Modélisation des variations glaciaires-interglaciaires du CO_2 atmosphérique :
Rôle de l'érosion continentale

Modelling Glacial-Interglacial Atmospheric CO_2 Variations:
The Role of Continental Weathering

Guy MUNHOVEN

Laboratory of Planetary and Atmospheric Physics
Institut d'Astrophysique et de Géophysique
Université de Liège

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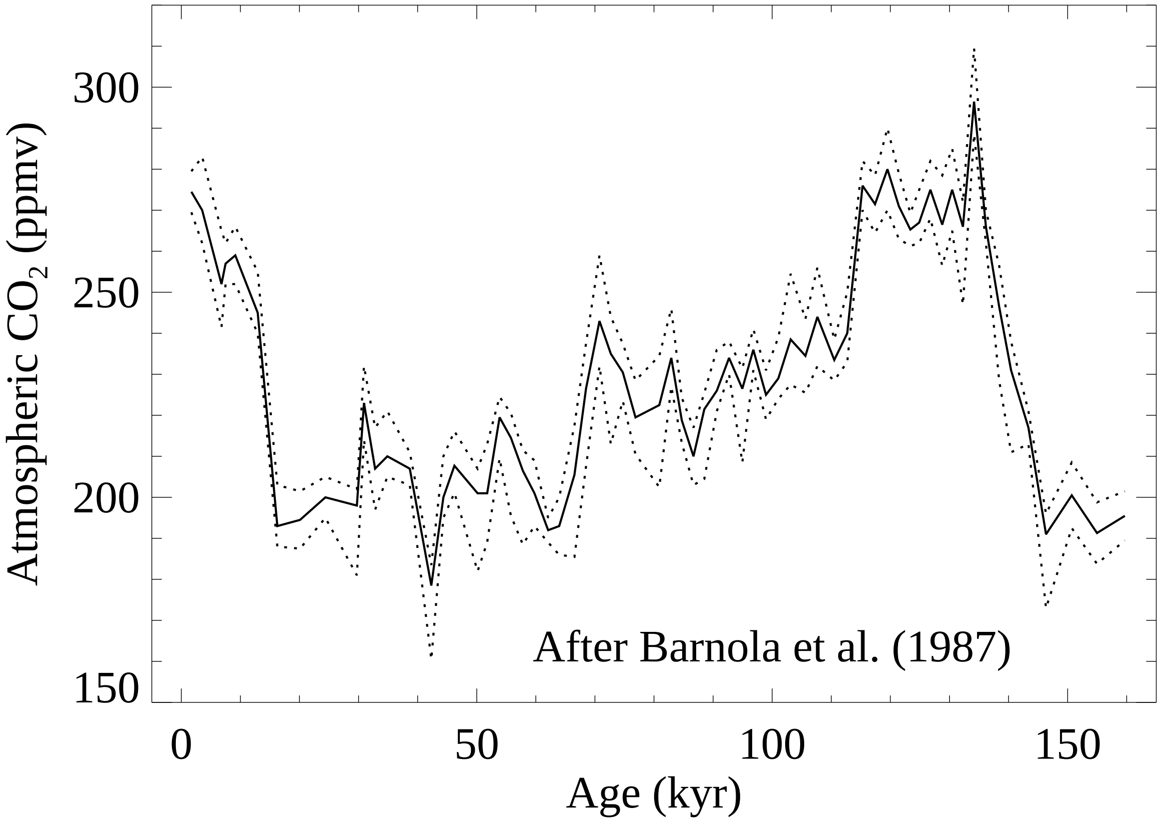
Glacial-Interglacial Atmospheric CO_2 Variations: The Vostok Record



- oscillation between
  - glacial level of 190 – 200 ppmv
  - interglacial level of 260 – 280 ppmv

- well correlated to climate

Outline of this Presentation

1. The Global Carbon Cycle
    - present-day/pre-industrial
    - glacial-interglacial changes
    - new hypothesis for CO_2 variations

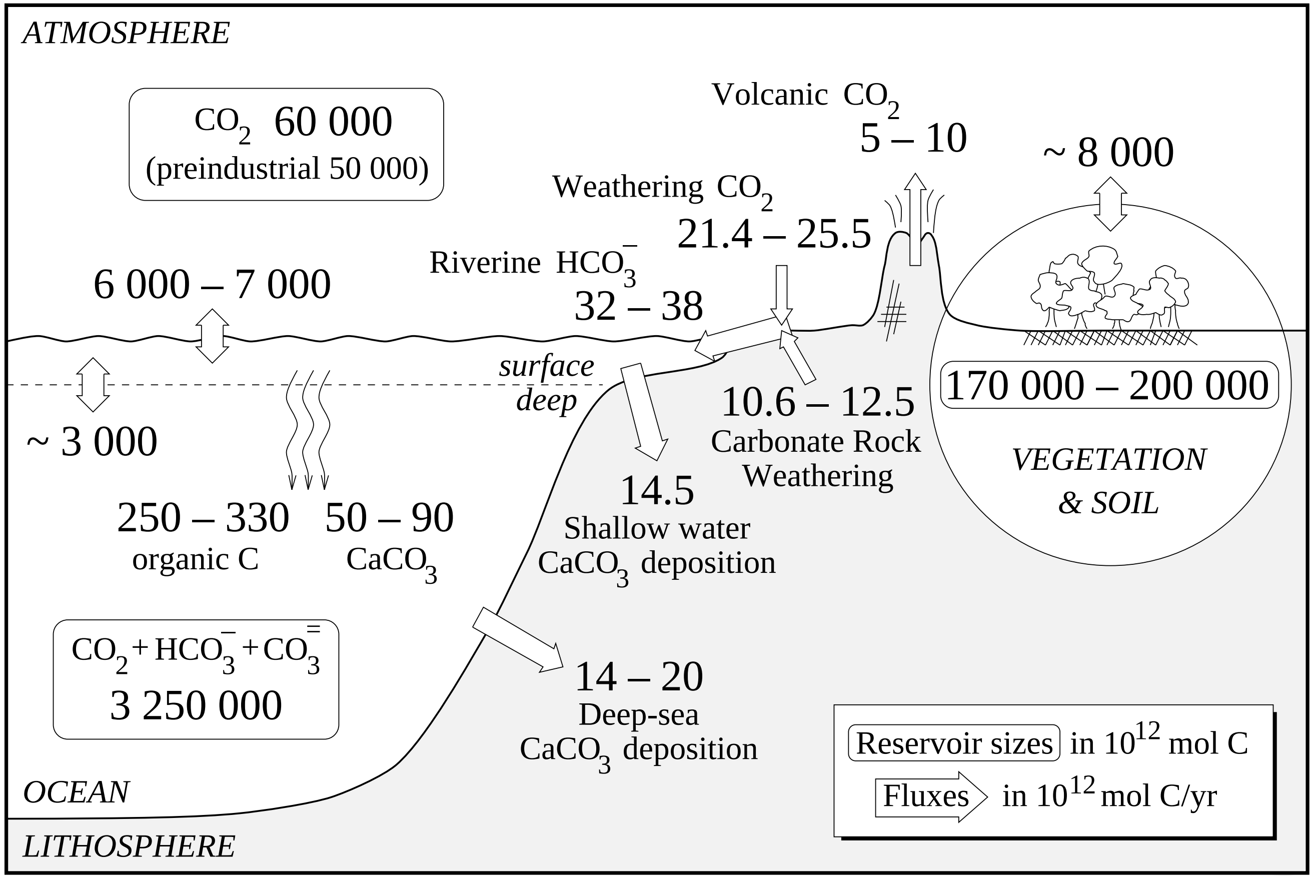
2. The Role of Continental Weathering in the Global Carbon Cycle
    - CO_2 consumption and HCO_3^- production
    - silicate vs. carbonate difference
    - influence of variations on atmospheric CO_2

3. Model of the Oceanic Carbon Cycle

4. Reconstructions and Simulations
    - marine tracers: ($^{87}Sr/^{86}Sr$,) Ge/Si
    - erosion model: GEM-CO_2

5. Conclusions and Future Work

The Carbon Cycle at Present and at Preindustrial Times



Marine Carbonate Chemistry

Chemical equilibria between carbonate species

$$\mathrm{CO_{2(aq)}} + 2\ \mathrm{H_2O} \rightleftharpoons \mathrm{HCO_3^-} + \mathrm{H_3O^+}$$

$$\mathrm{HCO_3^-} + \mathrm{H_2O} \rightleftharpoons \mathrm{CO_3^{2-}} + \mathrm{H_3O^+}$$

Special roles of different species

- atmospheric $p_{\mathrm{CO_2}} \longleftrightarrow [\mathrm{CO_{2(aq)}}]_{\mathrm{surface}}$
- $\mathrm{CaCO_3}$ deposition $\longleftrightarrow [\mathrm{CO_3^{2-}}]_{\mathrm{deep}}$

Speciation calculated from combinations

- Dissolved Inorganic Carbon

$$C_{\mathrm{T}} = [\mathrm{CO_{2(aq)}}] + [\mathrm{HCO_3^-}] + [\mathrm{CO_3^{2-}}]$$

- Total Alkalinity

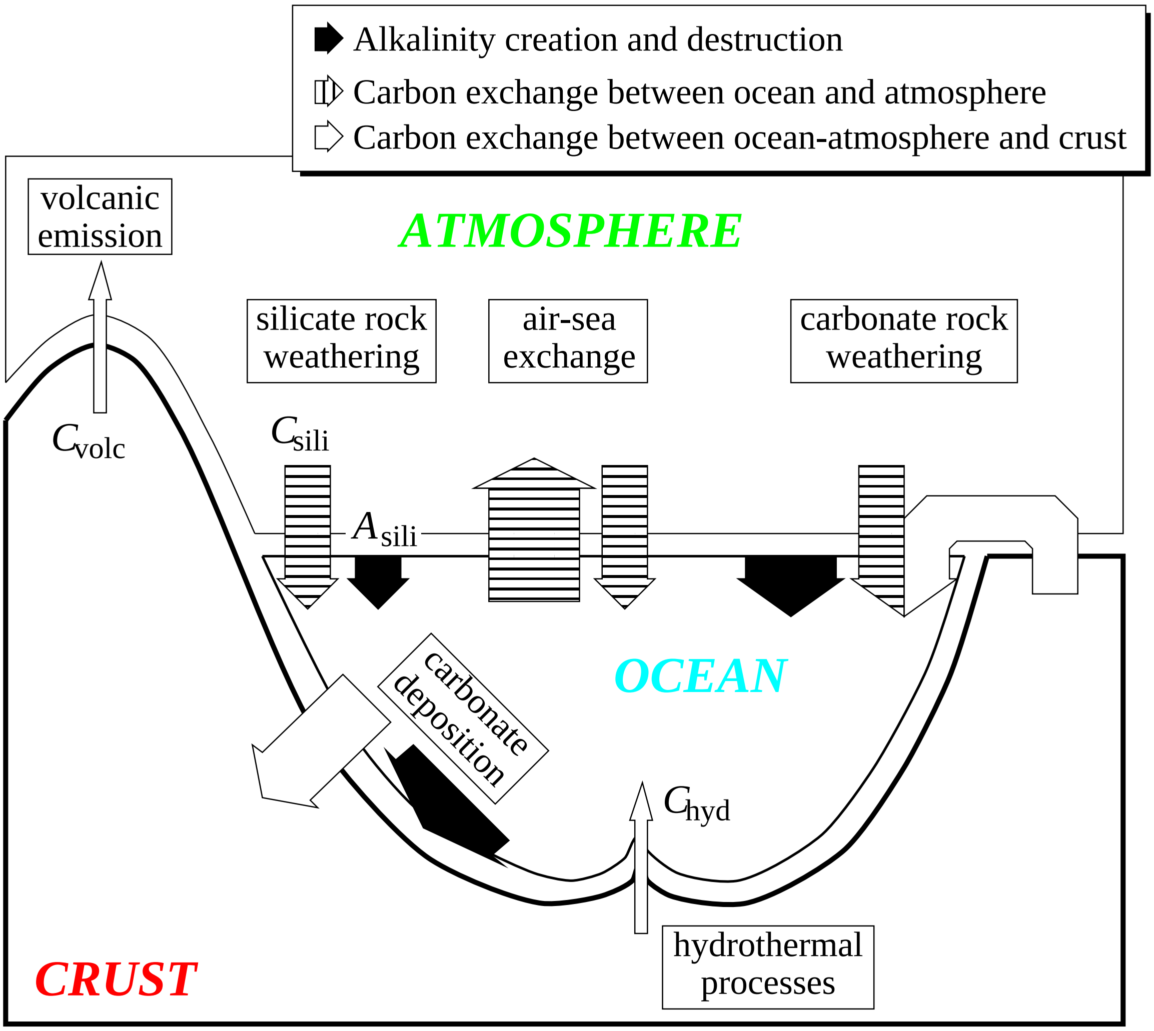
$$A_{\mathrm{T}} \simeq [\mathrm{HCO_3^-}] + 2\,[\mathrm{CO_3^{2-}}] + [\mathrm{B(OH)_4^-}] + [\mathrm{OH^-}] - [\mathrm{H_3O^+}]$$

General rules

$$C_{\mathrm{T}} \xrightarrow{\oplus} p_{\mathrm{CO_2}} \qquad C_{\mathrm{T}} \xrightarrow{\oplus} [\mathrm{CO_3^{2-}}]$$

$$A_{\mathrm{T}} \xrightarrow{\ominus} p_{\mathrm{CO_2}} \qquad A_{\mathrm{T}} \xrightarrow{\oplus} [\mathrm{CO_3^{2-}}]$$

The Role of Continental Weathering in the Global Carbon Cycle



Sources and Sinks of Dissolved Inorganic Carbon and of Alkalinity in the Ocean

Sources: continental weathering

- carbonate minerals: *congruent* dissolution

$$\mathrm{CaCO_3 + CO_2 + H_2O \longrightarrow Ca^{2+} + 2\,HCO_3^-}$$

- silicate minerals: *incongruent* dissolution

$$\begin{aligned}\text{silicate mineral} + b\,\mathrm{CO_2} + \text{water} &\longrightarrow \\ &\text{secondary minerals} + \\ &\text{cations} + b\,\mathrm{HCO_3^-} + s\,\mathrm{H_4SiO_4}\end{aligned}$$

Sinks: deposition of biogenic carbonates

$$\mathrm{Ca^{2+} + 2\,HCO_3^- \longrightarrow CaCO_3 + CO_2 + H_2O}$$

Basic Constraints and Properties of the System

- $\tau_{\text{carbon}} \simeq 100$ kyr — $\tau_{\text{alkalinity}} \simeq 50$ kyr

- Long time-scales (typically > 1 Myr)

$$\boxed{\text{Global budgets of carbon } (\widehat{C}) \text{ \& alkalinity } (\widehat{A}) \text{ balanced}} \Longrightarrow \boxed{\begin{array}{c} \frac{1}{2}C_{\text{sili}} = C_{\text{volc}} + C_{\text{hyd}} \\ (C_{\text{sili}} = A_{\text{sili}}) \end{array}}$$

- Glacial-interglacial time-scales (10 – 100 kyr):
  - ⋆ constraint fulfilled on average

    $\Longrightarrow$ fluctuations possible
  - ⋆ hydrothermal and volcanic activities exhibit only little variability
  - ⋆ new constraint

$$\frac{d\widehat{A}}{dt} - 2\,\frac{d\widehat{C}}{dt} = C_{\text{sili}} - \overline{C_{\text{sili}}}$$

The Silicate Weathering Hypothesis

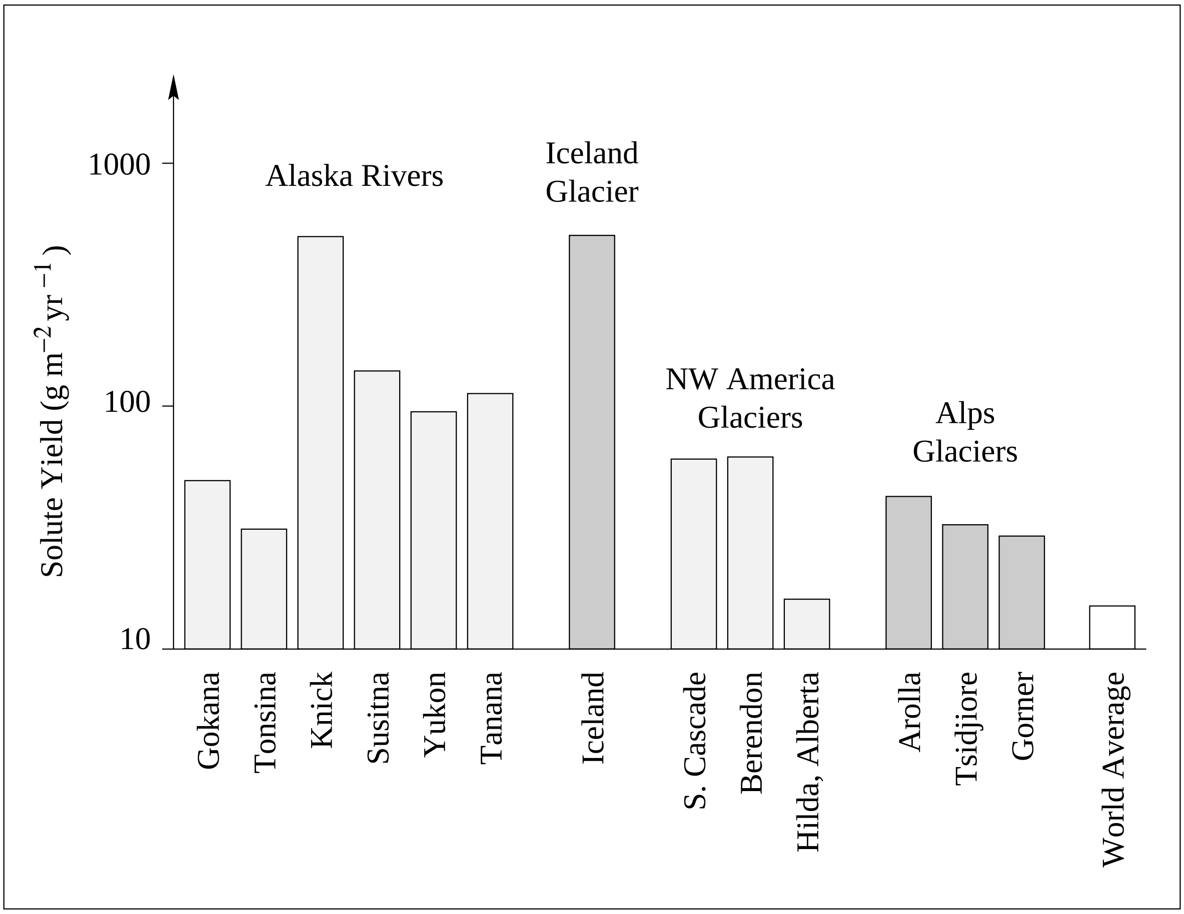
An increased consumption of CO_2 by weathering processes — and more specifically by silicate weathering — during glacial times plays a significant role in reducing atmospheric CO_2 levels.

However:

- large areas covered by ice-sheets
- climate conditions colder and drier

$\Longrightarrow$ reduction of global weathering rates

Specific Solute Yield From Glaciated Basins

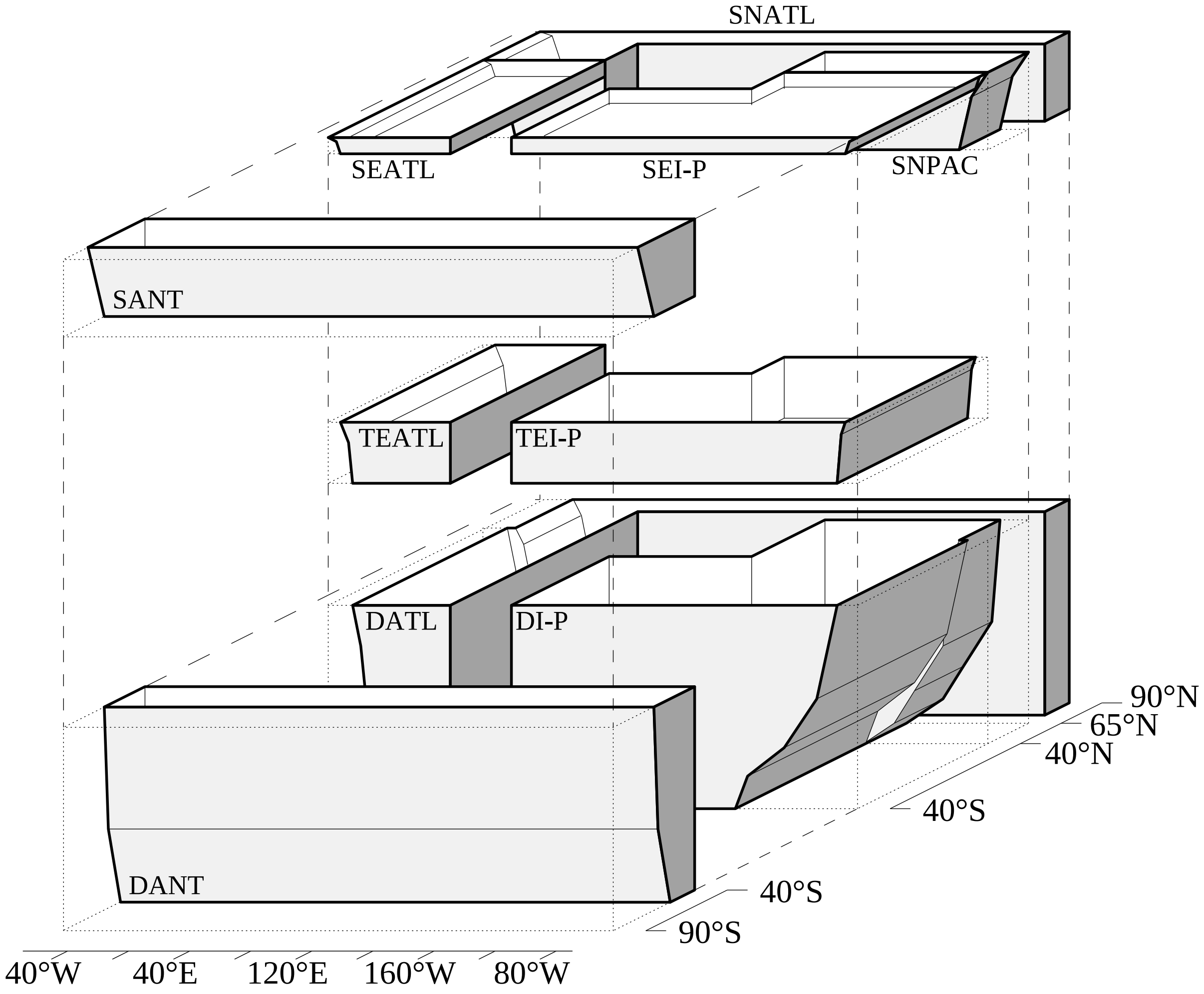


On the other hand:

- production of fine-grained, easily weatherable materials by glaciers
- observation: specific solute yields from partially glaciated basins much higher than average

$\Longrightarrow$ net effect difficult to predict

Model of the Oceanic Carbon Cycle



Atlantic

Antarctic

Indo-Pacific

Model Characteristics

Configuration

- Volumes and salinities:
  sea level & 5 depth profiles
- Sea level $\div \Delta\delta^{18}$O (SPECMAP)
- Temperatures from reconstructions

Modelled tracers

- C_T – dissolved inorganic carbon
- A_T – total alkalinity
- PO_4 – phosphate
- O_2 – oxygen
- p_{CO_2} – atmospheric CO_2
- δ^{13}C, Δ^{14}C

Water circulation

- derived from Hamburg OGCM velocity field
- calibrated on Δ^{14}C distribution

Material Fluxes

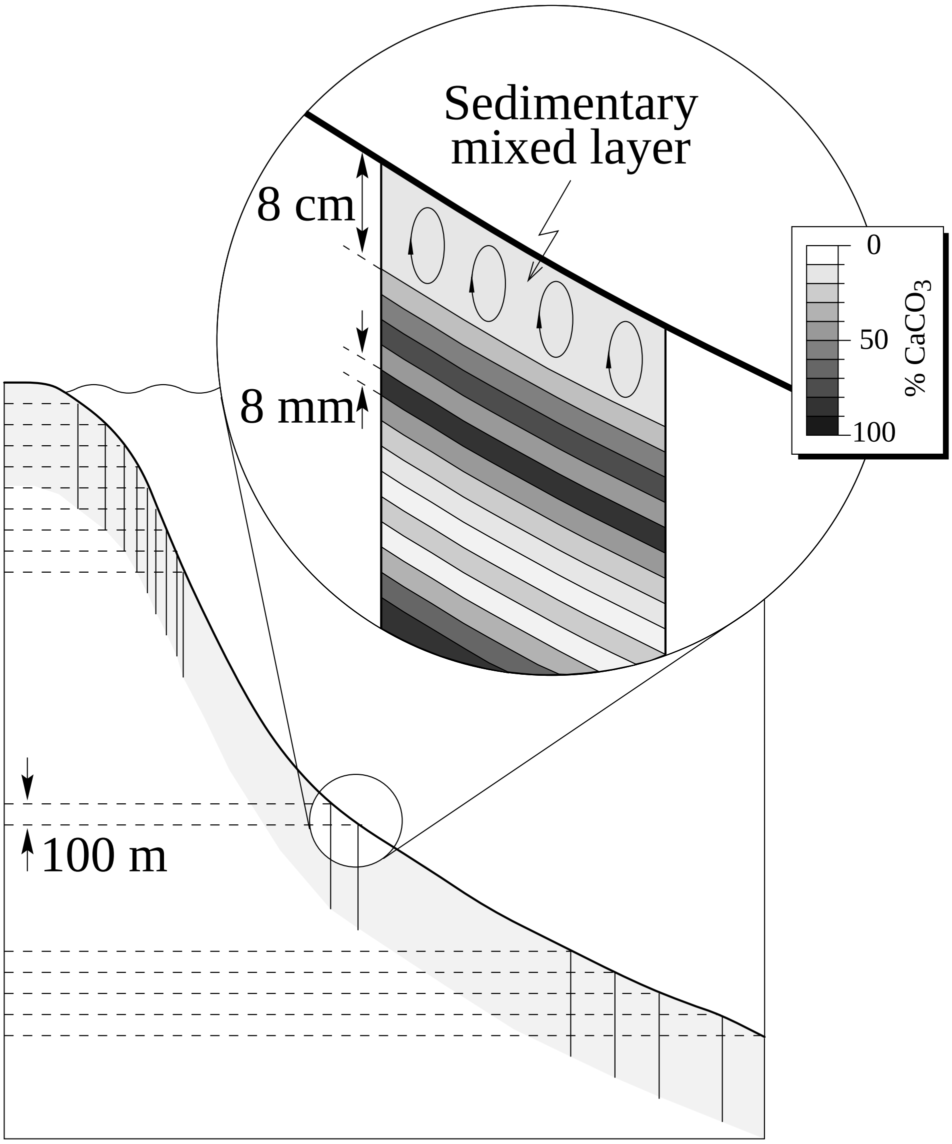
Organic matter fluxes

- Surface $\longrightarrow$ Thermocline and Deep: proportional to $\mathcal{F}_{\mathrm{PO}_4}$ entering Surface
- complete remineralization in Thermocline and Deep reservoirs
- following C/N/P = 106/16/1

Carbonate fluxes

- Continental margins
  - Coral-reefs:
    - $\ast$ depth < 100 m
    - $\ast$ rate of sea level change
    - $\ast$ $7{,}0 \times 10^{12}$ mol $\mathrm{CaCO_3}$/yr (0–5000 yr BP)
  - Banks and shelves:
    - $\ast$ $\div$ flooded area
    - $\ast$ $7{,}5 \times 10^{12}$ mol $\mathrm{CaCO_3}$/an (0–5000 yr BP)
- Open ocean
  - production $\div$ organic production
  - Deep: dissolution/accumulation determined by *Sedimentary Shell Model*

Sedimentary Shell Model



Reconstructions and Simulations
Tracer-based Approaches

I. Seawater ^{87}Sr/^{86}Sr

- used for Cenozoic and Phanerozoic studies
- problematic data for glacial-interglacial times

Results and conclusions

- role of silicate weathering processes cannot be neglected for atmospheric CO_2
- insufficient characterization of silicate weathering products by ^{87}Sr/^{86}Sr

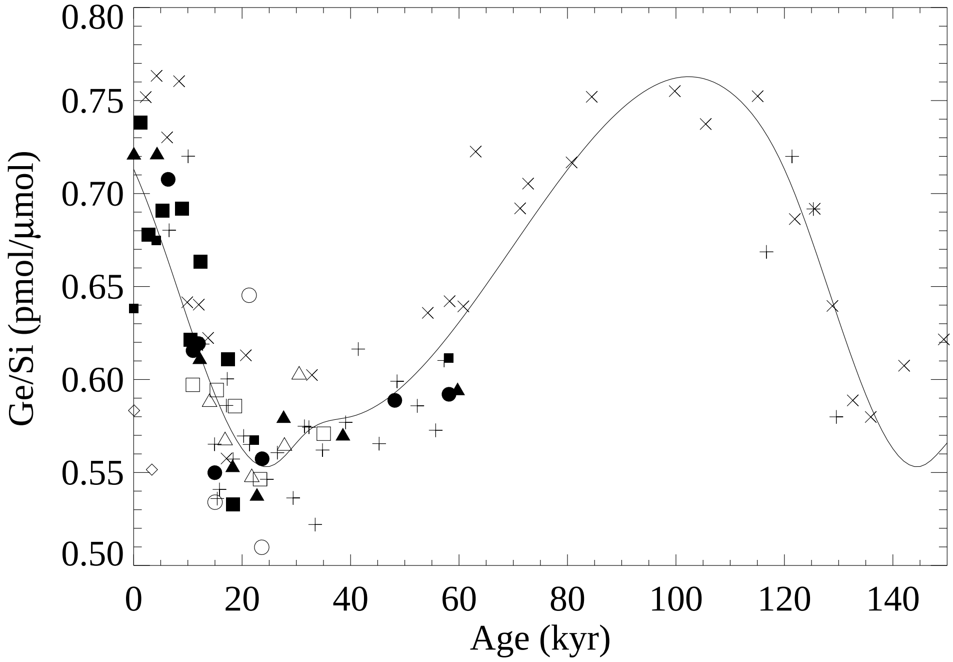
⇒ possible to construct weathering scenario both in agreement with Vostok CO_2 and seawater ^{87}Sr/^{86}Sr records

But:

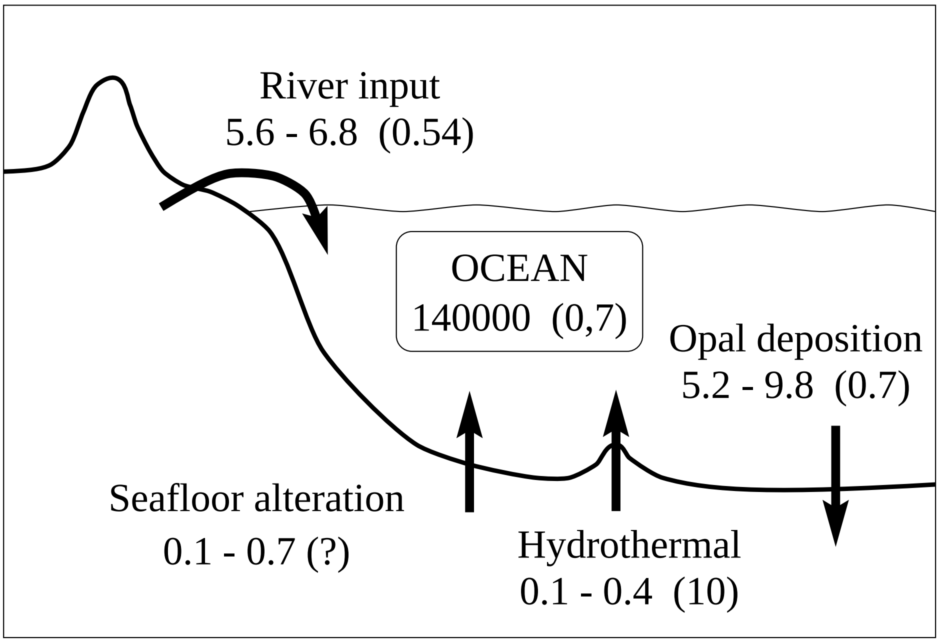
- Data withdrawn: impossible to reproduce them

II. Seawater Ge/Si

Ge/Si: Glacial-interglacial Variations



Oceanic Ge and Si Cycles



Reservoir size : 10^{12} mol Si (Ge/Si: 10^{-6} mol/mol)

Flux : 10^{12} mol Si/yr (Ge/Si: 10^{-6} mol/mol)

Seawater Ge/Si — methodology

- Interpretation of $(\mathrm{Ge/Si})_{\mathrm{opal}}$
  - ⋆ biological fractionation (-20%, 0%)
  - ⋆ opal accumulation (constant rate/resid. time)
  - ⋆ runoff variations (-20%, 0%, $+20\%$)
  - ⋆ $(\mathrm{Ge/Si})_{\mathrm{hyd}}$ (5×10^{-6}, 10×10^{-6}, 20×10^{-6})

  $\Longrightarrow$ riverine dissolved Si flux at LGM
  2 – 3.5 times present-day value

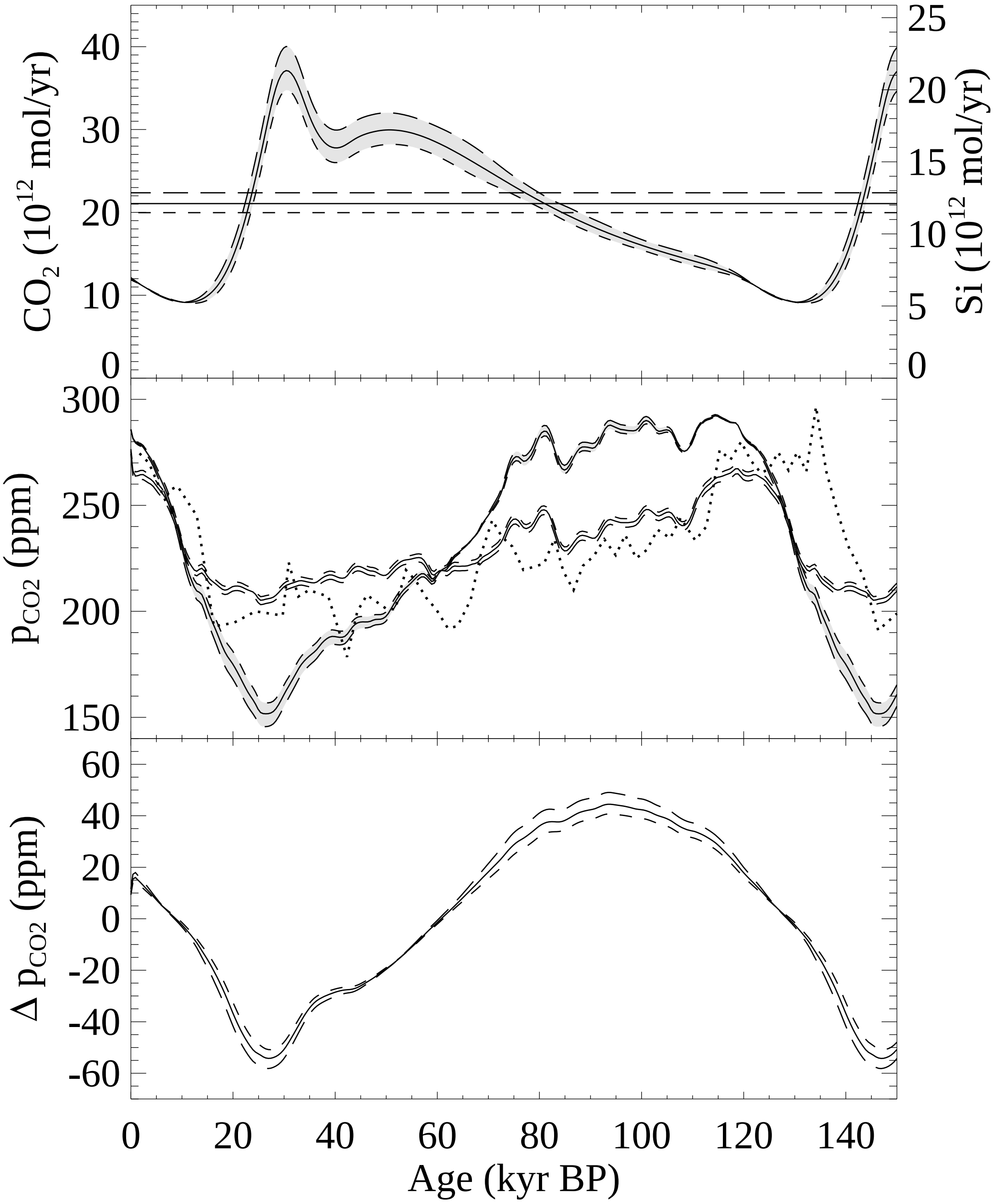
- *Si flux* $\longrightarrow$ *HCO_3^- flux* conversion

  Analysis of
  weathering intensity $\longleftrightarrow$ $[\mathrm{HCO_3^-}]_{\mathrm{sili}}/[\mathrm{H_4SiO_4}]$
  relationship

  - ⋆ global average: $1{,}76 \pm 0{,}10$
  - ⋆ Amazon: 1.04 – 1.10
    Congo/Zaire: 0.55
  - ⋆ $\Rightarrow$ temperate and cold areas: ~ 3.2

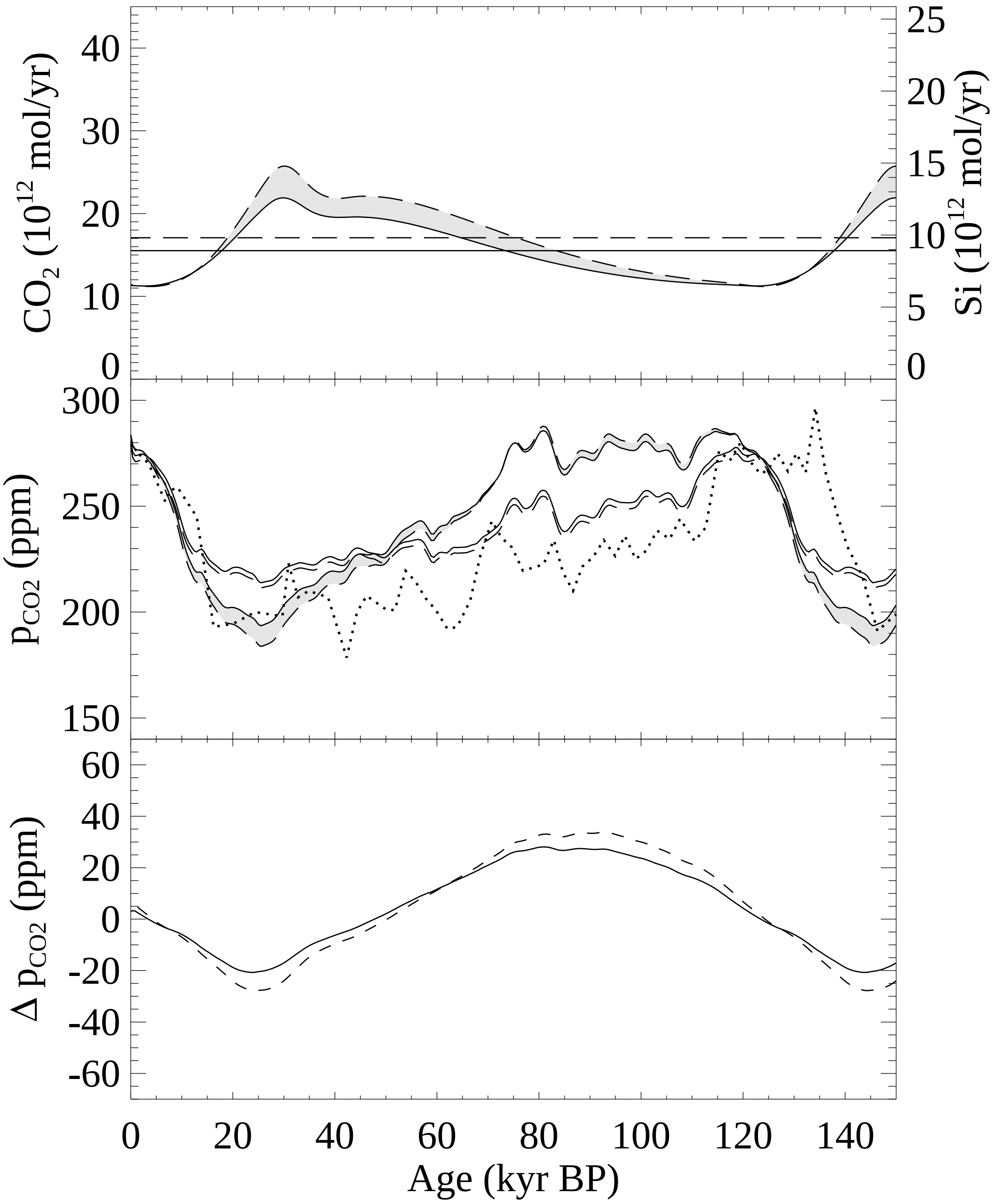
  Adopted approach: $[\mathrm{HCO_3^-}]_{\mathrm{sili}}/[\mathrm{H_4SiO_4}] \equiv 1.76$

Ge/Si-based Approach — Results



Inversion for $\tau = 20000$ yr,
without biological fractionation,
for runoff variations of -20, 0 or $+20\%$

Ge/Si-based Approach — Results (II)



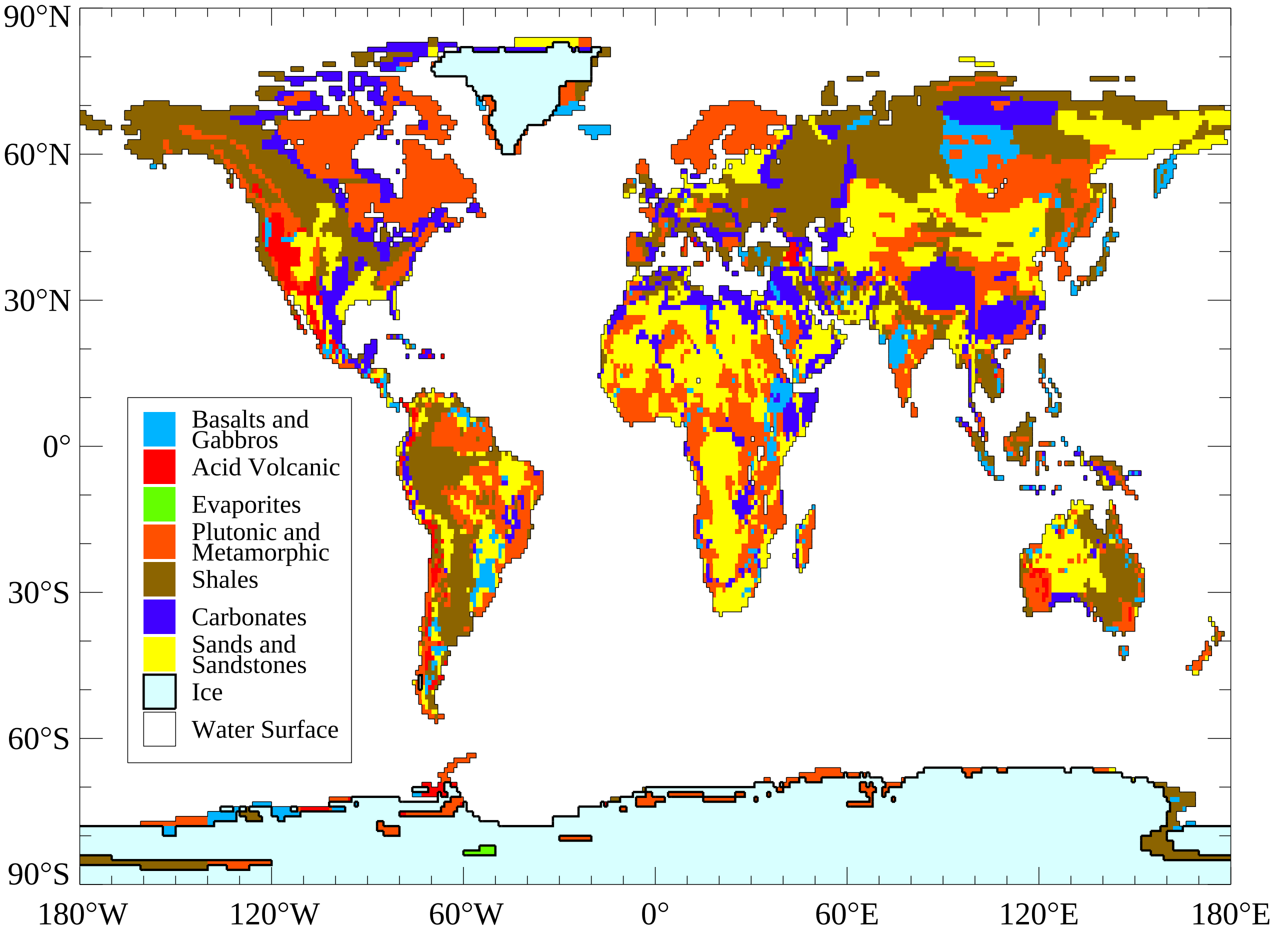
Inversion with constant opal accumulation rate or with $\tau = 20000$ yr, with biological fractionation of -20%, with constant runoff

Reconstructions and Simulations
GEM-CO_2 Erosion Model

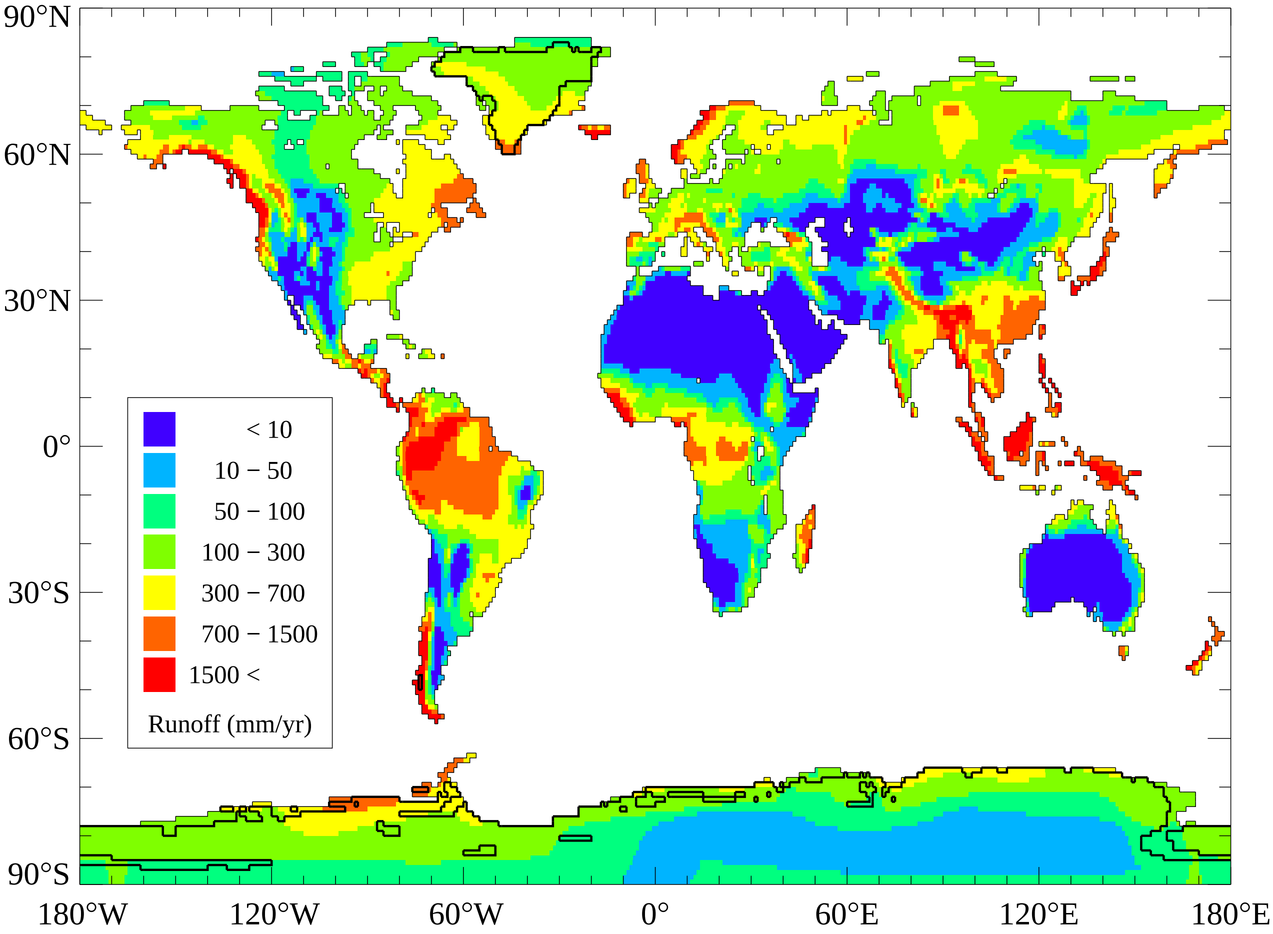
GEM-CO_2 – Global Erosion Model for CO_2 fluxes

- calculates atmospheric CO_2 consumption rate and corresponding HCO_3^- transfer as a function of
  - outcropping rock type
  - runoff intensity
- Problems to resolve in order to apply GEM-CO_2 under LGM climate conditions
  - adaptation of present-day lithological map to LGM geography (ice, continental margins)
  - reconstruction of LGM runoff distribution

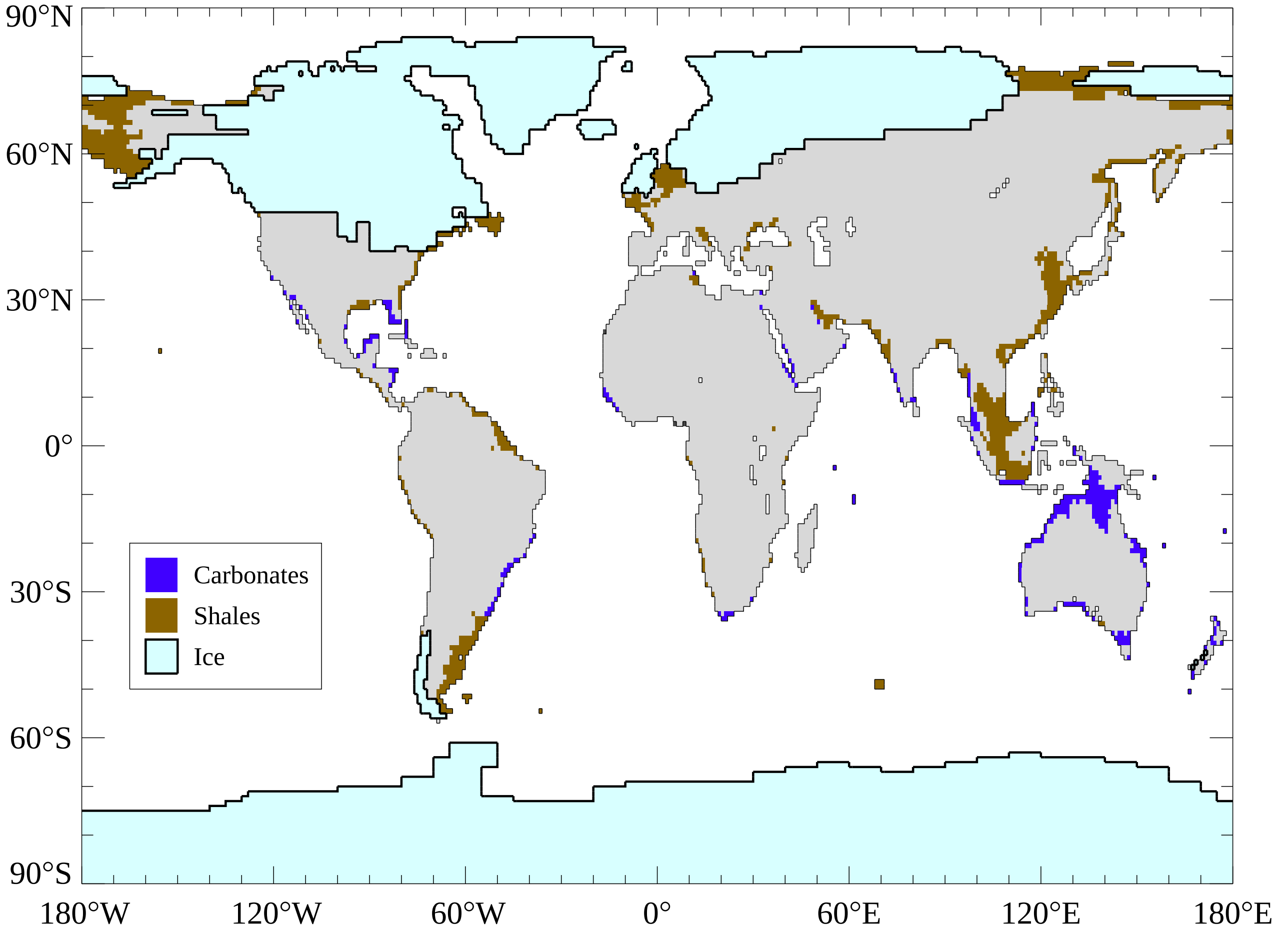
Present-day Lithology



UNESCO Runoff



Continental Margin Lithology and Ice-sheet Extension at the Last Glacial Maximum



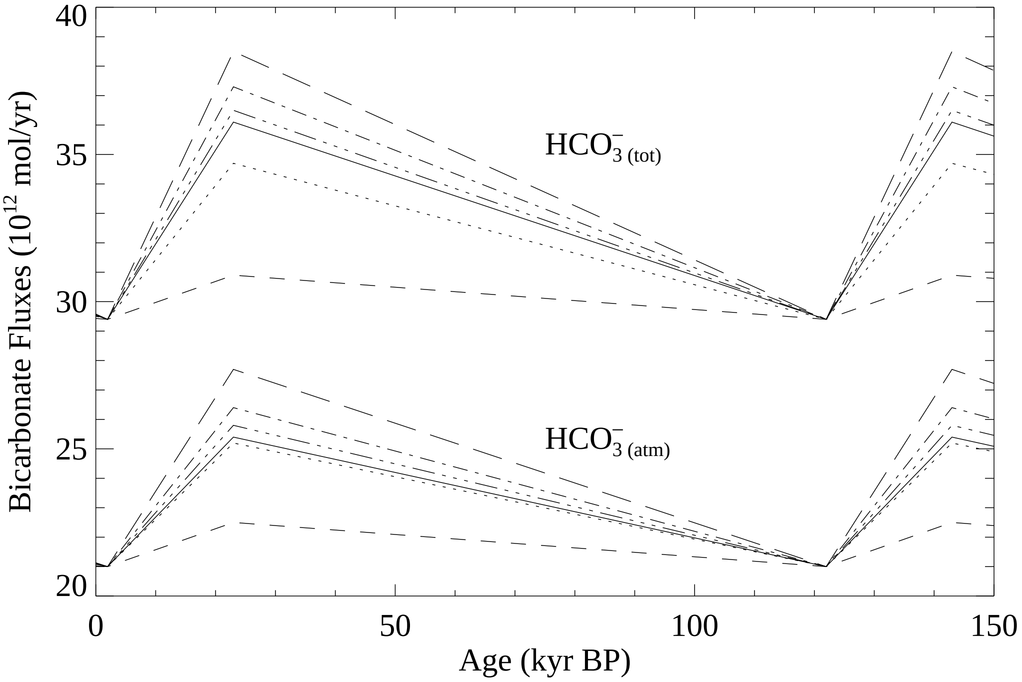
Runoff Reconstruction Methodology

- Observational constraints ⟶ trends
- GCM climatologies: GISS, ECHAM2, LMD4bis, LMD5ter
- 2 methods used to derive runoff distributions from GCM climatologies
  - $D^{\text{GCM}} = P^{\text{GCM}} - E^{\text{GCM}}$
  - empirical model relating runoff to
    - seasonality of precipitation
    - temperature
    - morphology

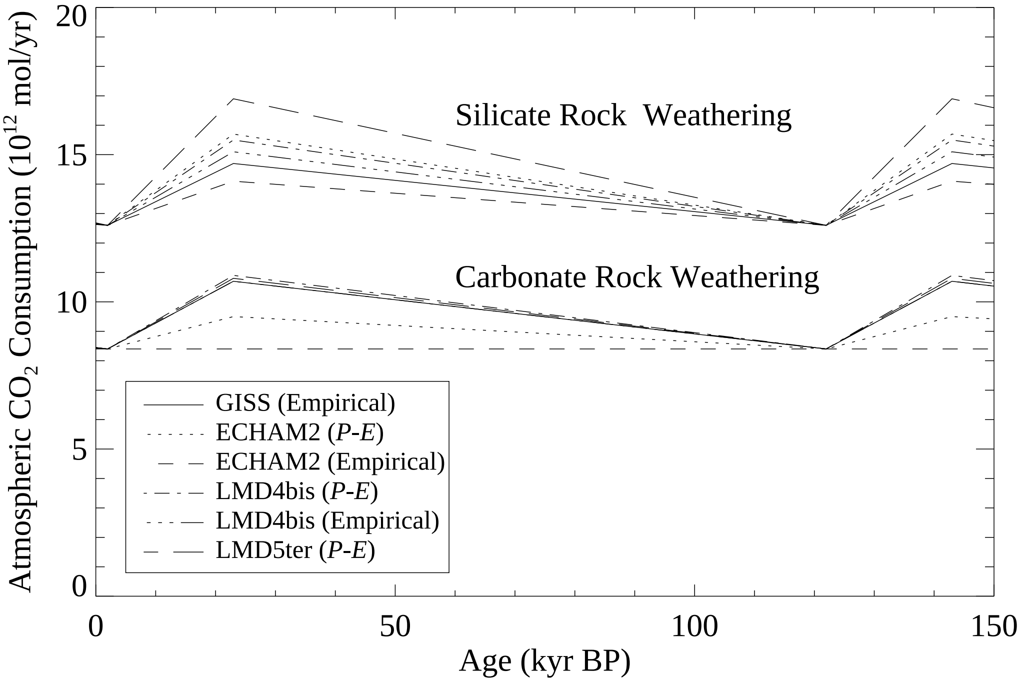
    $\Rightarrow D^{\text{GCM}} = fct(P^{\text{GCM}}, T^{\text{GCM}}, \text{terrain parameters})$
- $$\Delta D = D^{\text{GCM}}(\text{LGM}) - D^{\text{GCM}}(\text{Present})$$
  $$D(\text{LGM}) = D(\text{Present}) + \Delta D$$
- GEM-CO_2 ⟶ $HCO^-_{3\,(\text{atm})}$ & $HCO^-_{3\,(\text{tot})}$ at LGM

Bicarbonate Transfer to the Ocean

Atmosphere/Lithosphere Contributions

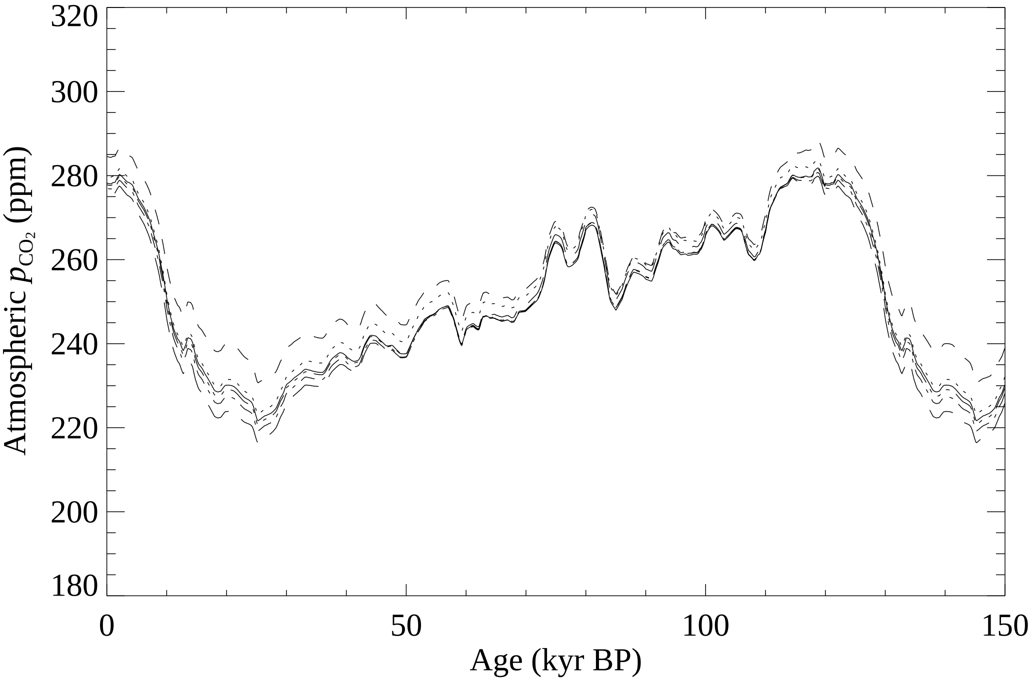


Silicate/Carbonate Contributions

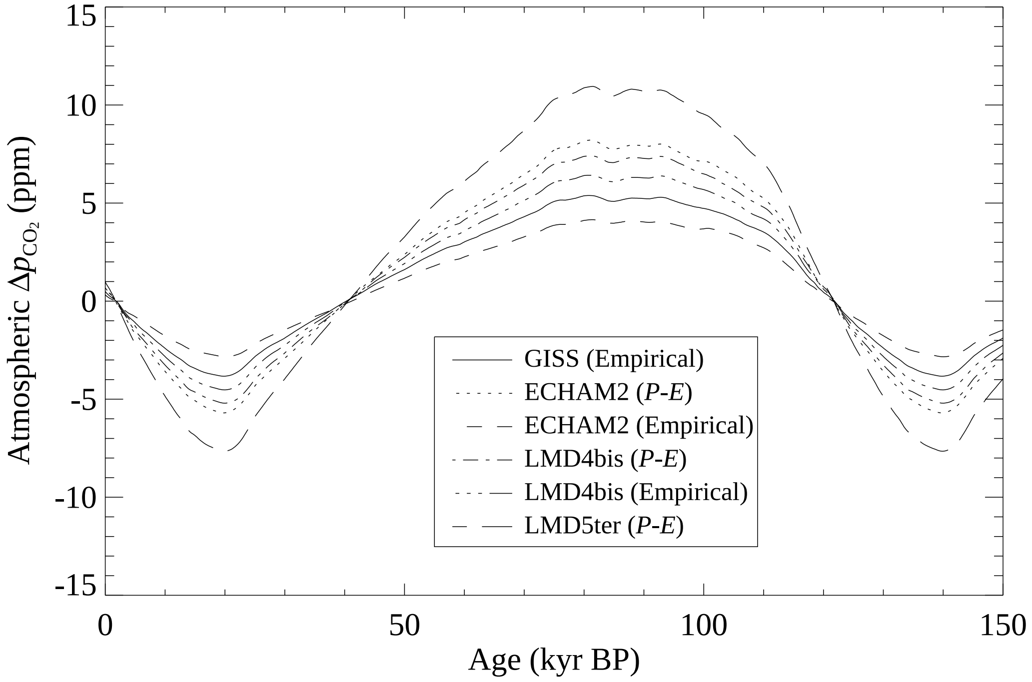


GEM-CO_2 — Results

Evolution of Atmospheric CO_2



Net Contribution from Silicate Weathering



Conclusions and Future Work

- Development of an oceanic carbon cycle model
- Test of a new hypothesis to explain glacial-interglacial atmospheric CO_2 variations

  Silicate Weathering Hypothesis
- Reconstruction of CO_2 consumption and HCO_3^- production rates based on two different methods
  - interpretation of marine tracers
  - model of continental erosion
- Contrasting Results
- Perspectives
  - quantitative study of the impact of glaciers on global weathering rates
  - systematic analysis of $[HCO_3^-]_{\mathrm{sili}}/[H_4SiO_4]$
  - further development of the carbon cycle model