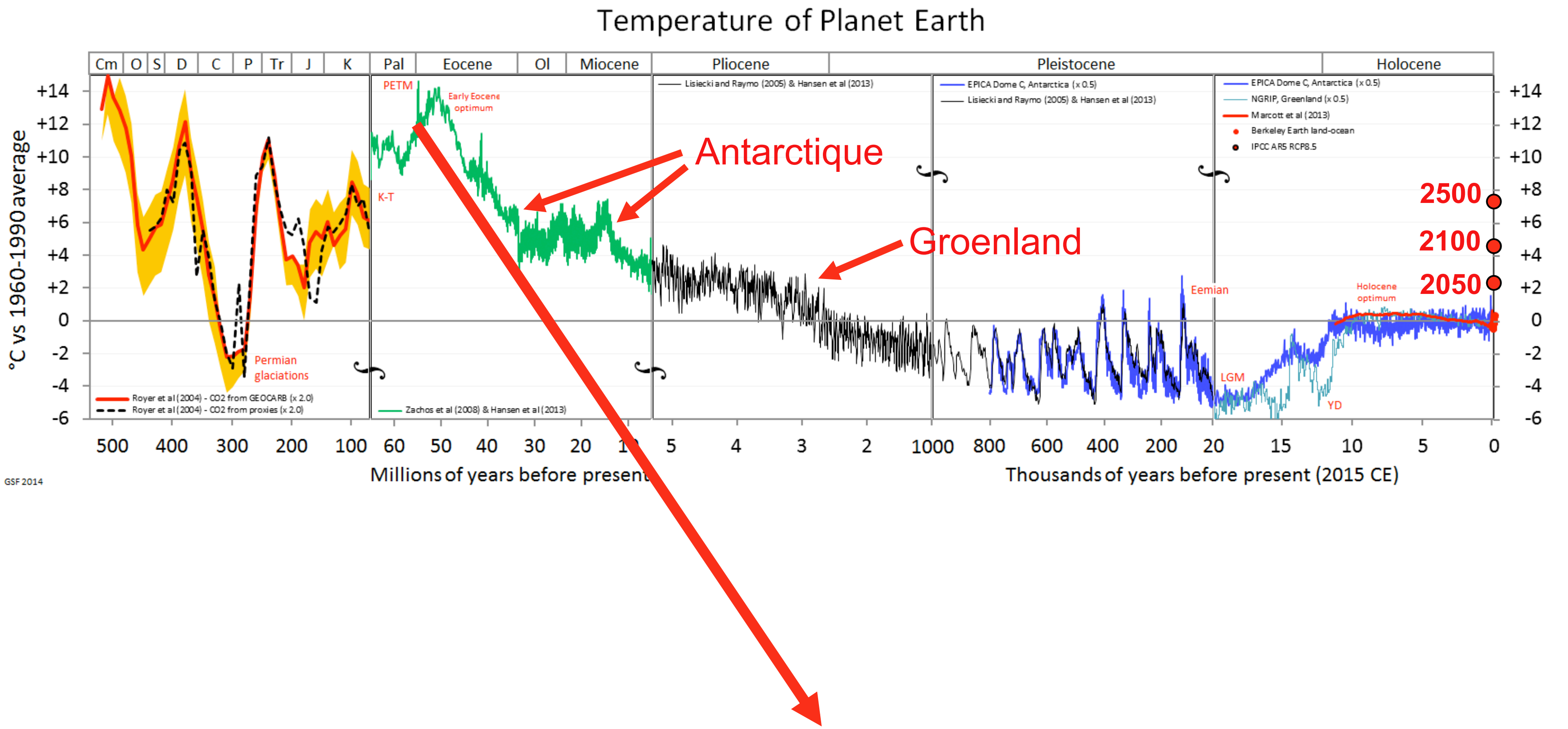
Vertèbres de crocodilien

Tropical forest in the arctic area

- palm trees, coniferous,…

- crocodiles, turtles, mammals, …

A short history of climate

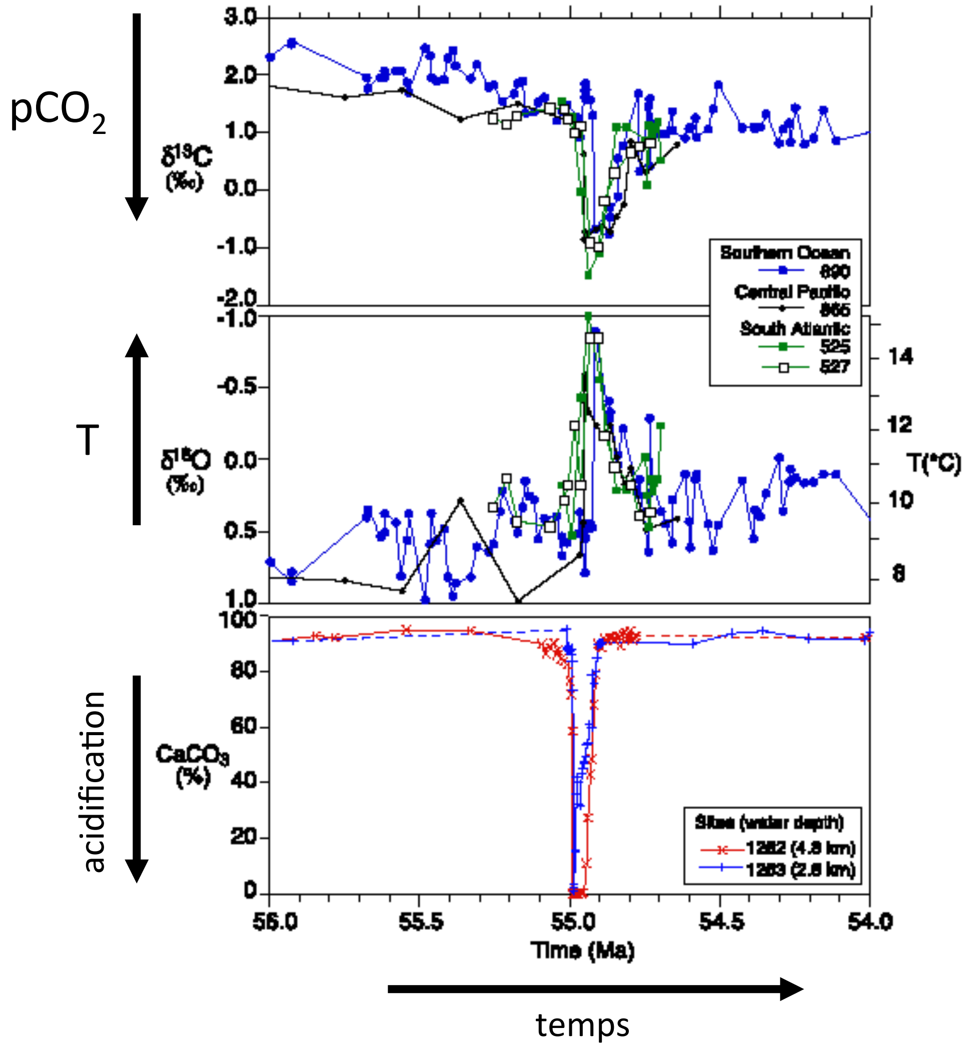


Paleocene – Eocene transition

Paleocene-Eocene transition

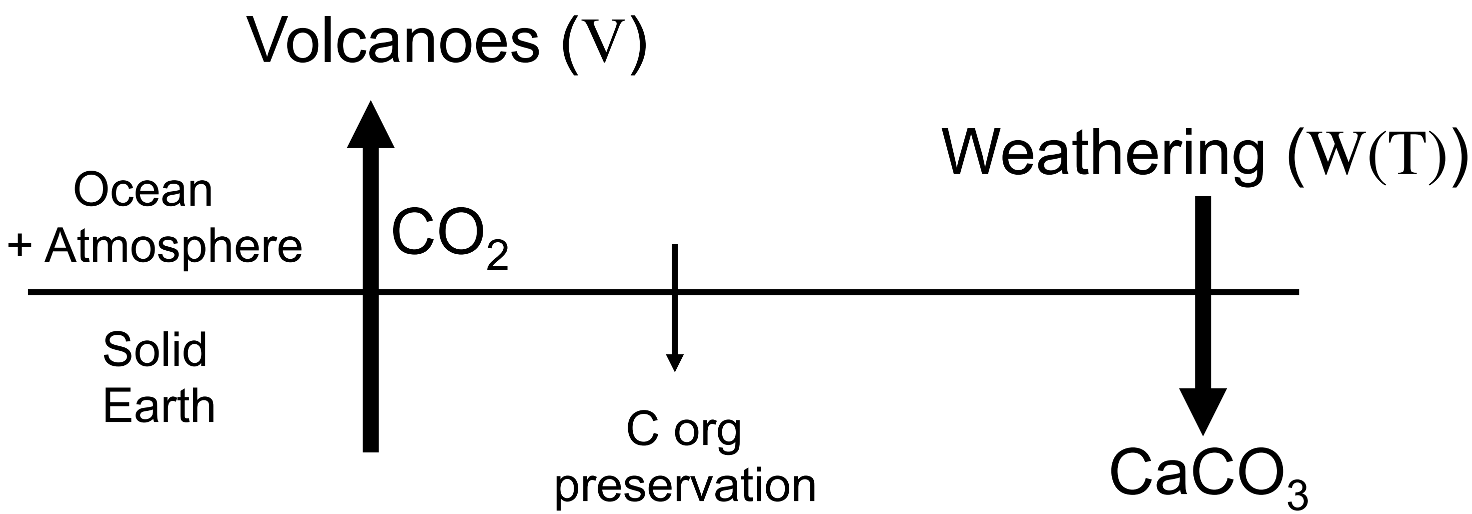
- Impulse response to a greenhouse gas perturbation
(~ 1000 - 5000 PgC)

- recovery time
 ~ 200 000 ans



(Zachos et al, Science 2001)

The Earth thermostat : carbon



$$\frac{dC}{dt} = V - W(T)$$

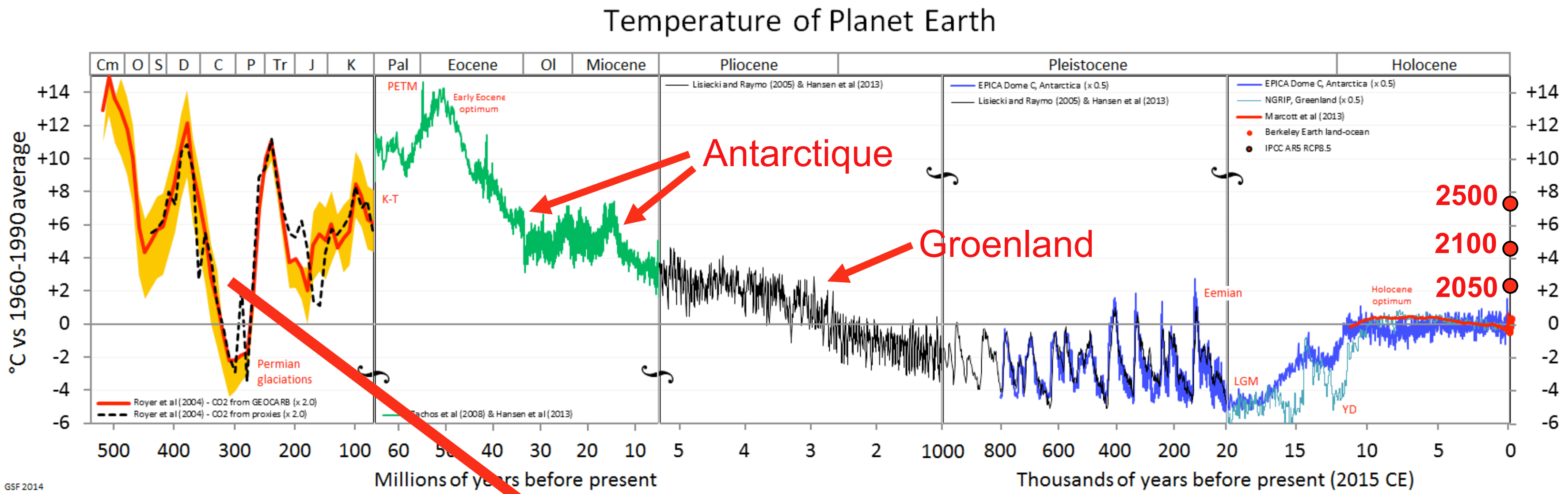
- « Fast » regulation (~ 200 000 years)

The Earth thermostat : carbon

- ✓ Explains the stability of Earth's climate in the « liquid water » range (eg. why snowball-Earth is an exception)
- ✓ Fits with some observations (eg. Paleocene-Eocene)
- ✓ Good geochemical basis

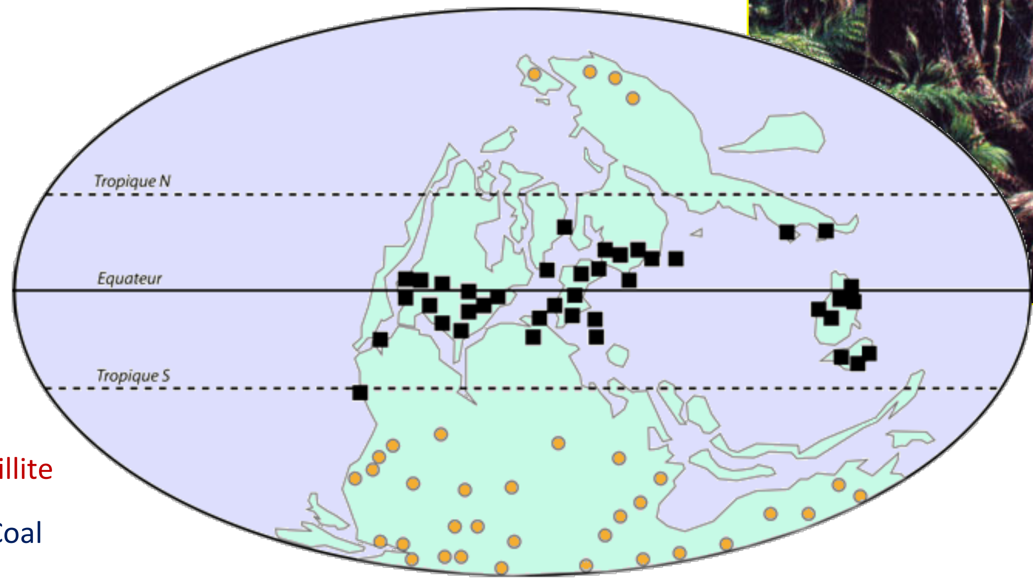
- is too efficient to account for the observed variability
- Role for organic carbon
- And for calcium cycle

A short history of climate



Carboniferous

Carboniferous



● tillite

■ Coal

Astronomical forcing of the carbon cycle ?

Pälike et al, 2006

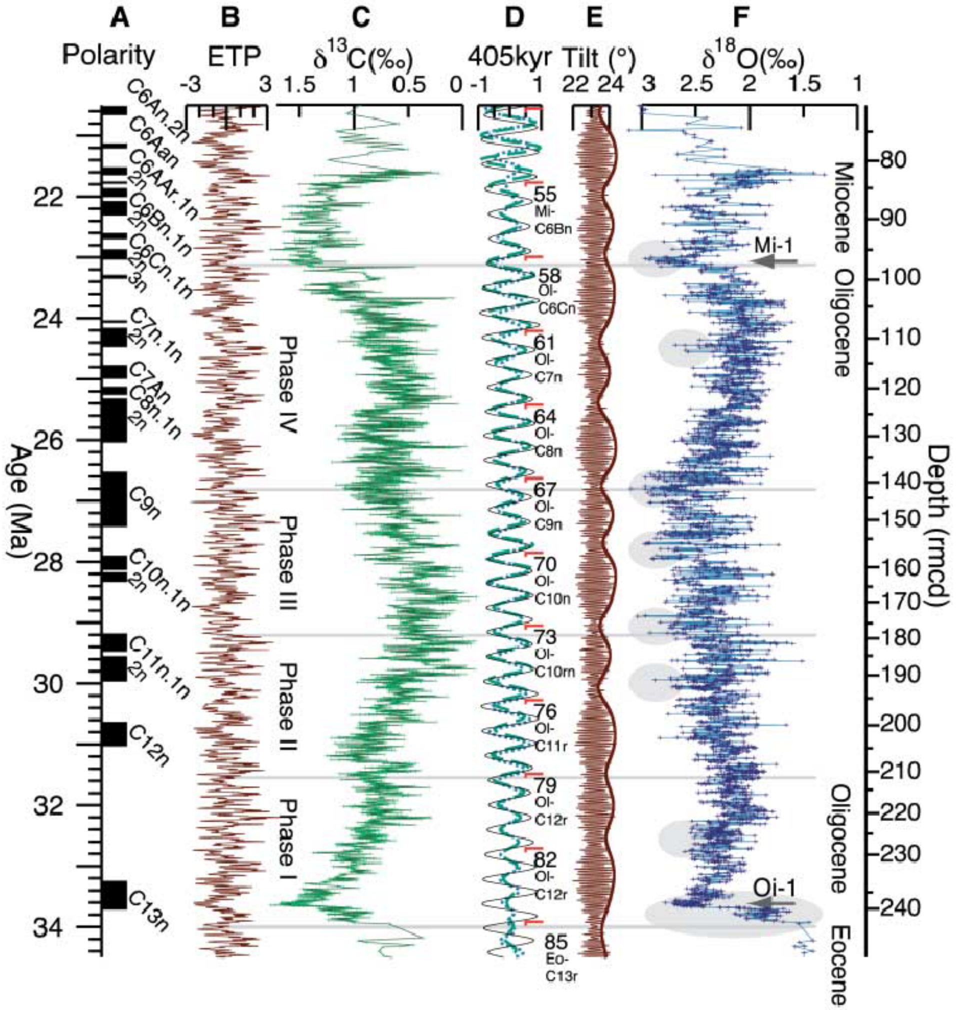
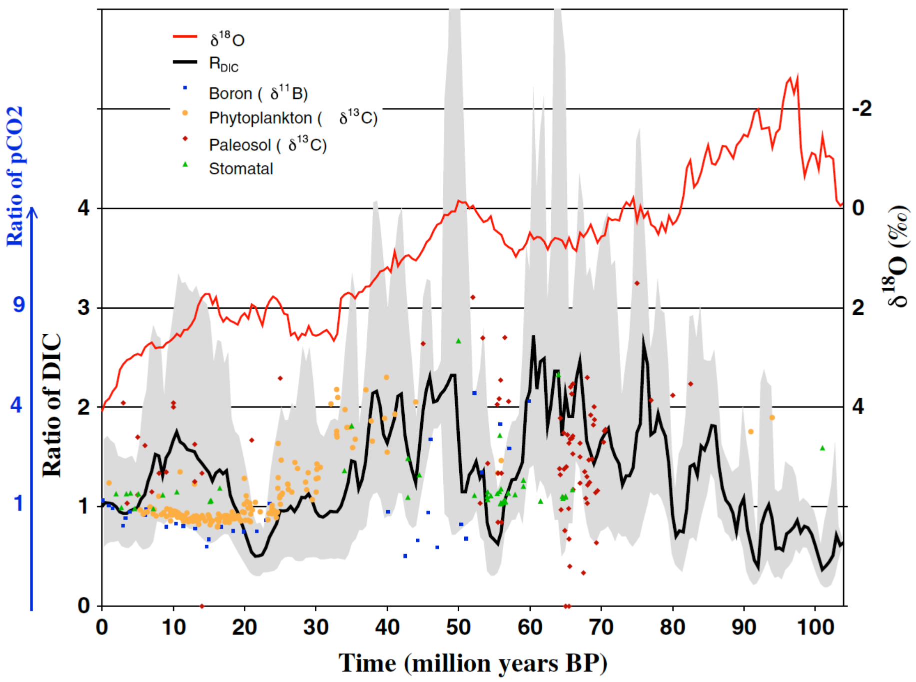
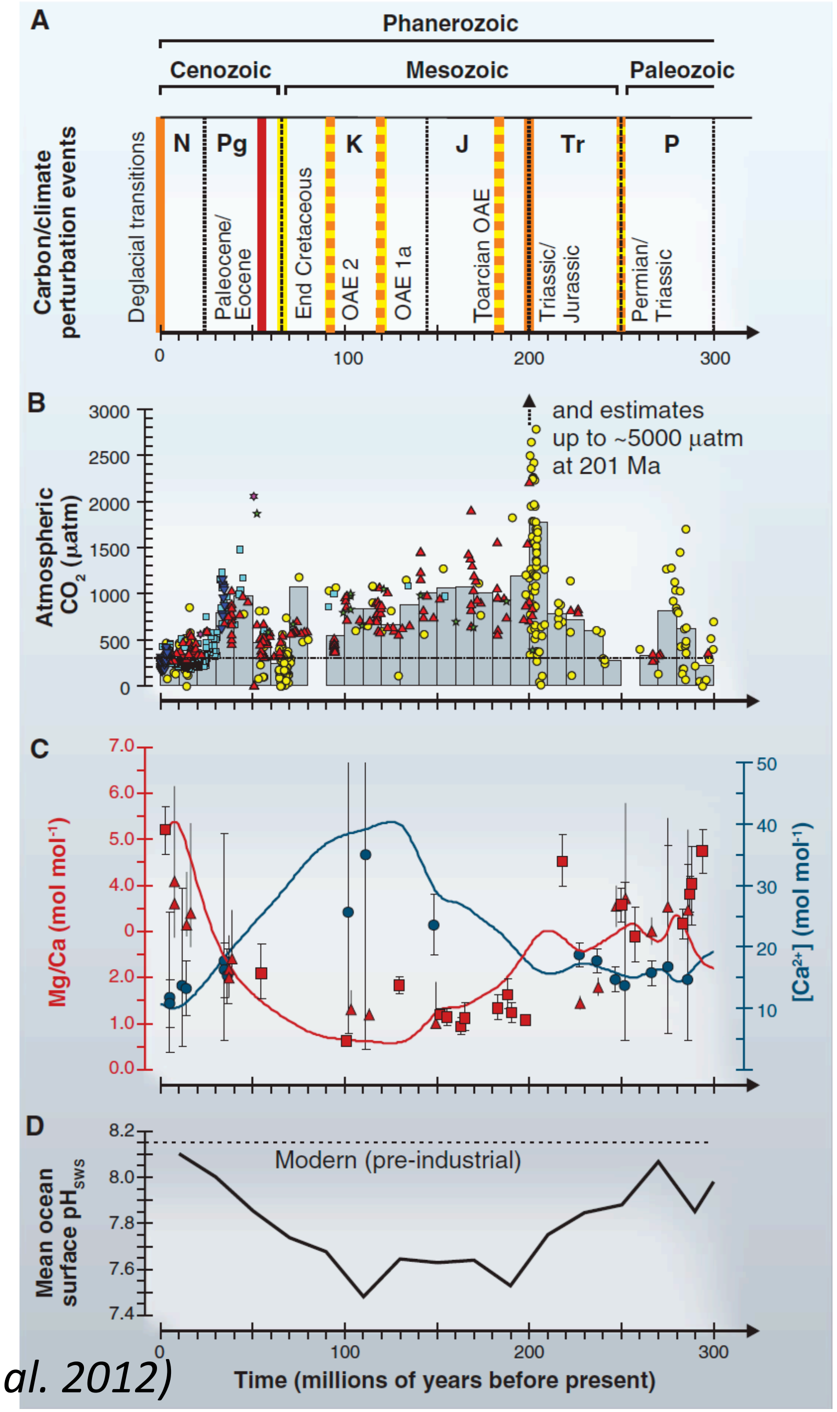


Fig. 1. Oligocene Pacific benthic stable isotope data from ODP Site 1218. **(A)** Astronomically age-calibrated magnetic polarity record for Leg 199, based on (*12*, *14*, *15*, *21*). **(B)** Calculated normalized mix of the orbital parameters eccentricity, obliquity (tilt), and climatic precession [ETP, devised in (*40*)], using (*16*). **(C)** Benthic carbon isotope measurement from foraminiferal calcite. **(D)** Bandpass filtering (*41*) to extract the 405-ky eccentricity component from astronomical eccentricity (solid line), benthic inverted $\delta^{13}C$ isotopes (dashed line), and benthic inverted $\delta^{18}O$ isotopes (dotted line). Values close to –1 mark near-circular orbits (minimum 405-ky eccentricity). Also marked are absolute 405-ky eccentricity cycle numbers, counted from the present, following the naming scheme of (*5*). **(E)** Obliquity, and obliquity amplitude envelope (in degrees), from (*16*). **(F)** Benthic oxygen isotope measurements from foraminiferal calcite, Site 1218. Foraminiferal isotope measurements were adjusted to seawater equilibrium by adding 0.64‰ (*42*). Mi-1 and Oi-1 isotope events (*2*) are indicated along the core depth axis by arrows. Depth values are revised meters composite depth (rmcd) (*14*). Horizontal lines mark long-term Oligocene phases. Gray ellipses mark maximum $\delta^{18}O$ during low obliquity amplitudes.

Role of the Ca cycle

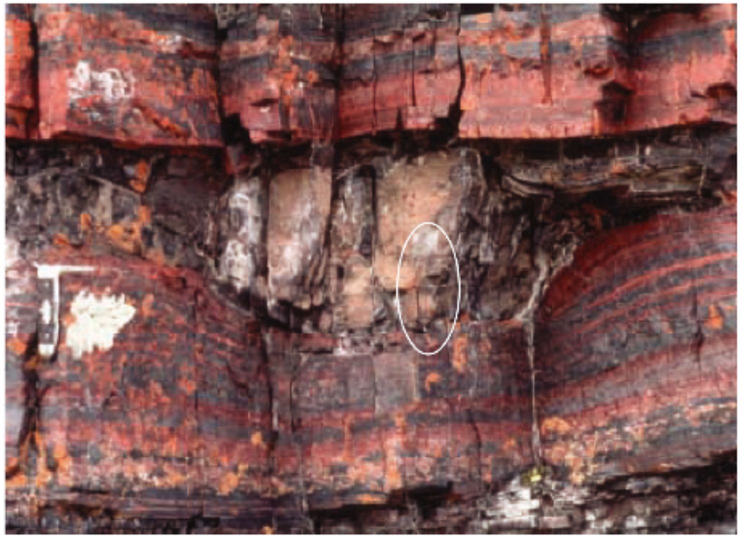


(Paillard et al. 2014)

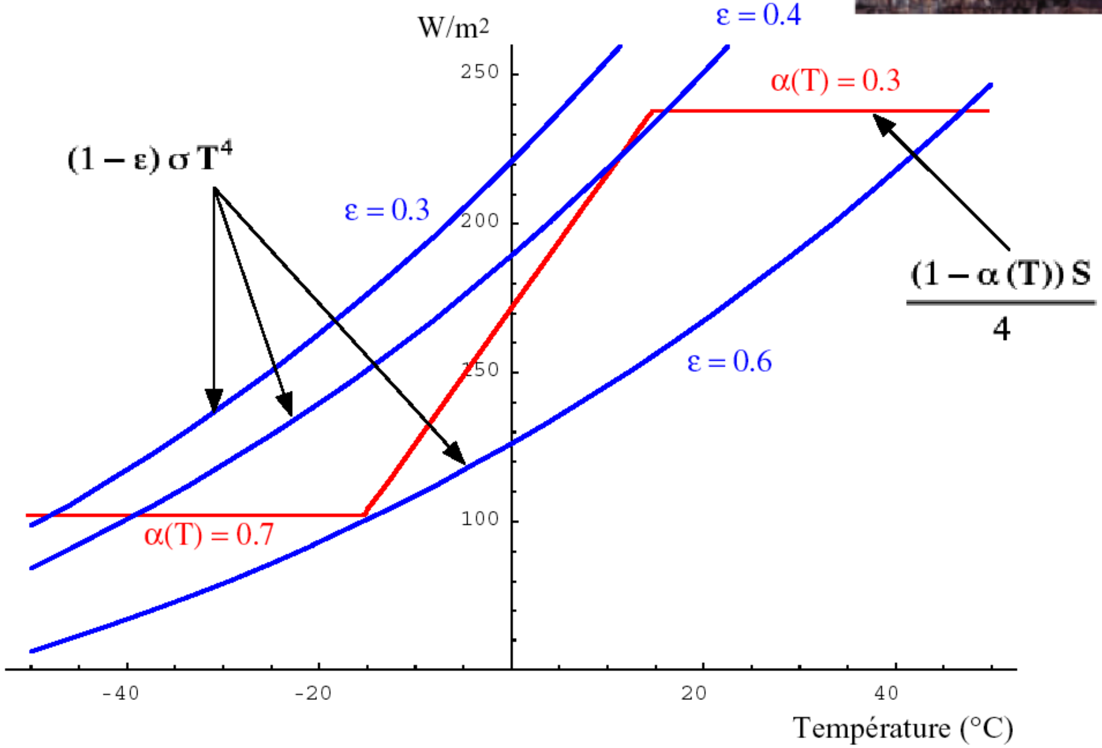


(Hoenisch et al. 2012)

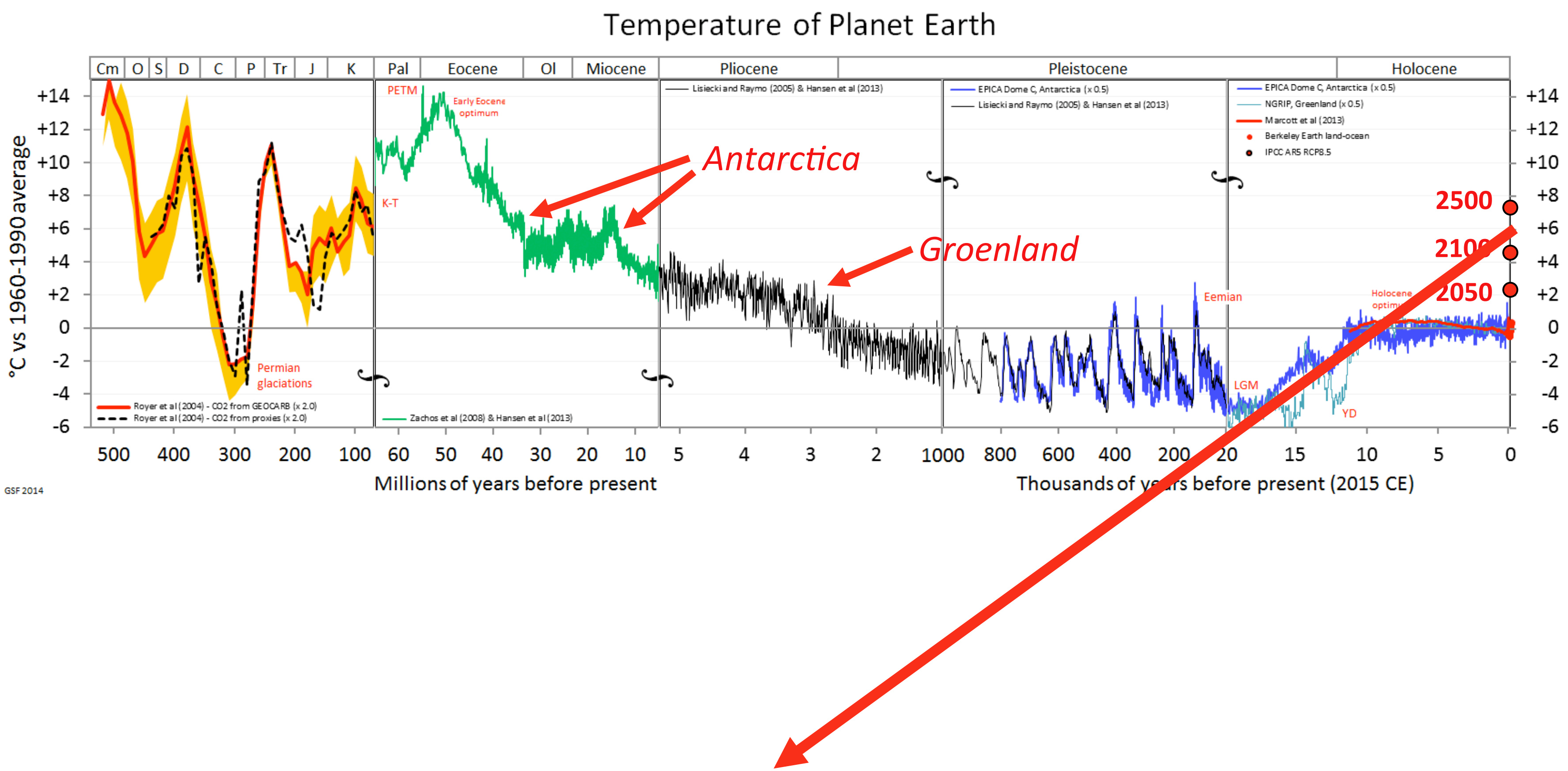
Snowball Earth



$$\frac{(1-\alpha(T))\,S}{4} = (1-\varepsilon)\,\sigma\,T^4$$

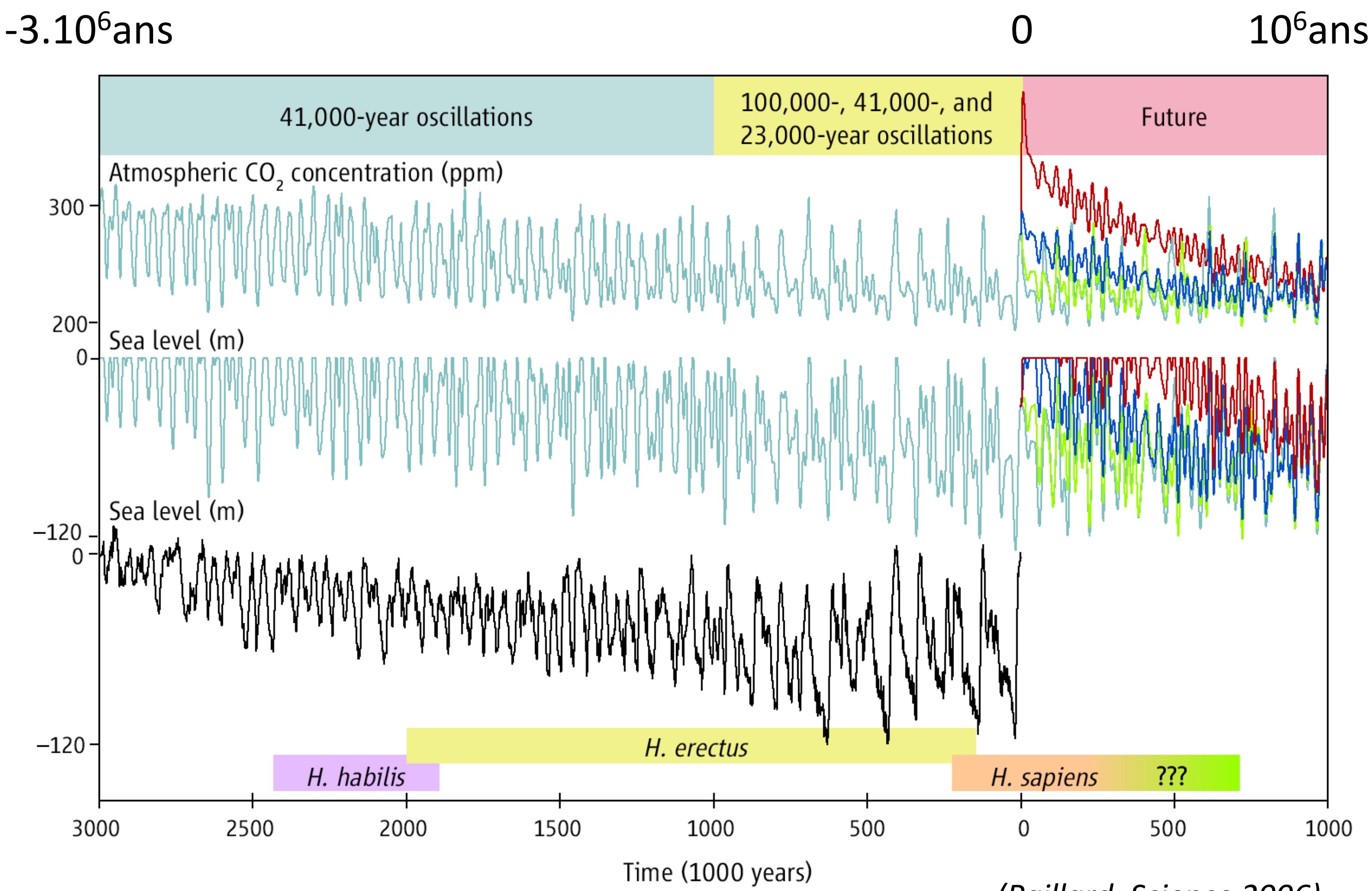


~~Paleo~~ Future climates



« Near » future ??

10^6 years

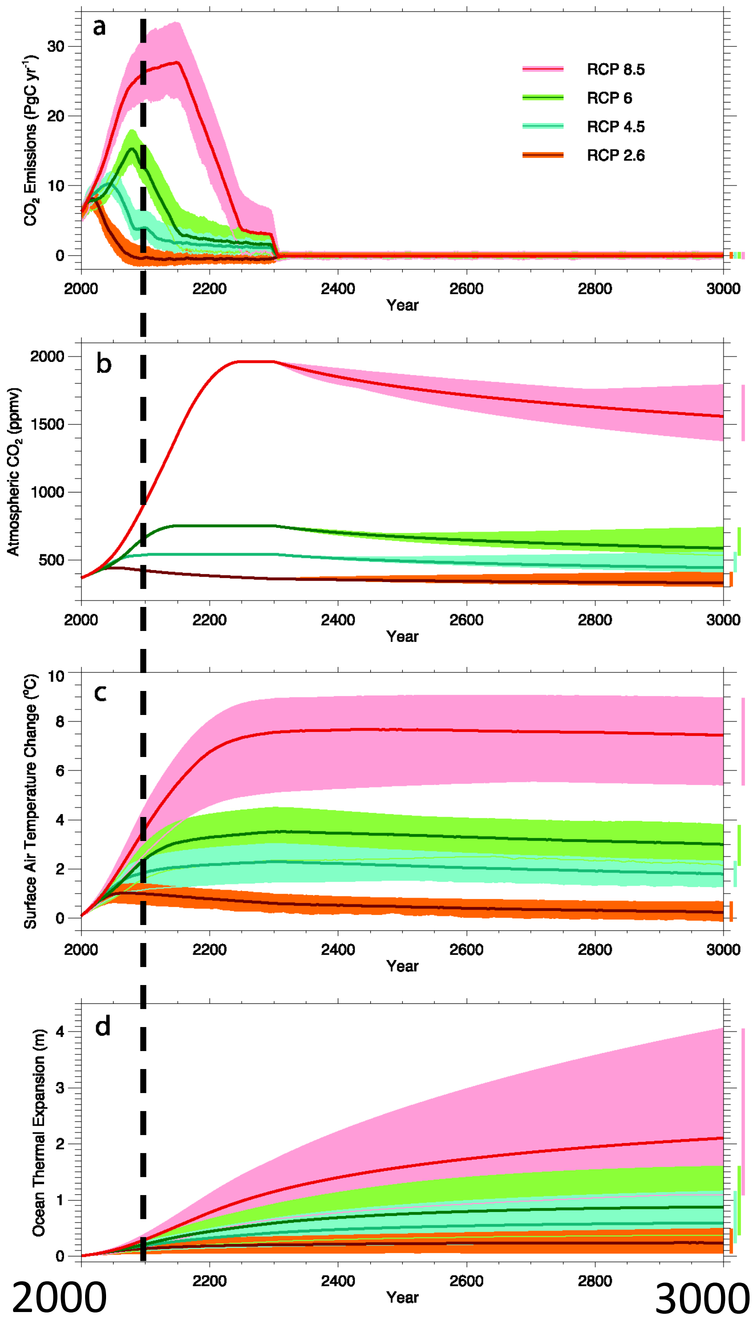


(Paillard, Science 2006)

Conceptual model for NH ice sheets + pCO_2

10^3 years

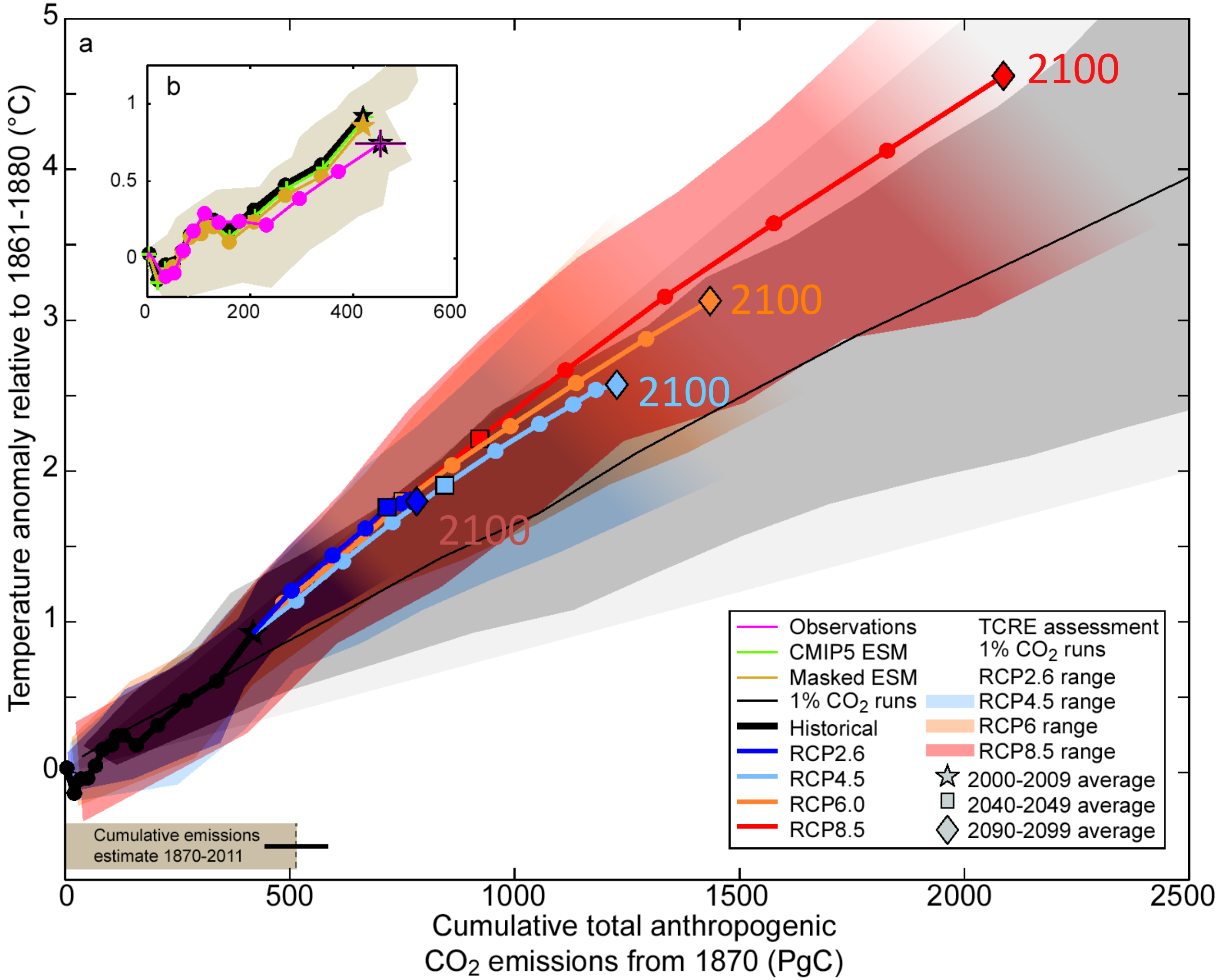
- CO_2 emissions in the XXI-XXIIth century
- pCO_2 is the integral of emissions
- Large thermal inertia of the ocean
- Slow components (eg. ice sheets,..) are not accounted for



(Zickfeld et al, 2013)

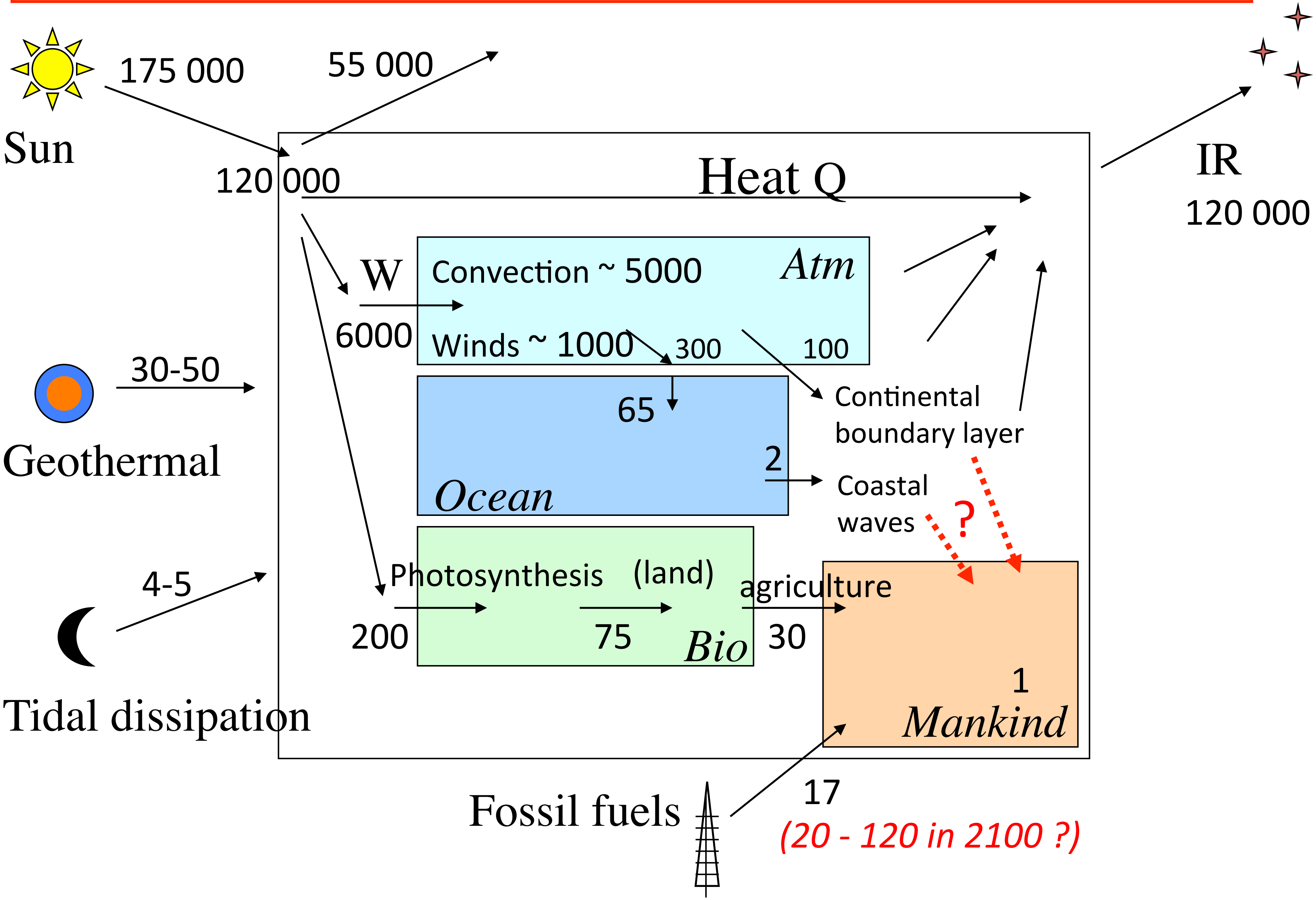
10^2 years

500 PgC = +1°C

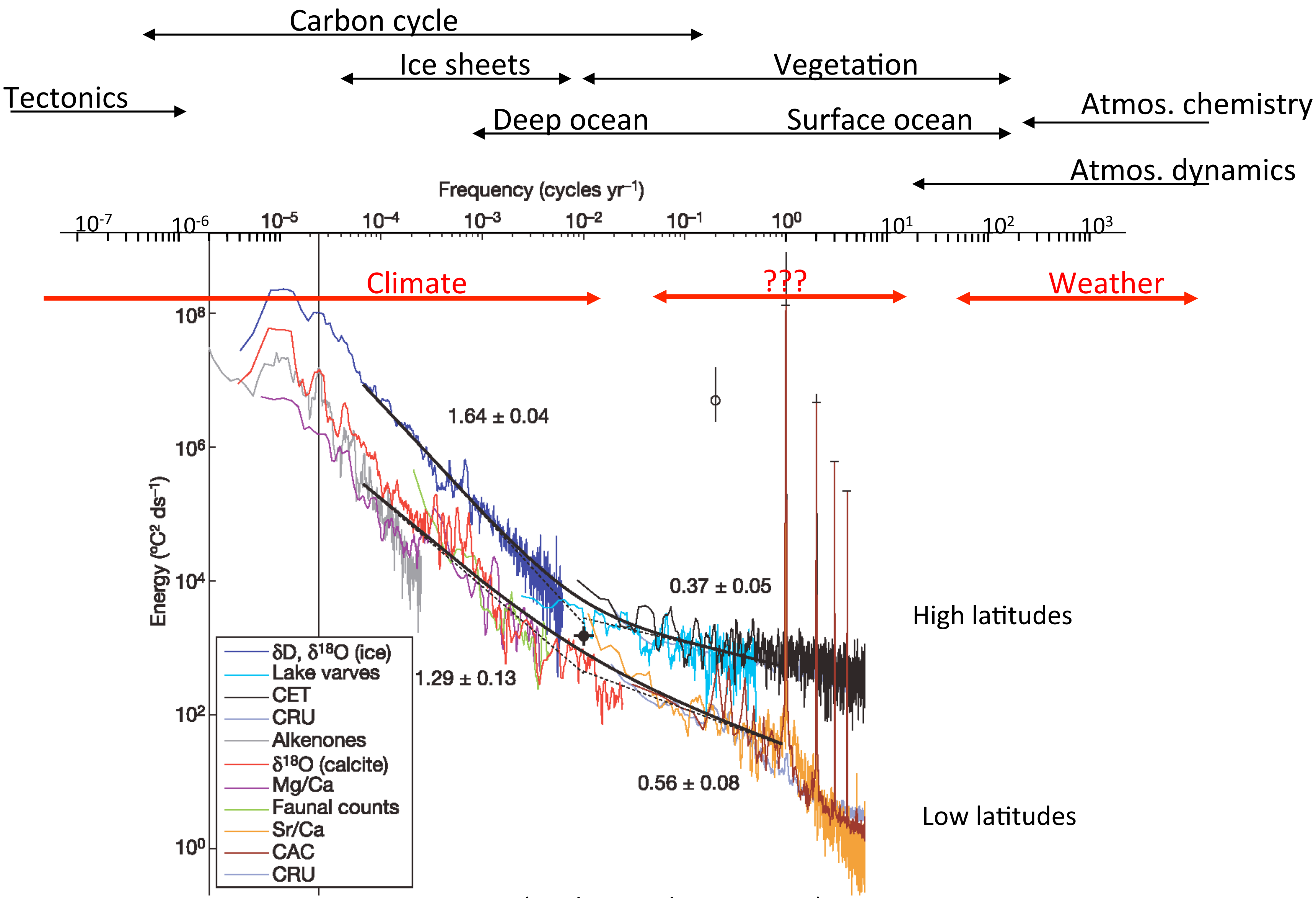


(IPCC 2014)

Energy fluxes (TW)

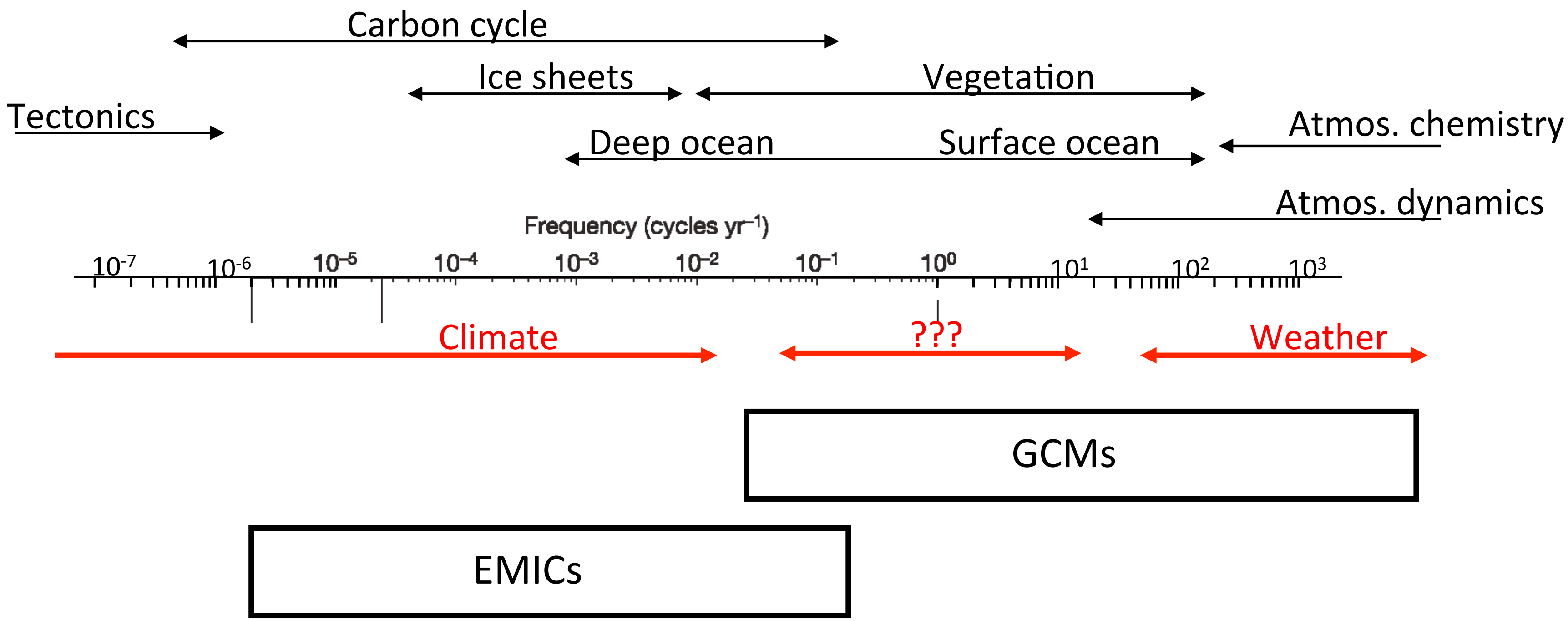


What is climate ? (what is a climatologist ?)



(Huybers and Curry, 2006)

What kind of numerical tools ?

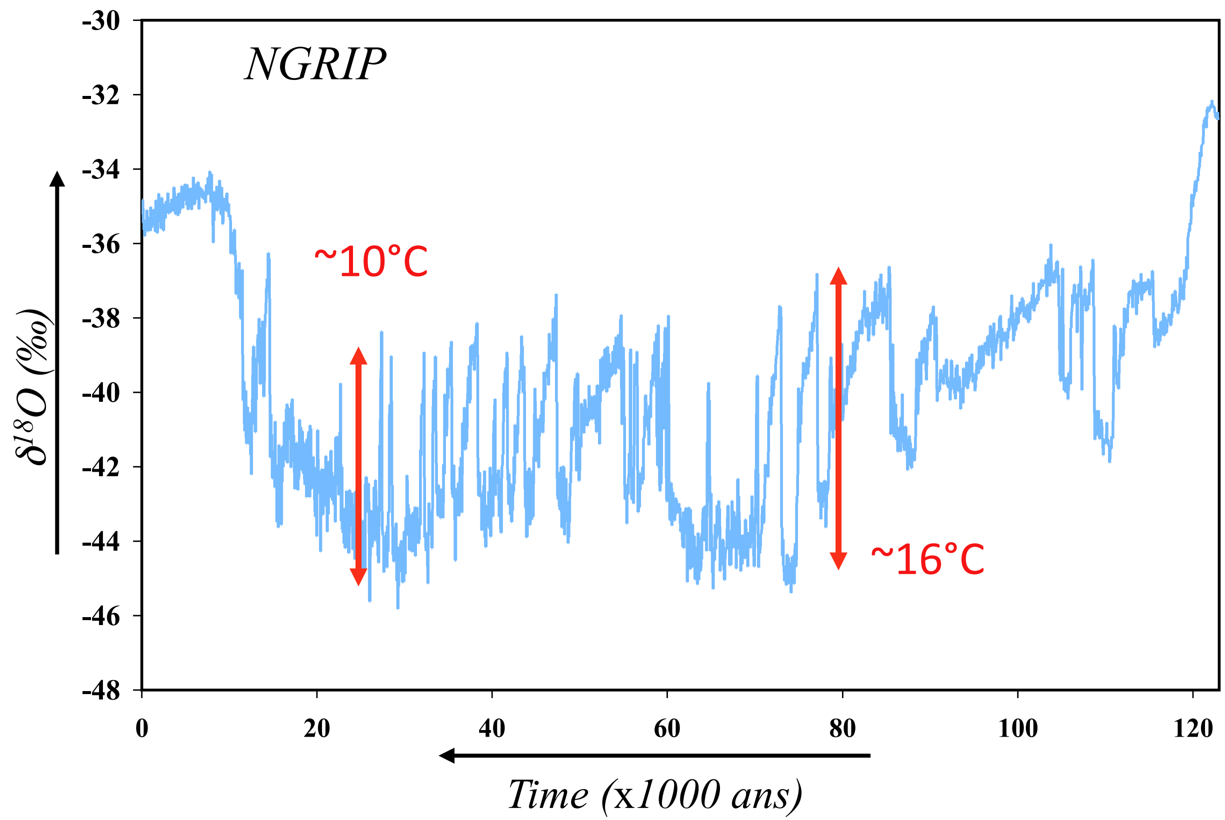


Surprises to come … ??

Large amplitude abrupt changes

- +10-16°C
- transitions

  < 100 ans



Surprises to come … ??

Abrupt sea level rise …

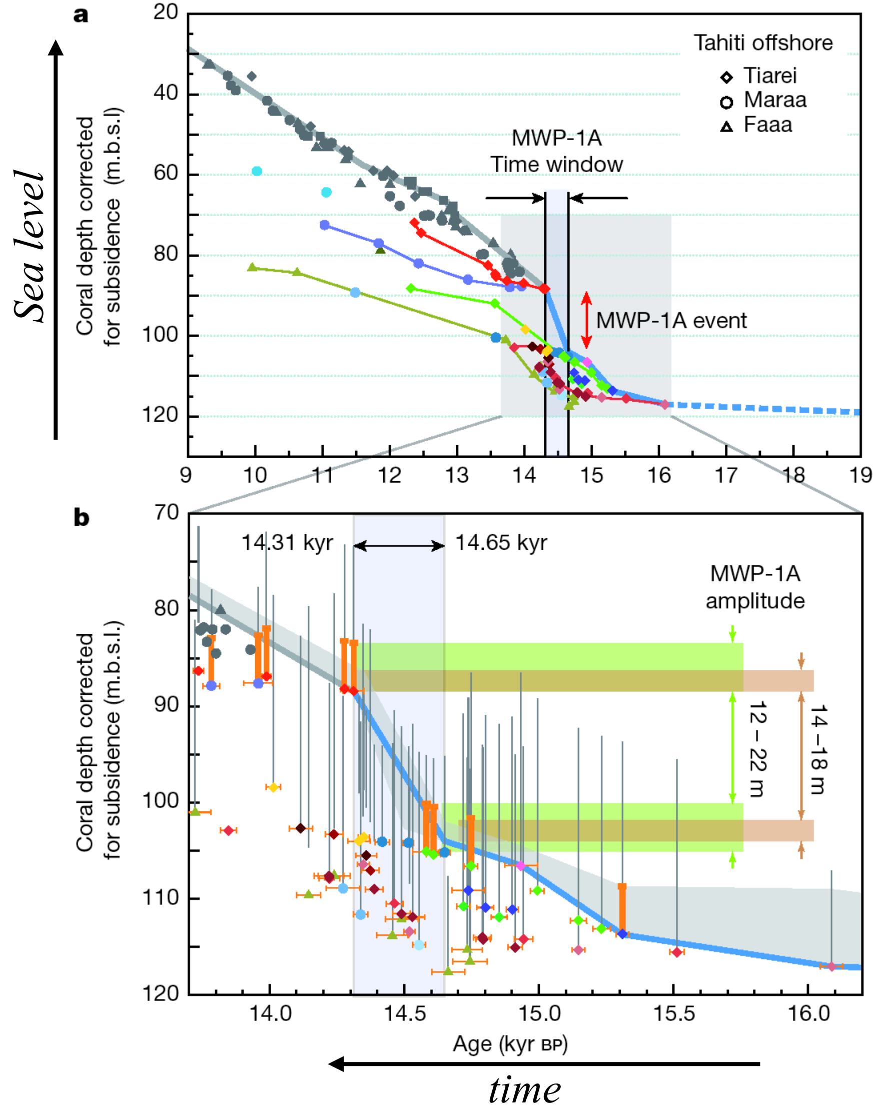
… like during the last deglaciation

MPW1a:

~ 14 600 years BP

+ 20 m in 300 years

(> 6 m/century)



(Deschamps et al., Nature 2012)

Some key points

- « Climate » is not a well-defined object.
- Phanerozoic climate did change (between roughly -5° and +12°) in close connection with the evolution of life.
- The large long-term variations are (probably) caused by changes in pCO_2 whose dynamics is poorly understood on these time scales.
- We need simpler tools (simple models and theories)

Thank you !