

The Global Climate Thermostat: Fact, fiction, and computer models

Andy Ridgwell



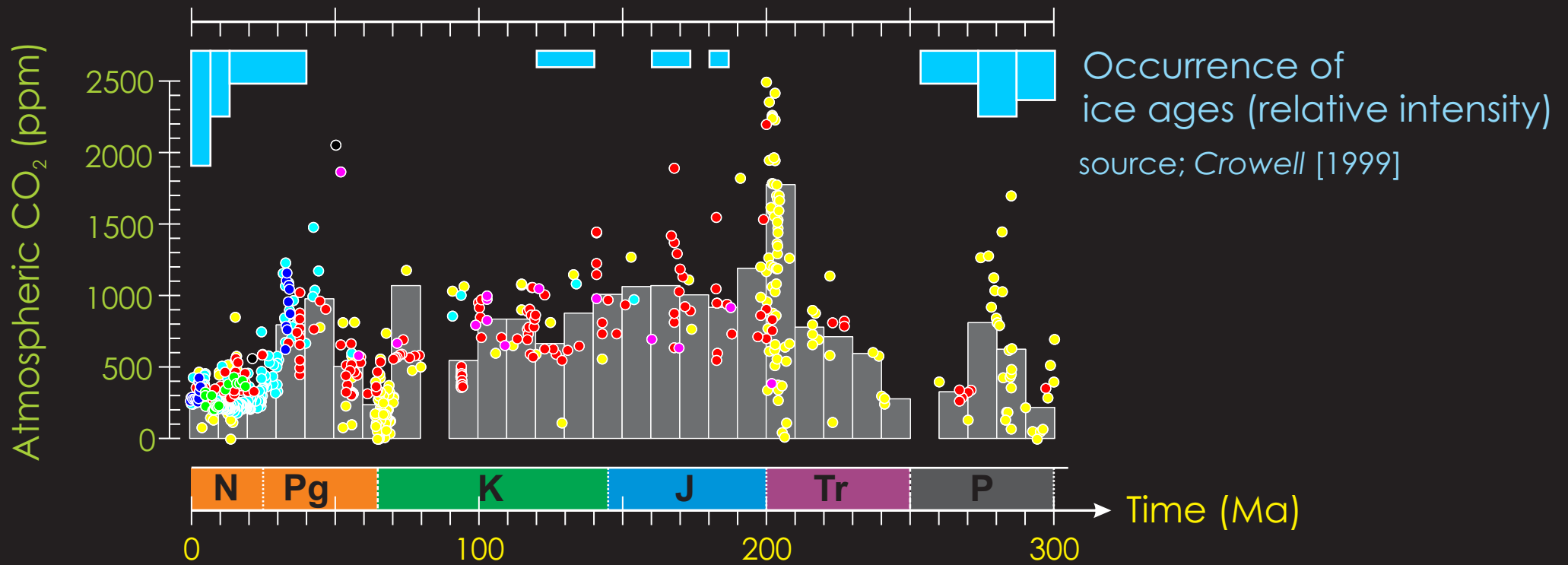
Regulation of global climate



Regulation of global climate



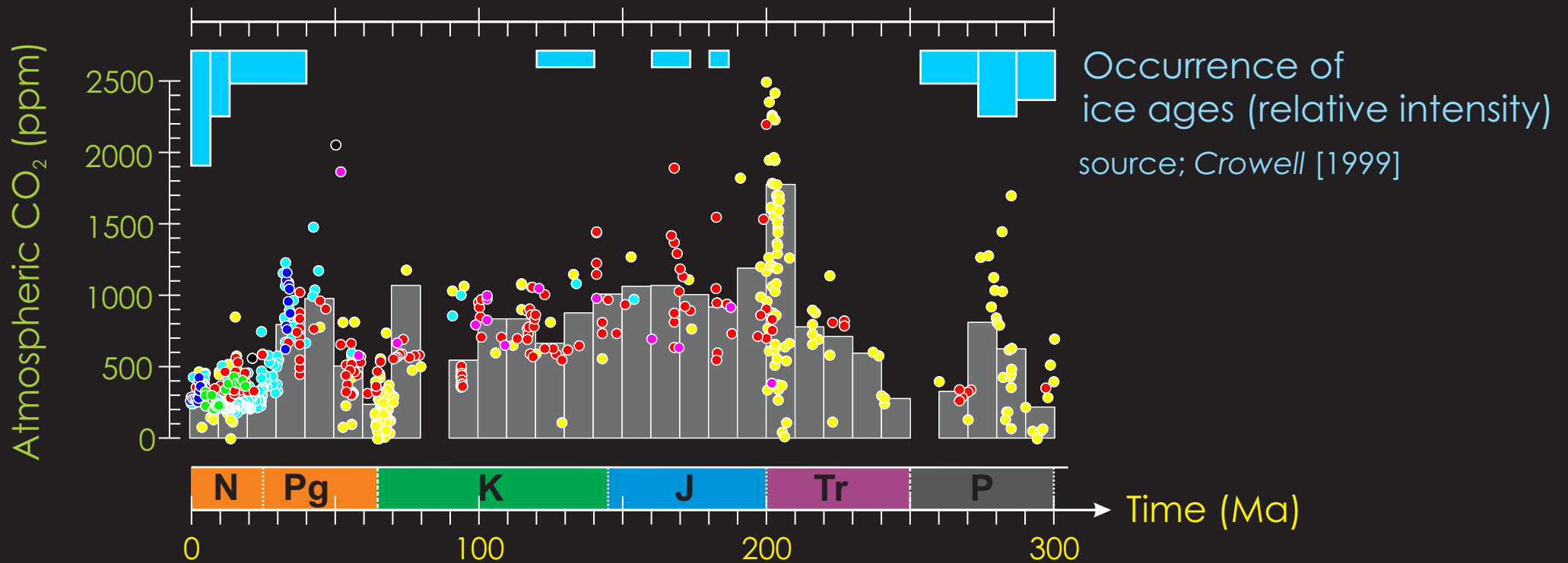
From: *Hönisch et al. [2012]*



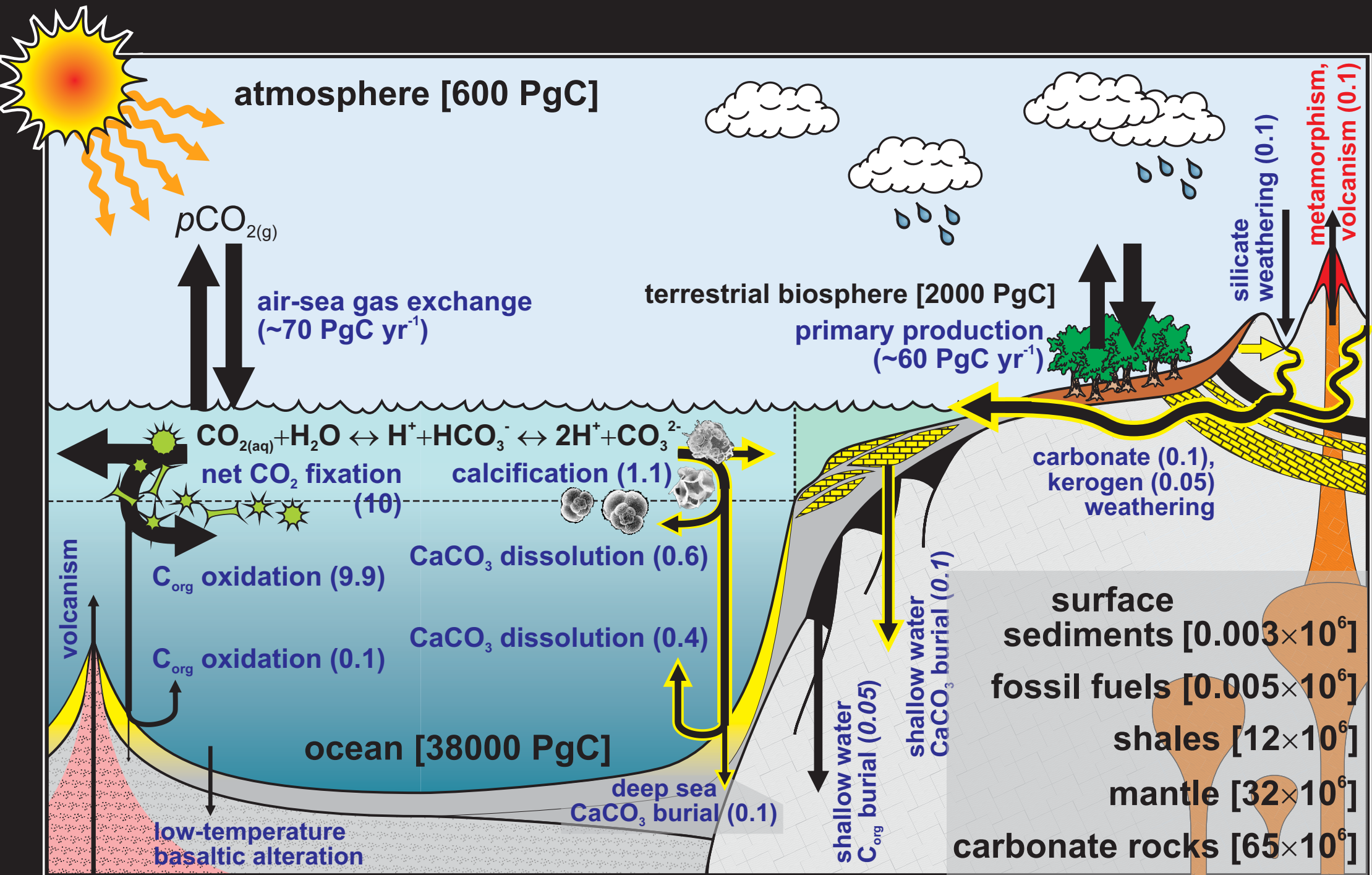
Regulation of global ~~climate~~ carbon cycling



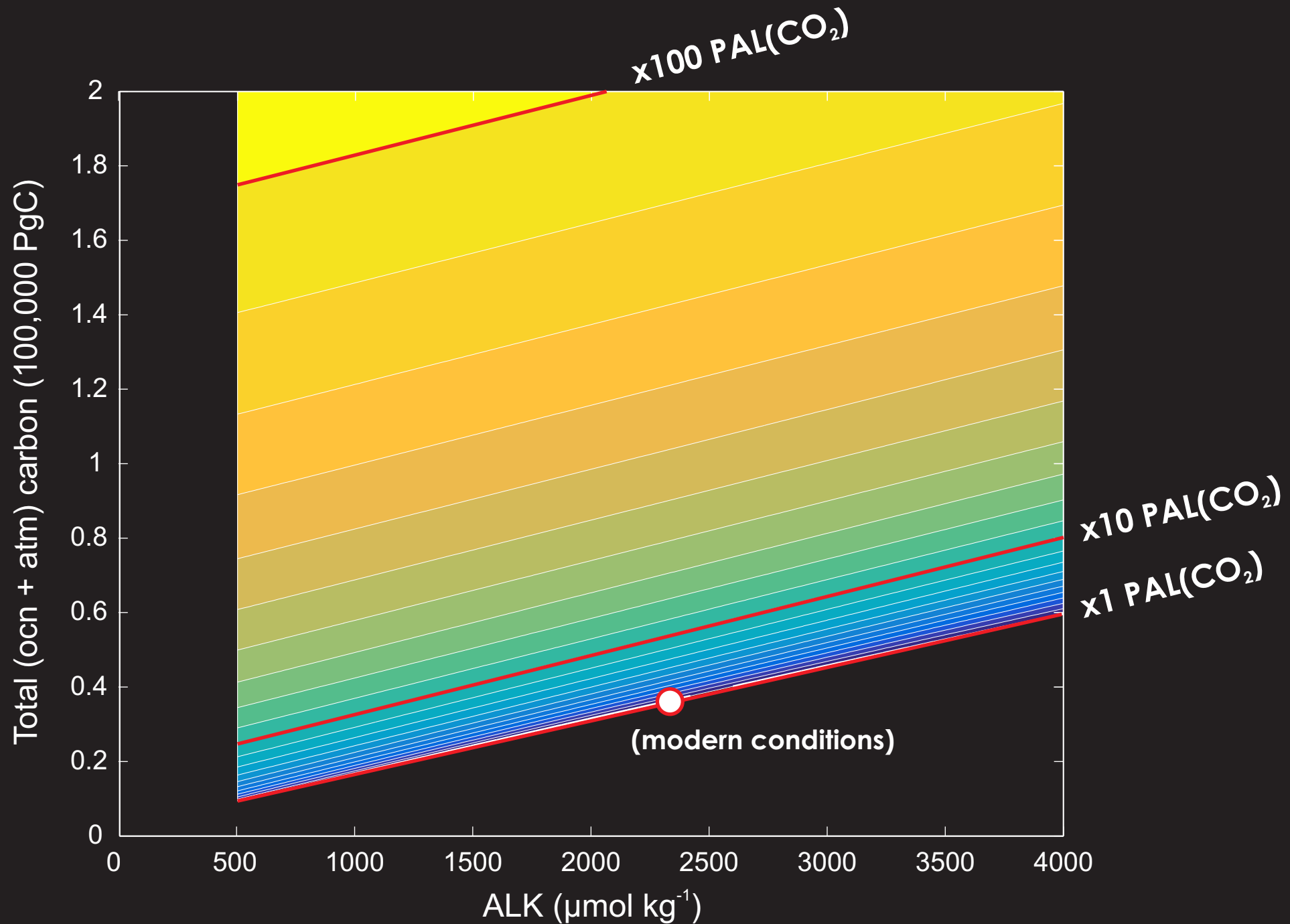
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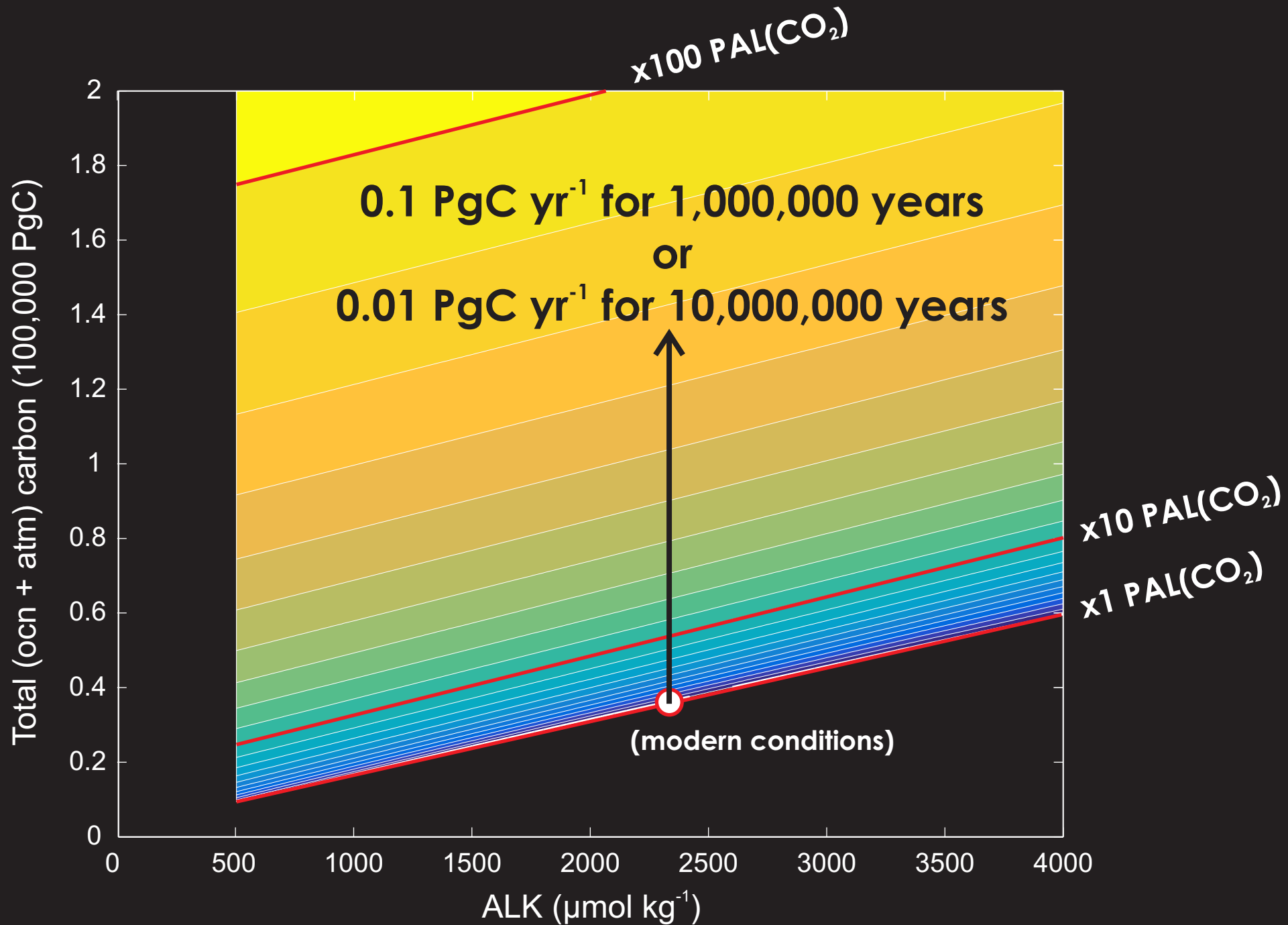
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Terrestrial weathering can be (approximately equally) divided into carbonate (CaCO_3) and calcium-silicate (' CaSiO_3 ') weathering:



Ultimately, the (alkalinity: Ca^{2+}) weathering products must be removed through carbonate precipitation and burial in marine sediments:



It can be seen that in (2) + (3), that the CO_2 removed (from the atmosphere) during weathering, is returned upon carbonate precipitation (and burial). In (1) + (3) (silicate weathering) CO_2 is permanently removed to the geological reservoir. This CO_2 must be balanced by mantle (/volcanic) out-gassing on the very long term.

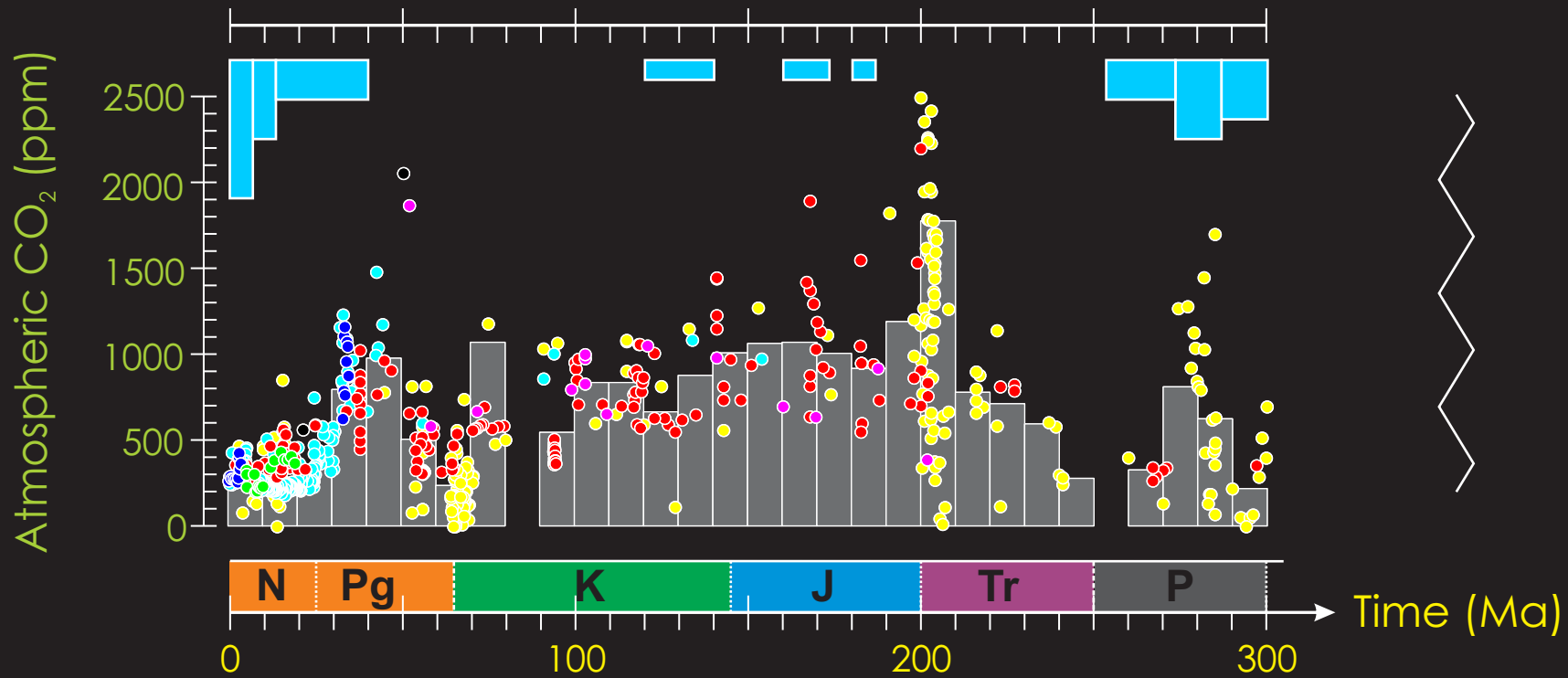
Regulation of global ~~climate~~ carbon cycling



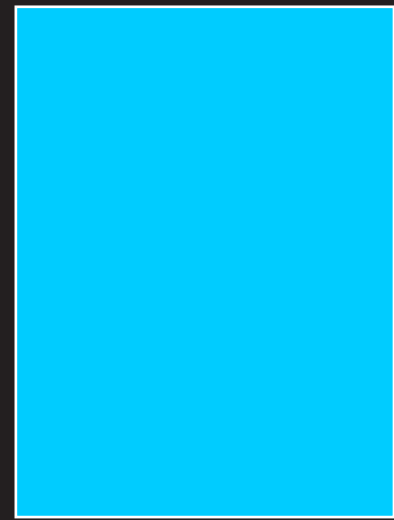
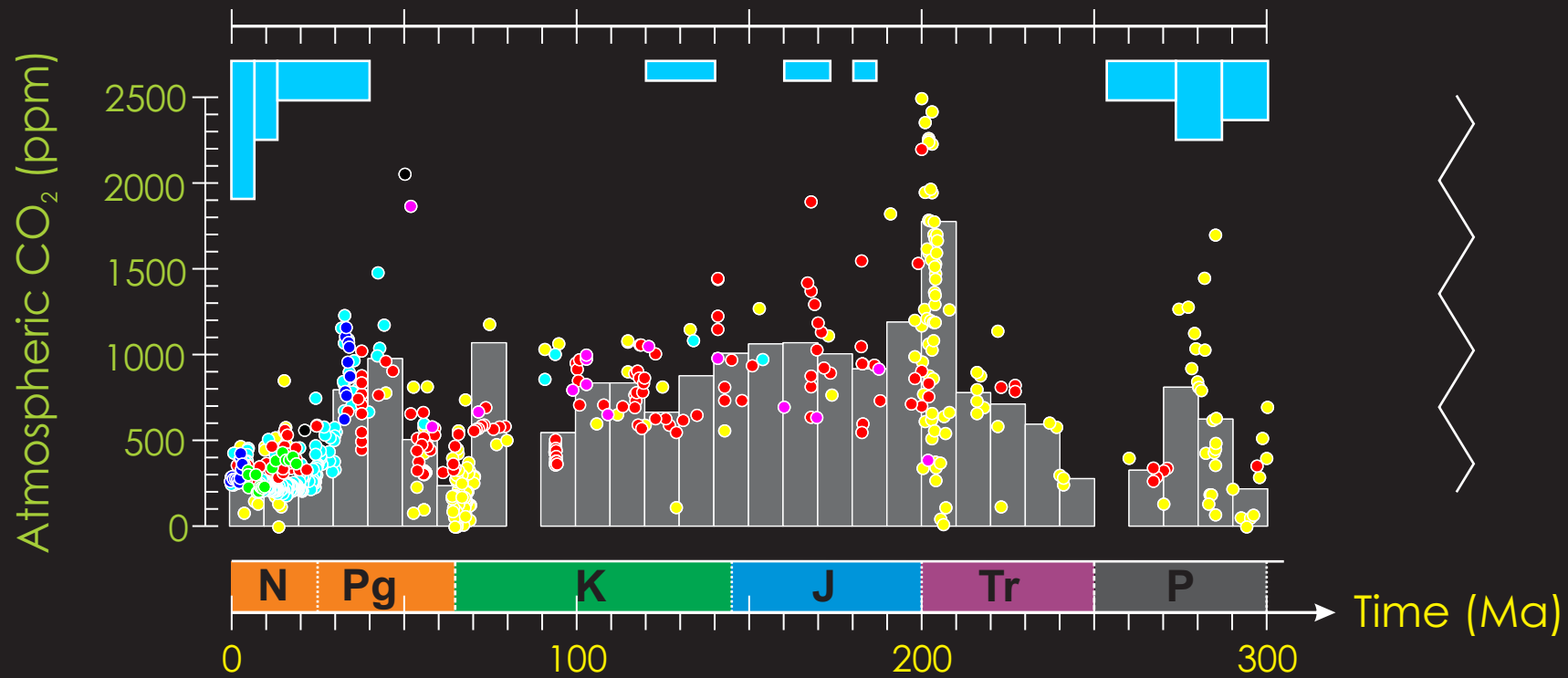
Furthermore, the rate of silicate weathering should scale with climate. Hence the **silicate weathering feedback** is formed:

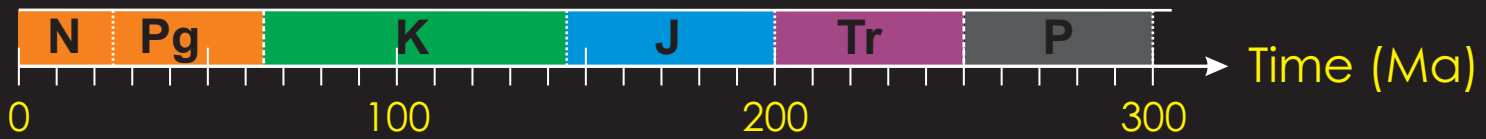
higher $p\text{CO}_2$ \rightarrow higher temperatures (& rainfall) \rightarrow higher weathering rates \rightarrow lower $p\text{CO}_2$

Regulation of global ~~climate~~ carbon cycling



Regulation of global ~~climate~~ carbon cycling





lies, damn lies, and computer models



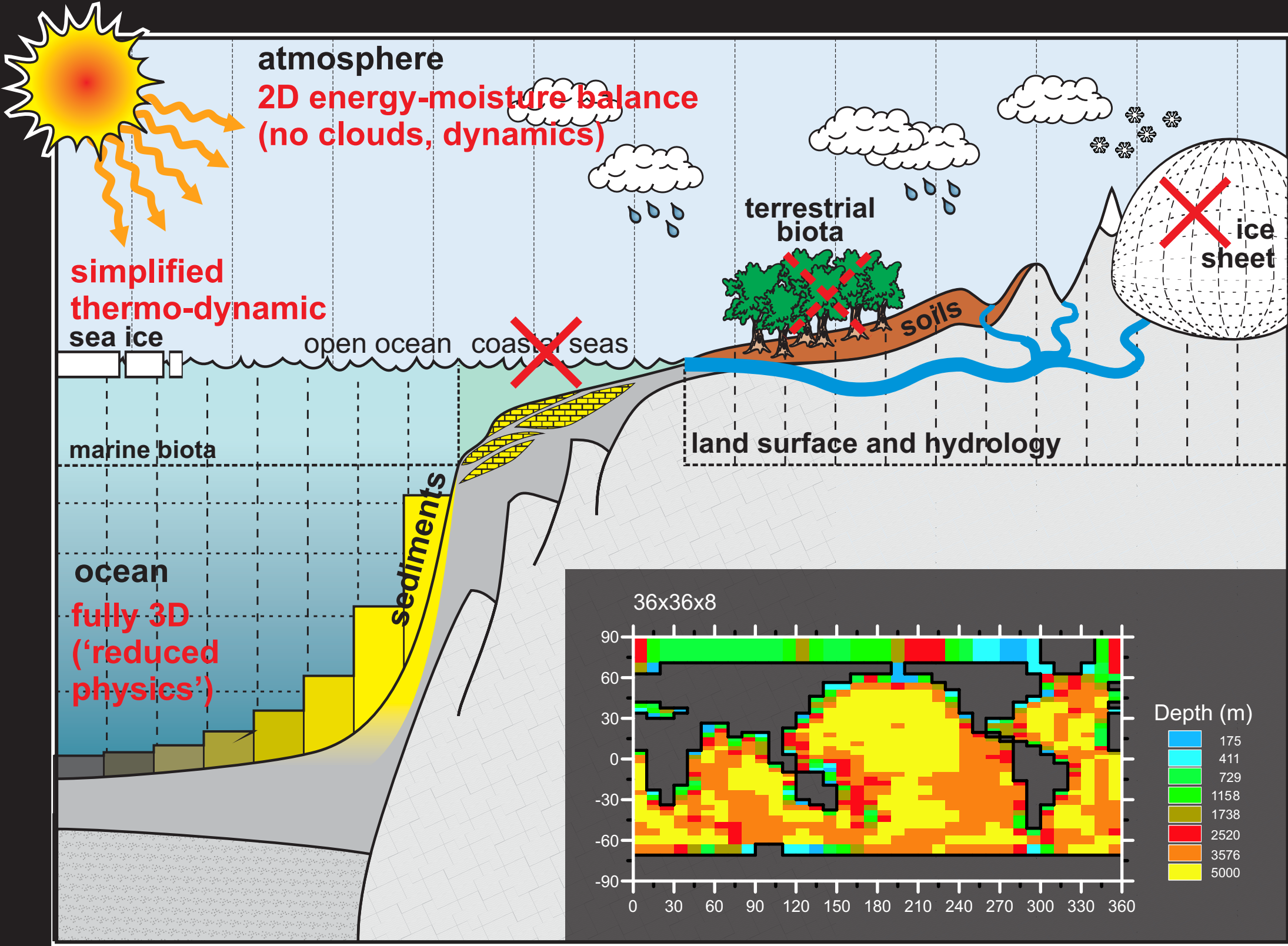
```
! calculate carbonate alkalinity
loc_ALK_DIC = dum_ALK &
& - loc_H4BO4 - loc_OH - loc_HPO4 - 2.0*loc_PO4 - loc_H3SiO4 - loc_NH3 - loc_HS &
& + loc_H + loc_HSO4 + loc_HF + loc_H3PO4

! estimate the partitioning between the aqueous carbonate species
loc_zed = ( &
& (4.0*loc_ALK_DIC + dum_DIC*dum_carbconst(icc_k) -
loc_ALK_DIC*dum_carbconst(icc_k))**2 + &
& 4.0*(dum_carbconst(icc_k) - 4.0)*loc_ALK_DIC**2 &
& )**0.5      loc_conc_HCO3 = (dum_DIC*dum_carbconst(icc_k) -
loc_zed)/(dum_carbconst(icc_k) - 4.0)

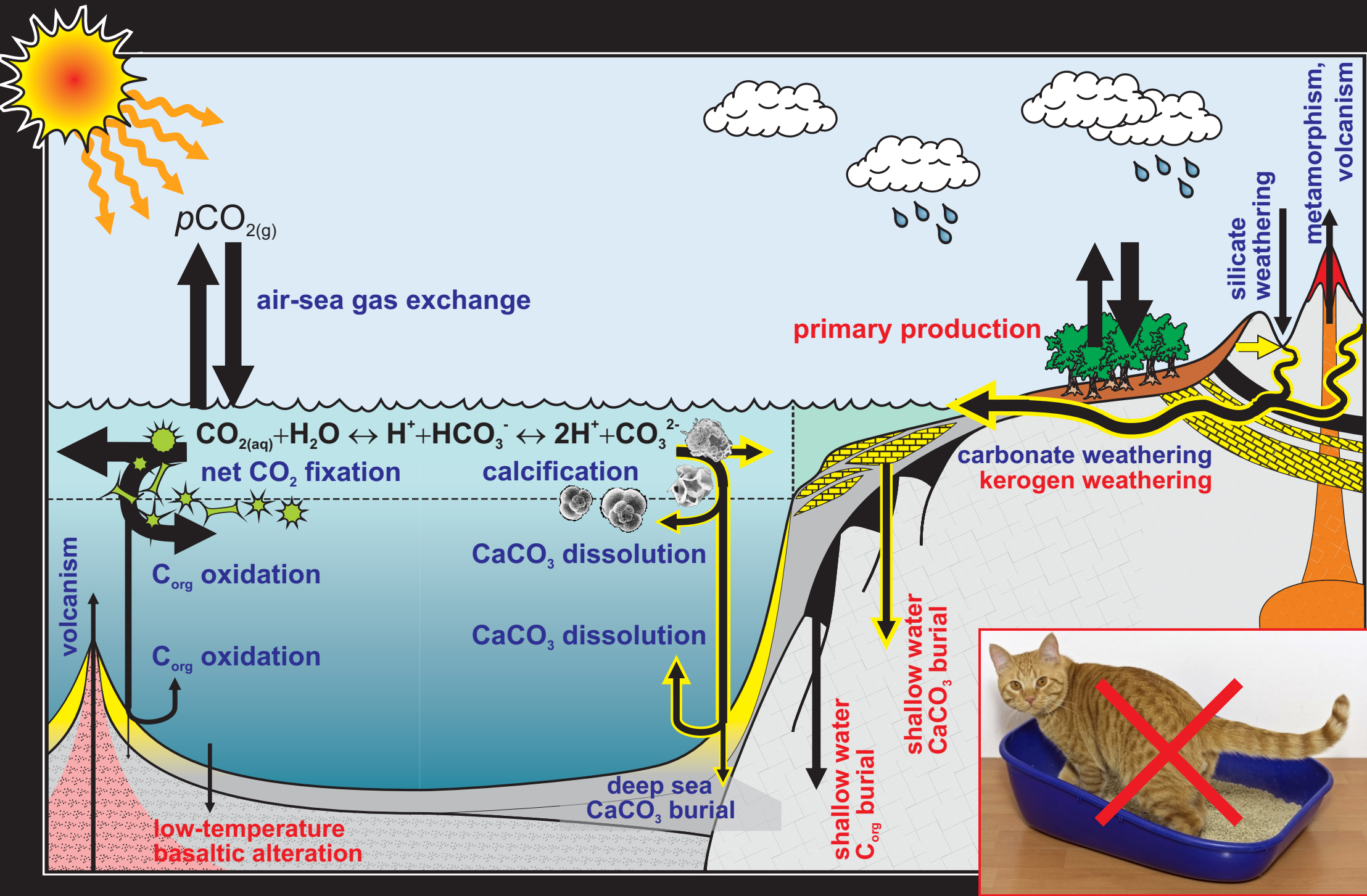
loc_conc_CO3 = &
& ( &
& loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
& 4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_conc_CO2 = dum_DIC - loc_ALK_DIC + &
& ( &
& loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
& 4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_H1 = dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_HCO3
loc_H2 = dum_carbconst(icc_k2)*loc_conc_HCO3/loc_conc_CO3
```



lies, damn lies, and computer models

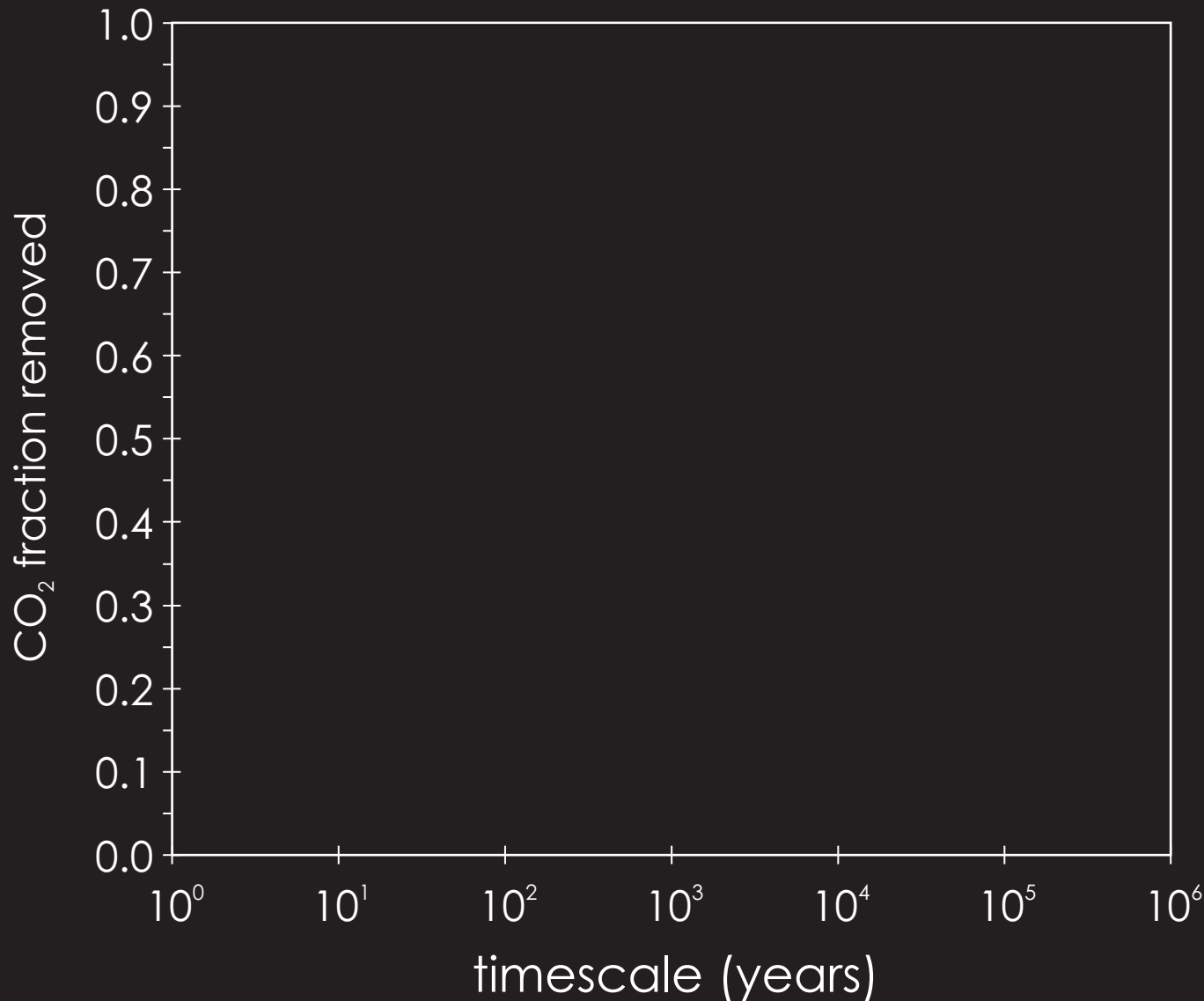


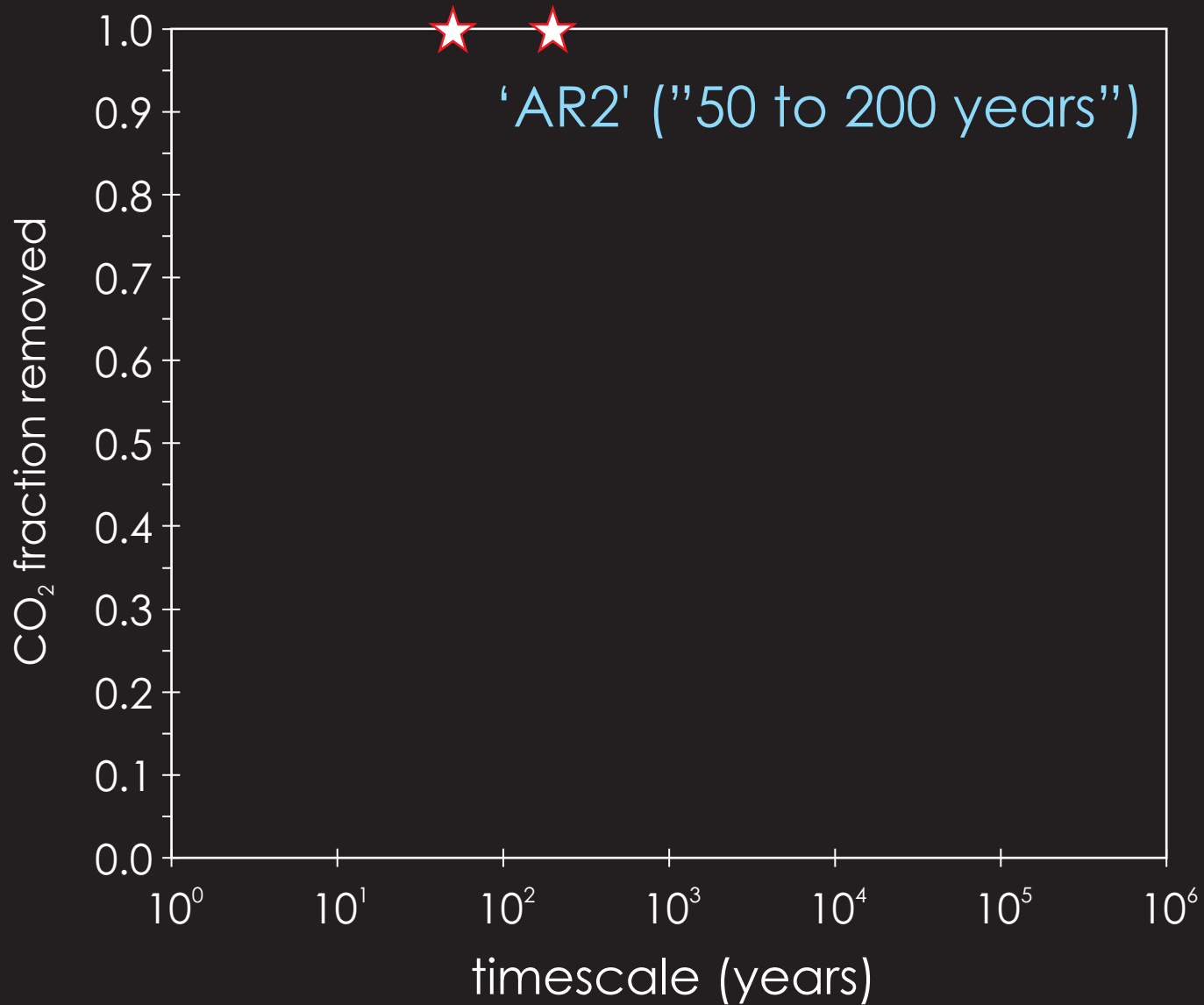
Regulation of global carbon cycling?



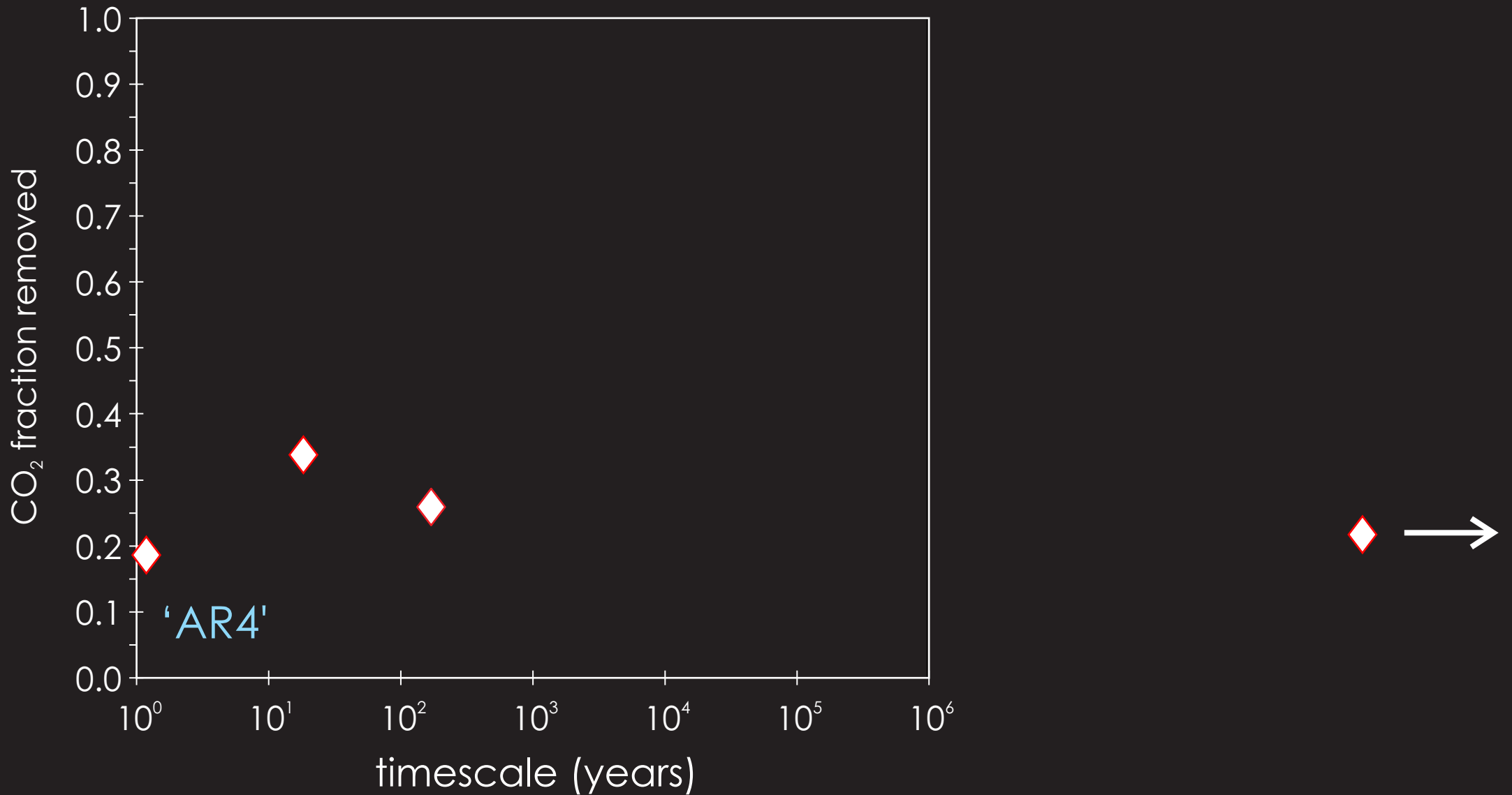


Cross-plot of the fraction of total CO_2 emissions to the atmosphere removed by a particular process (carbon sink), vs. the characteristic (e-folding) time-scale of that process (\log_{10} scale).





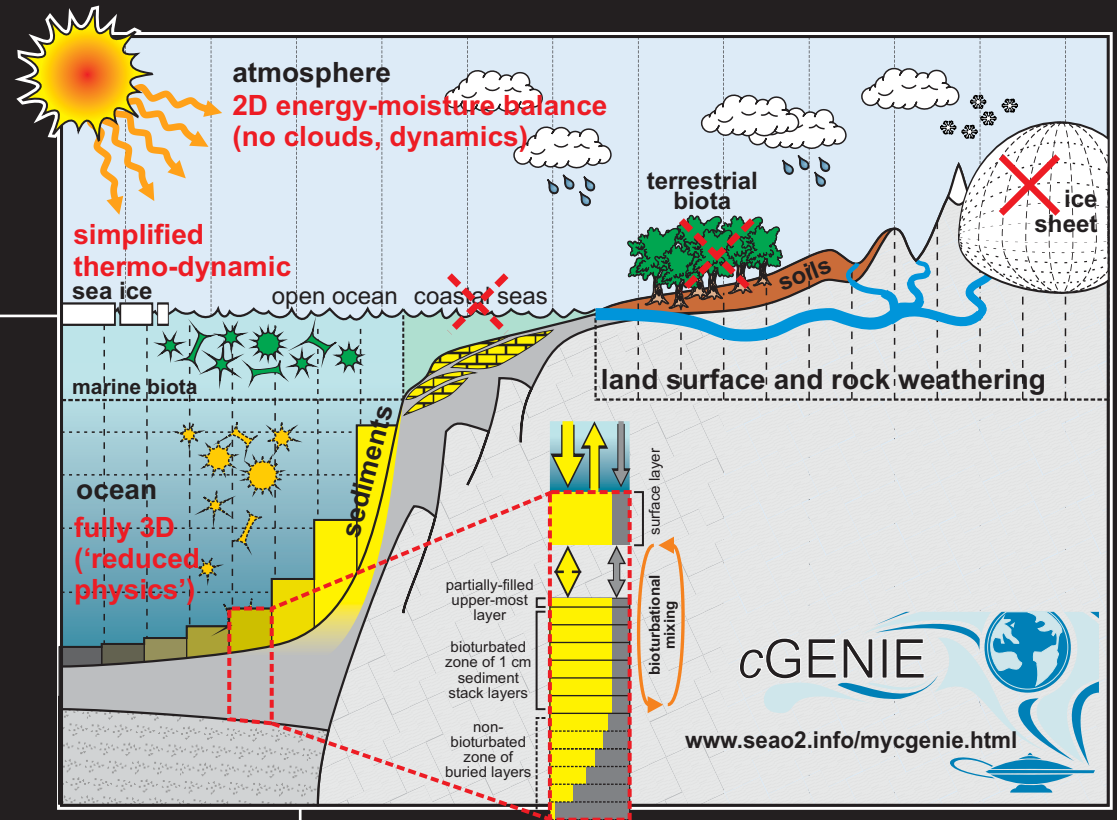
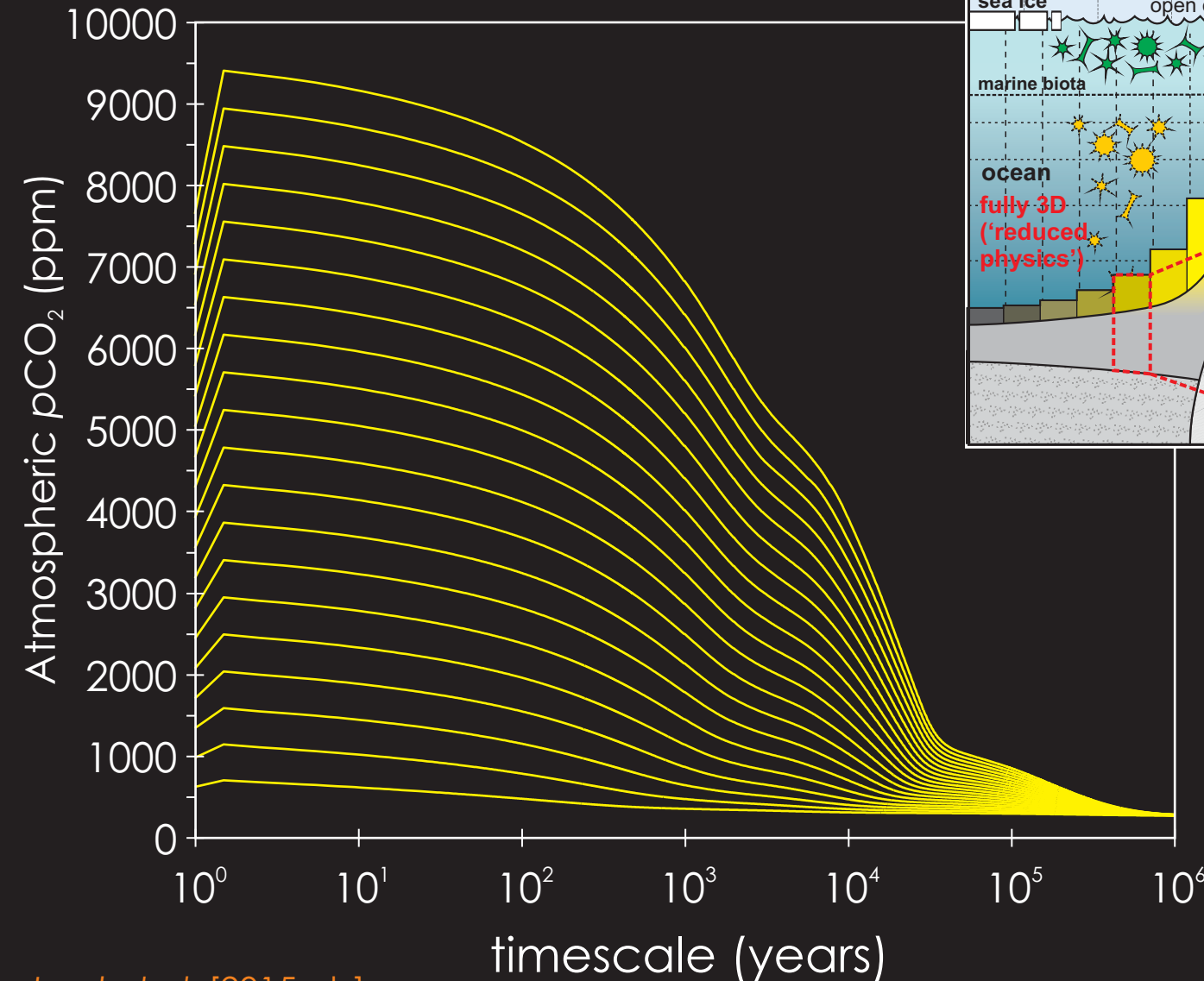
Impulse response function analysis of the 'long tail' of $\text{CO}_{2(\text{excess})}$



Impulse response function analysis of the 'long tail' of $\text{CO}_2(\text{excess})$



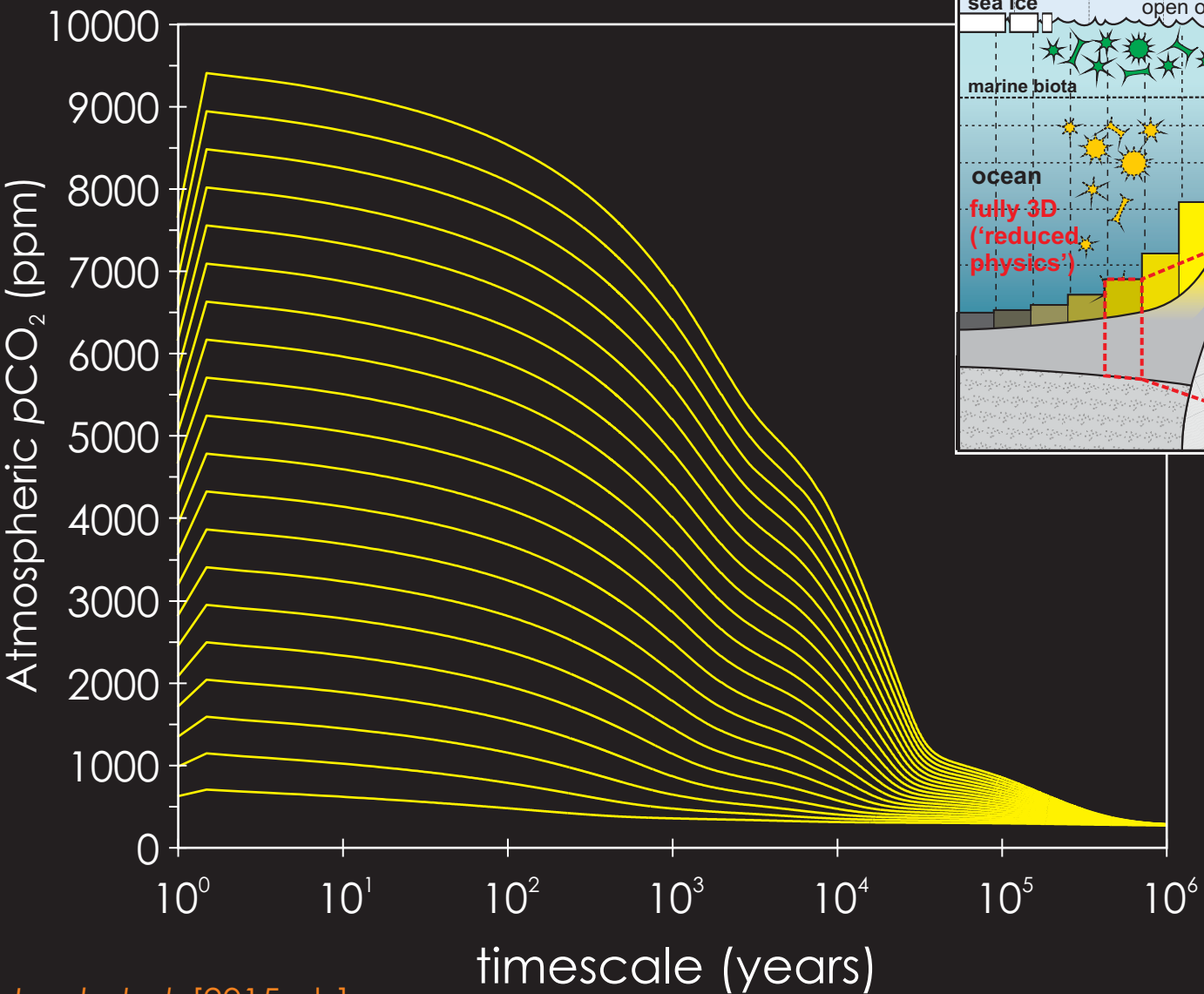
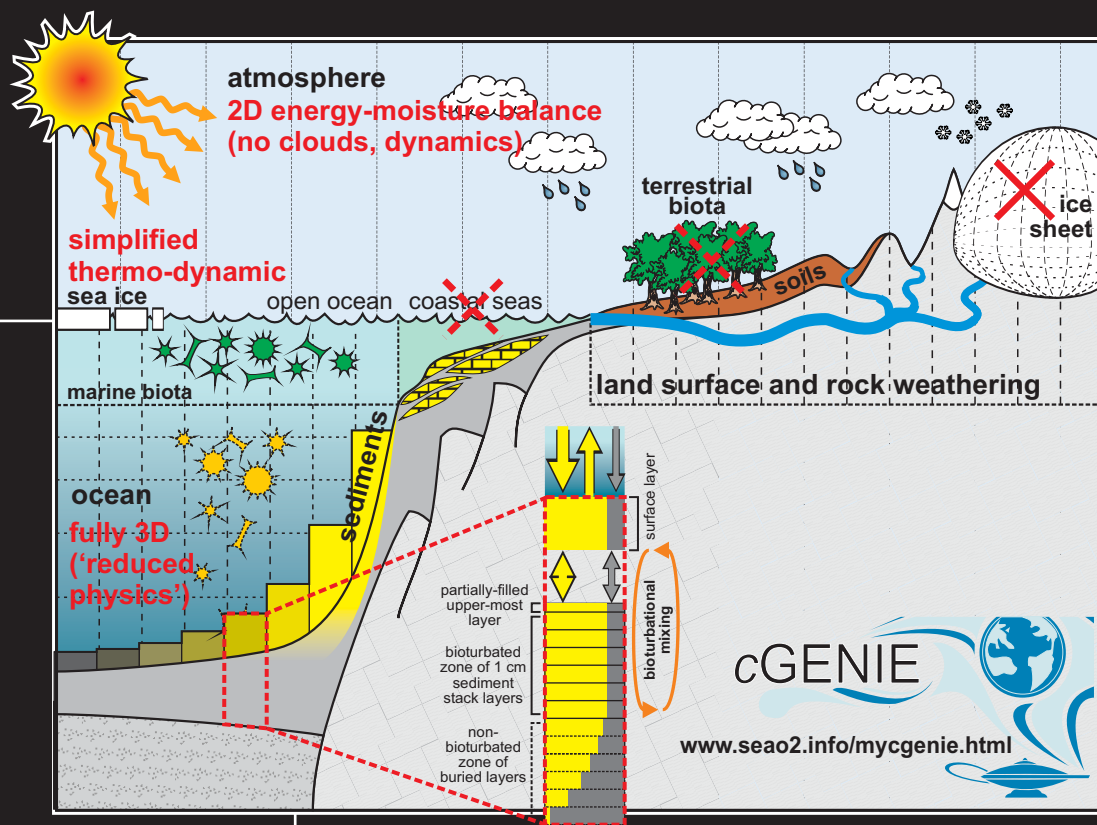
(1) Series of 1 Myr Earth system model experiments. CO_2 emissions from 1,000 to 20,000 PgC (GtC). Release interval: 1 yr.



Impulse response function analysis of the 'long tail' of CO_{2(excess)}



(1) Series of 1 Myr Earth system model experiments. CO₂ emissions from 1,000 to 20,000 PgC (GtC). Release interval: 1 yr.

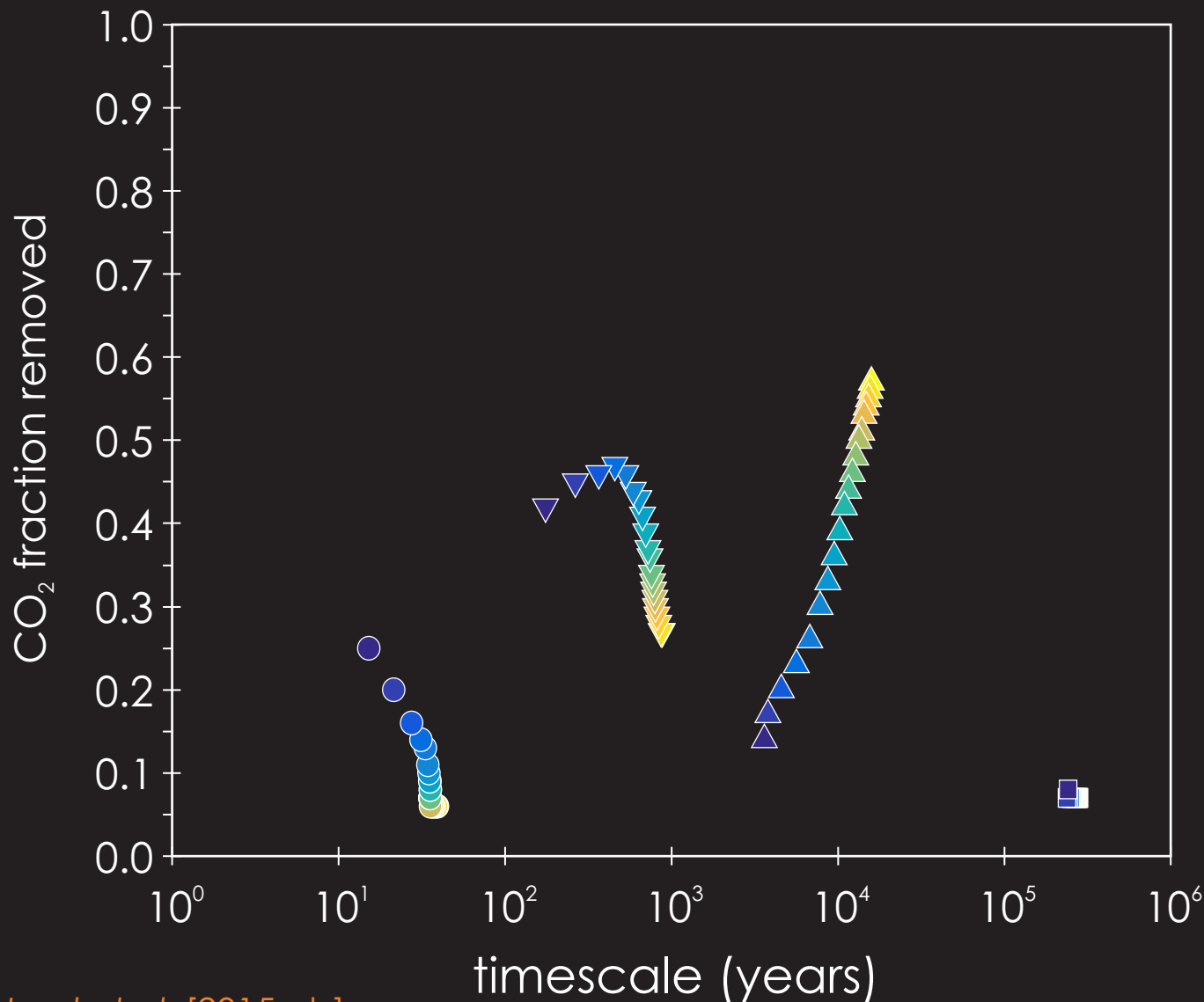


(2) Fit each CO₂ decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO₂ and time-scale associated with each.

(The resulting empirical model can be used in place of a mechanistic model for projecting the long-term fate of carbon release.)

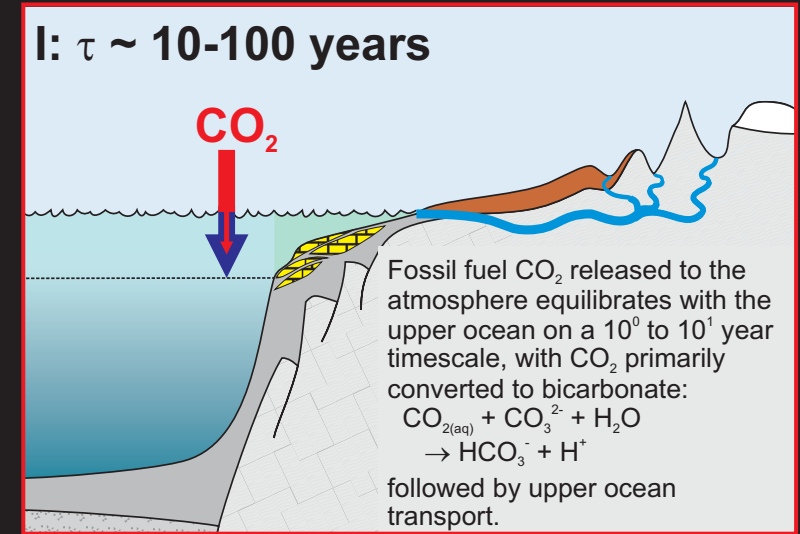
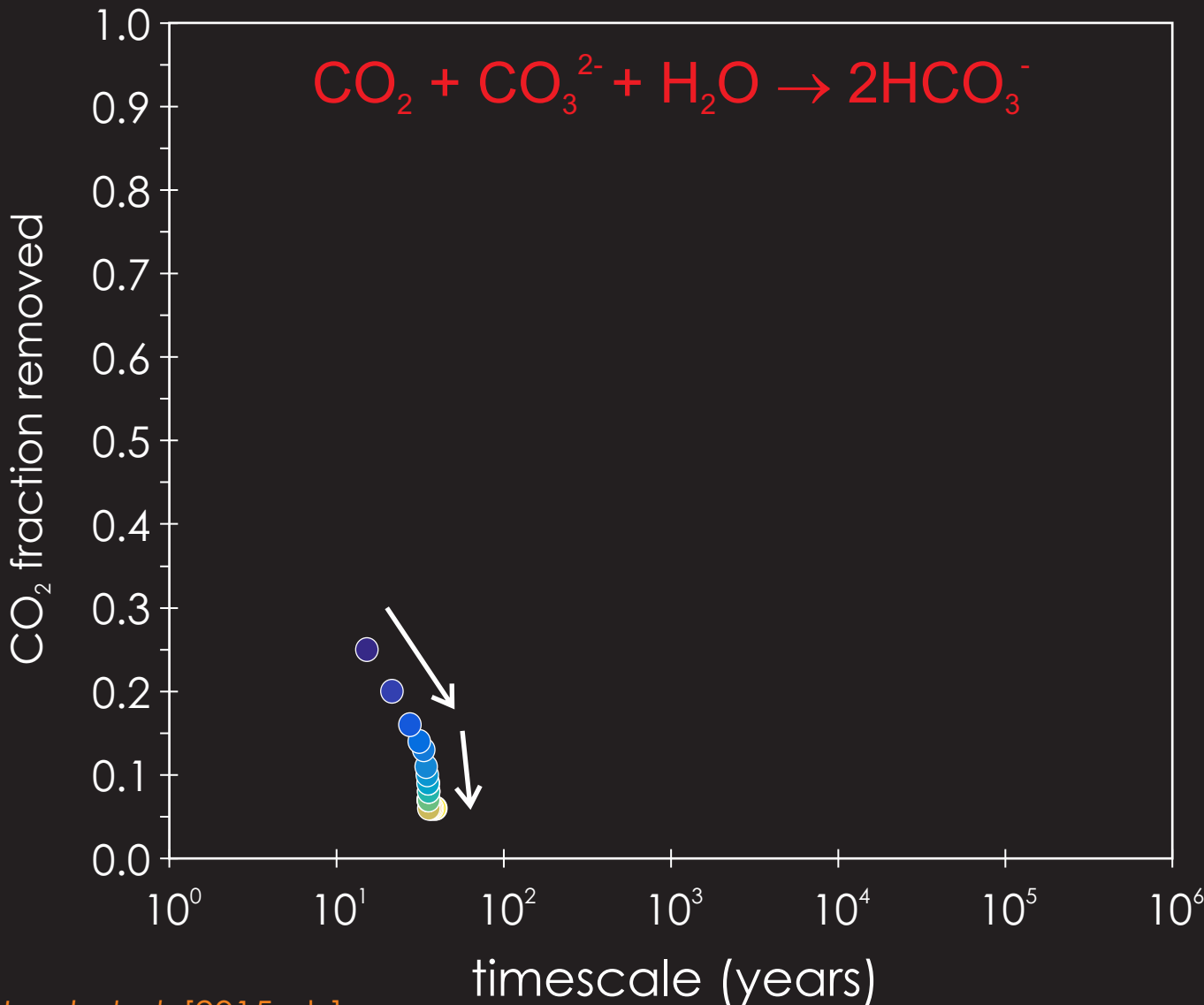


Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).



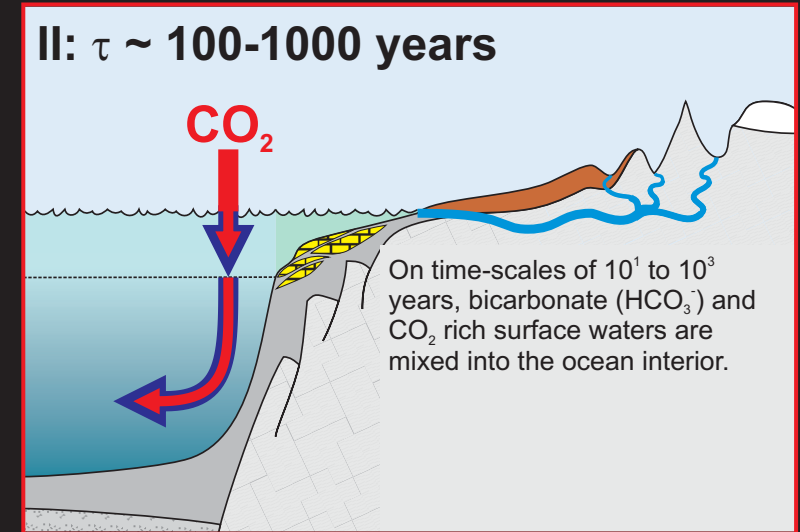
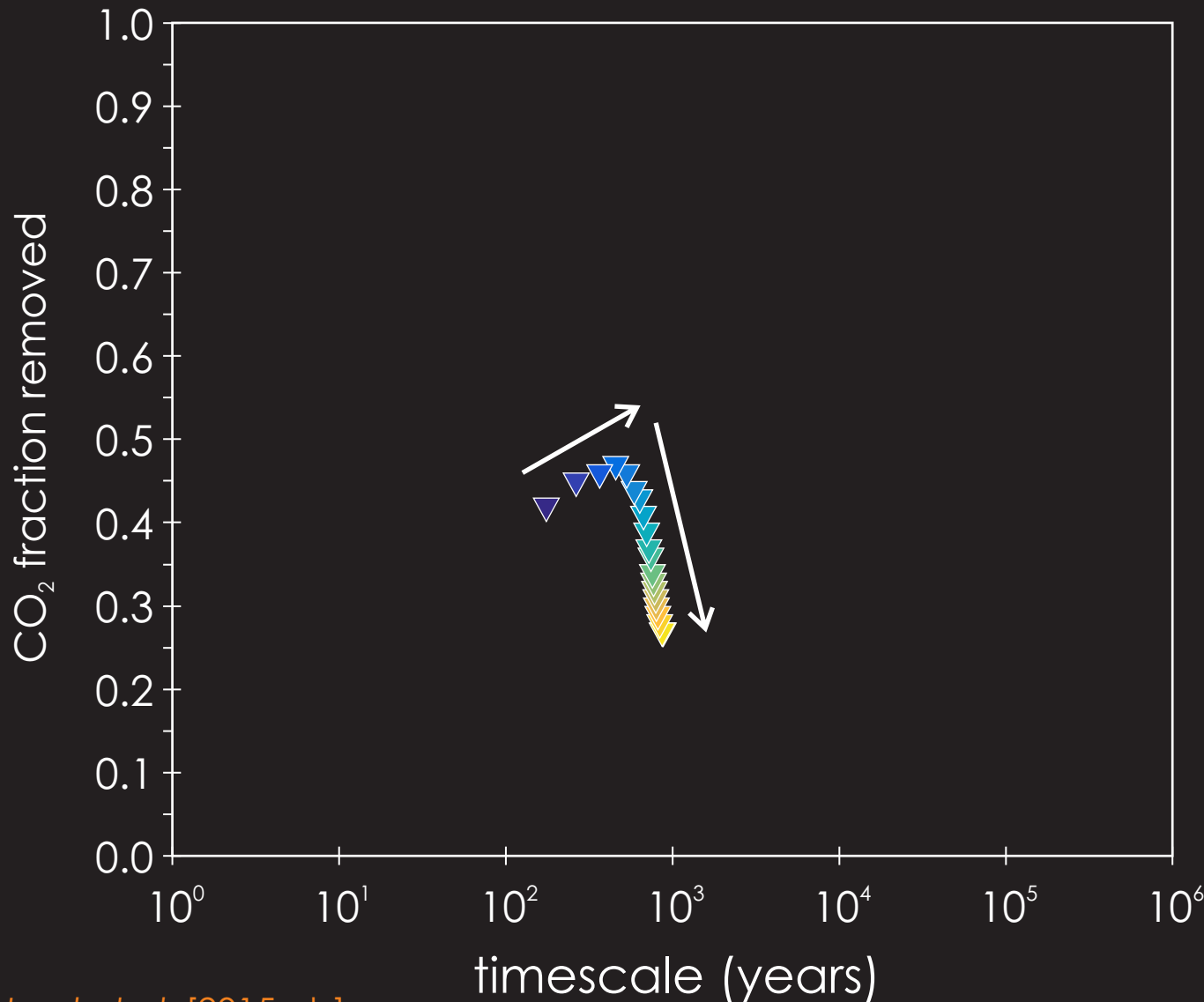


Depletion of mixed layer carbonate buffer;
ocean stratification and reduced surface
mixing. Warming and reduced CO_2 solubility.



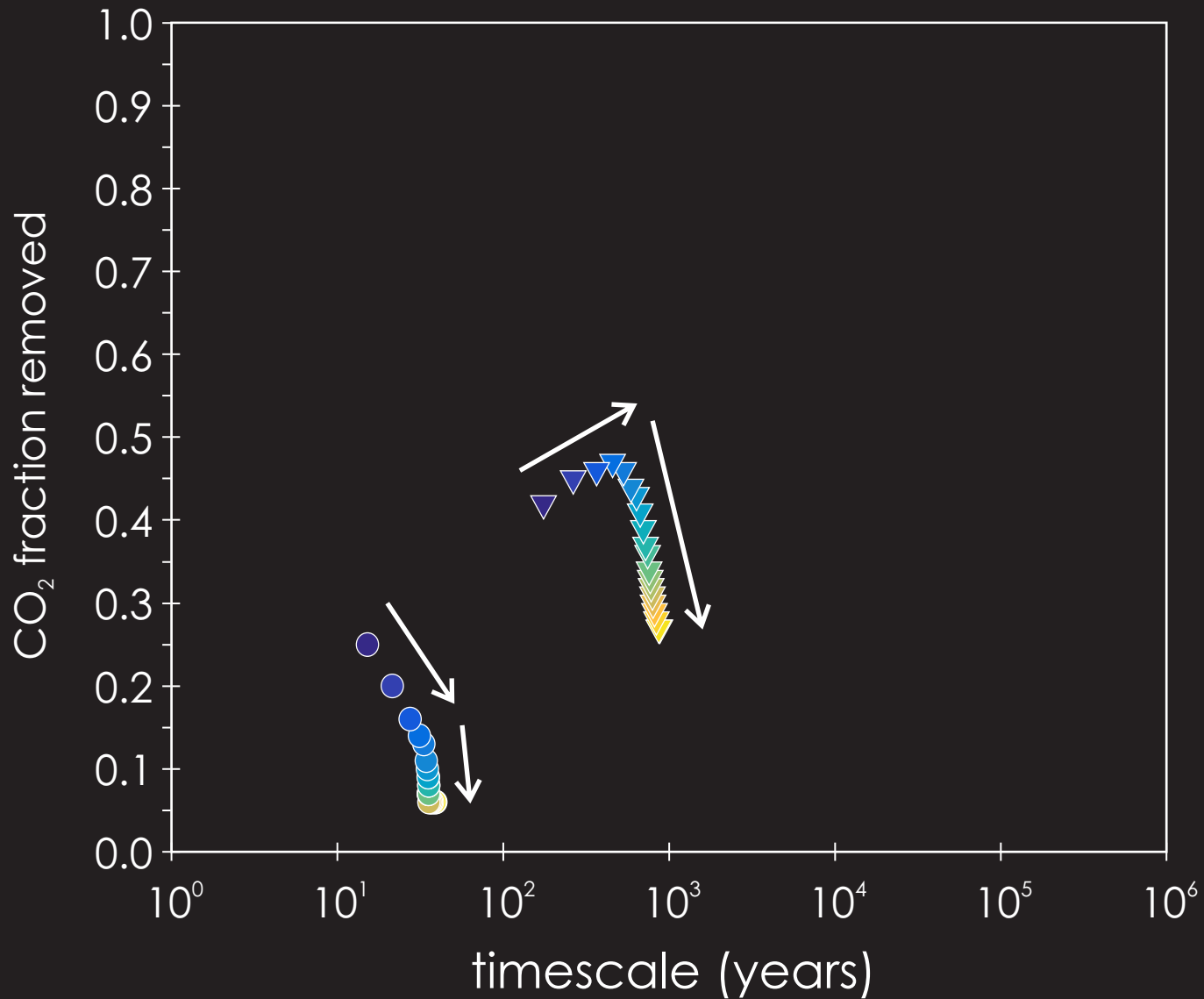


Ocean stratification and collapse of the AMOC
(in this particular model).
Threshold reached @ $\sim 4000 \text{ PgC}$?

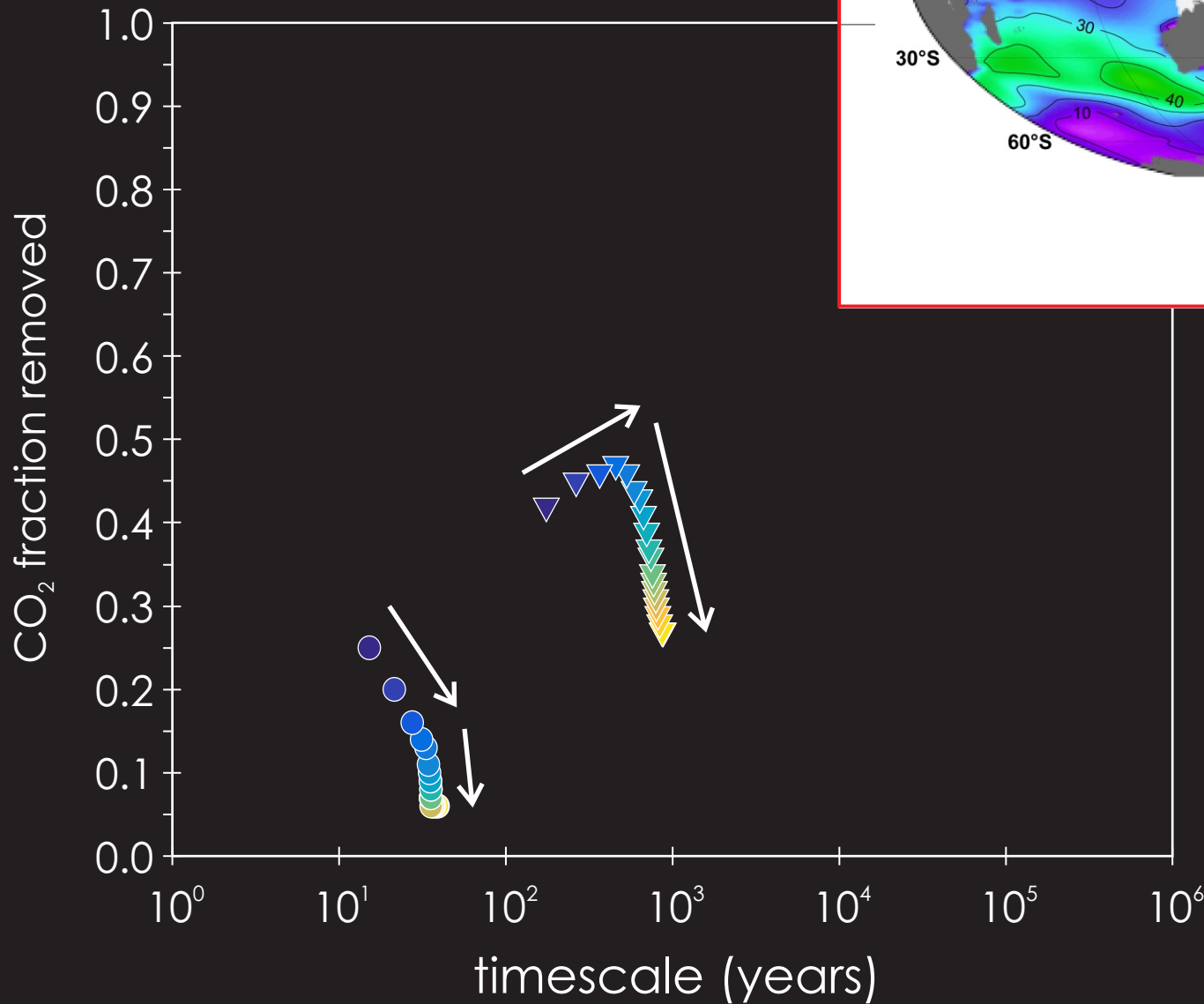
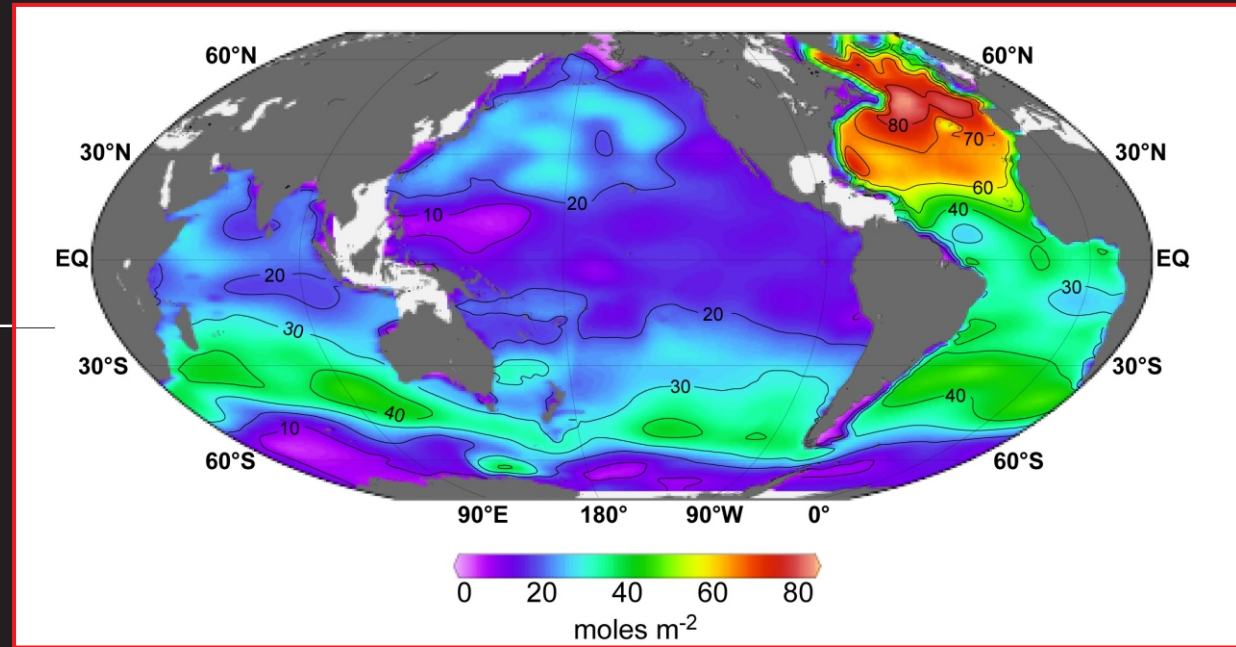




evidence?

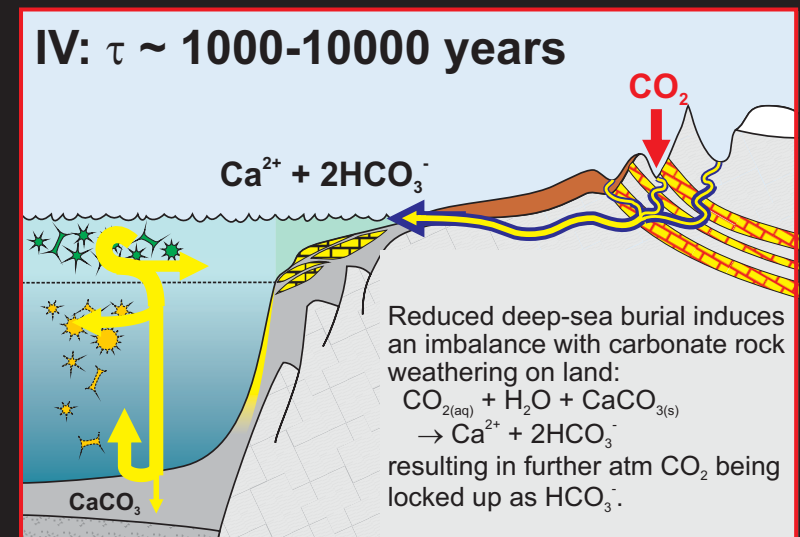
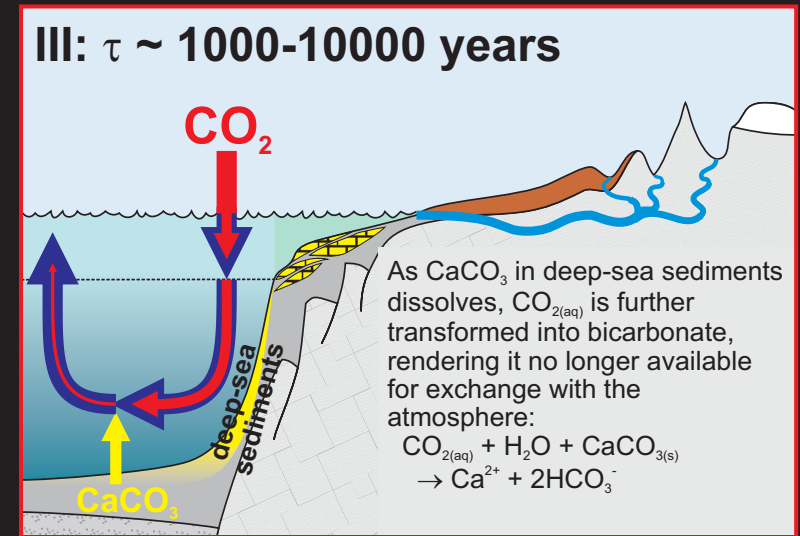
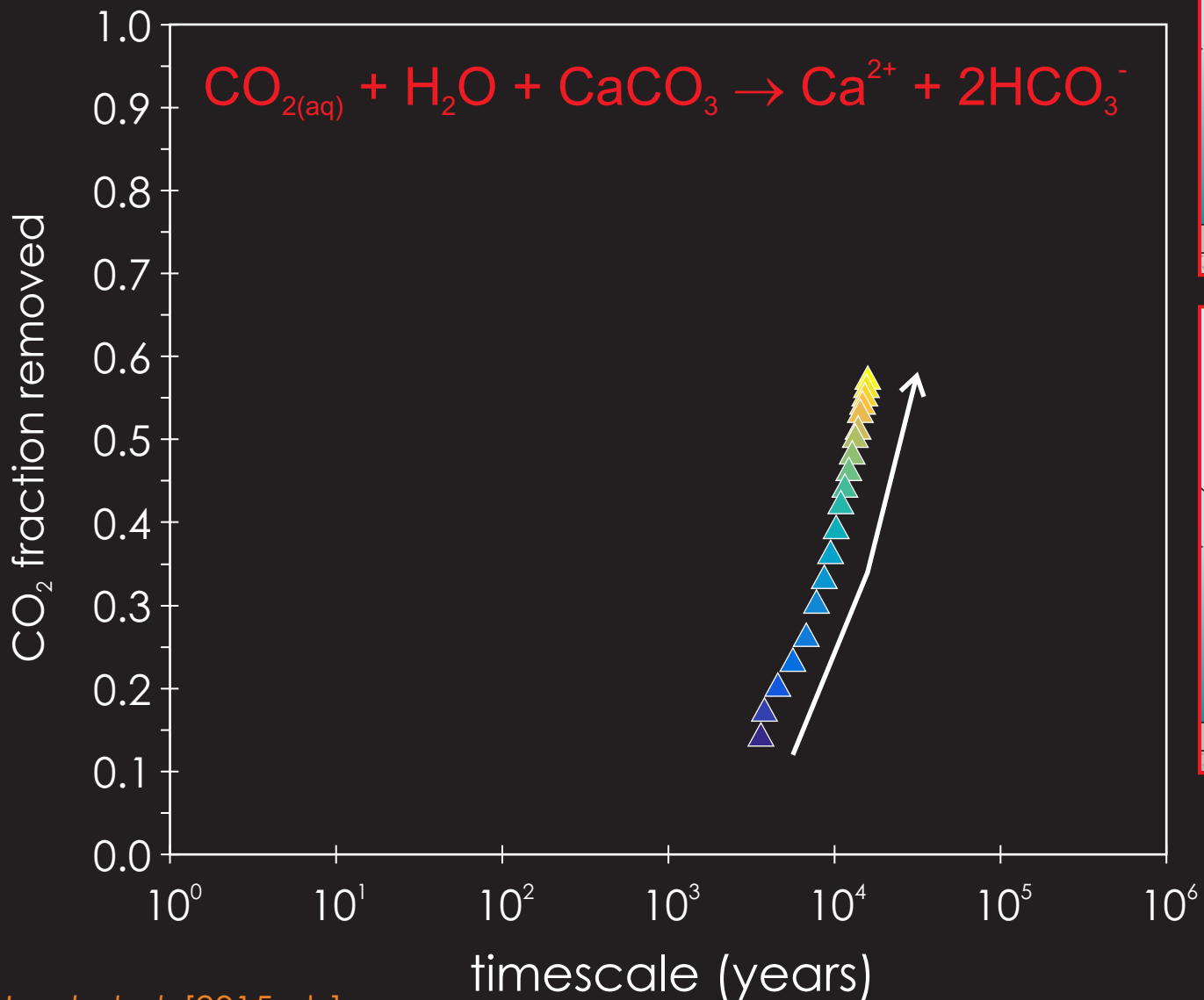


Impulse response function analysis of the 'long tail' of $\text{CO}_2(\text{excess})$



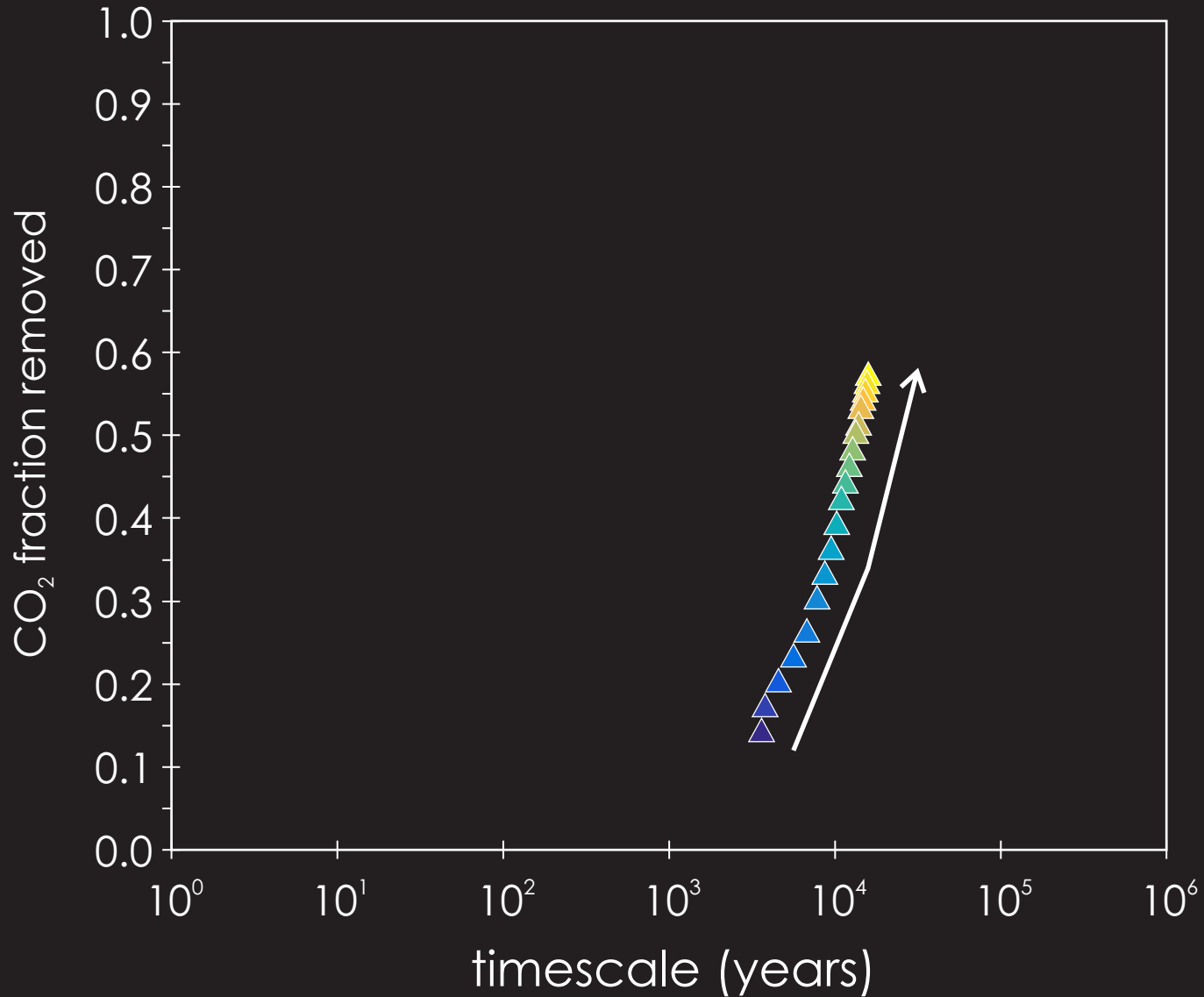


Geologic CO_2 removal via carbonate rocks and marine sediments – occurring on an increasing protracted time-scale.





evidence?

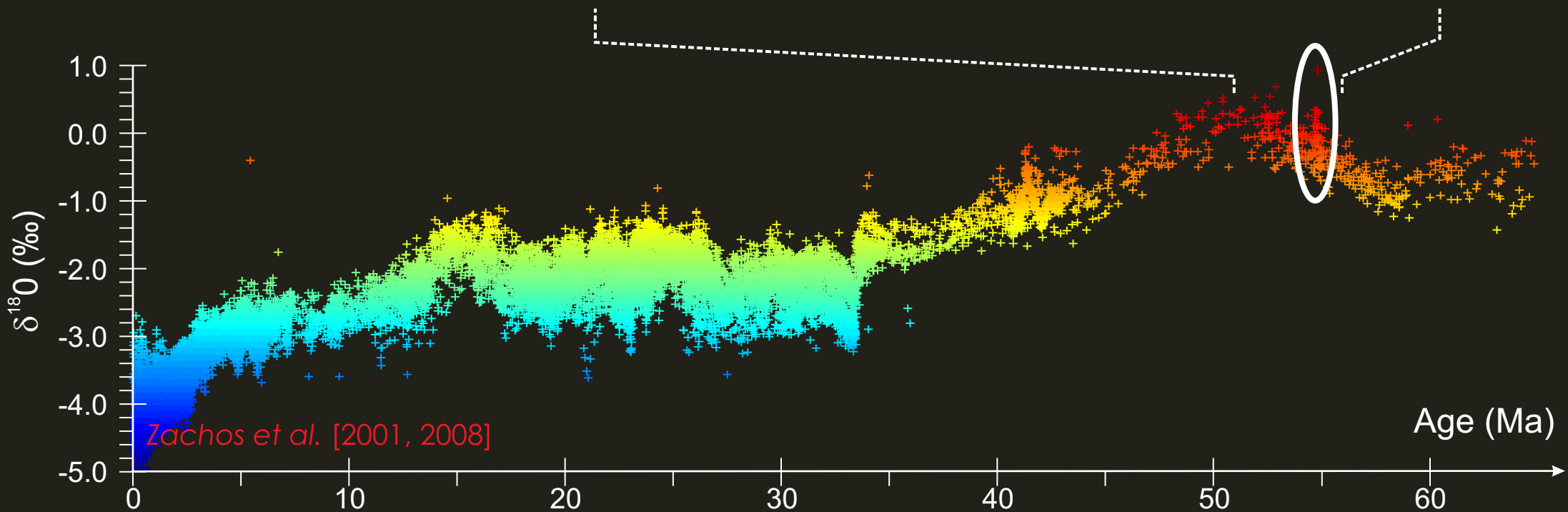
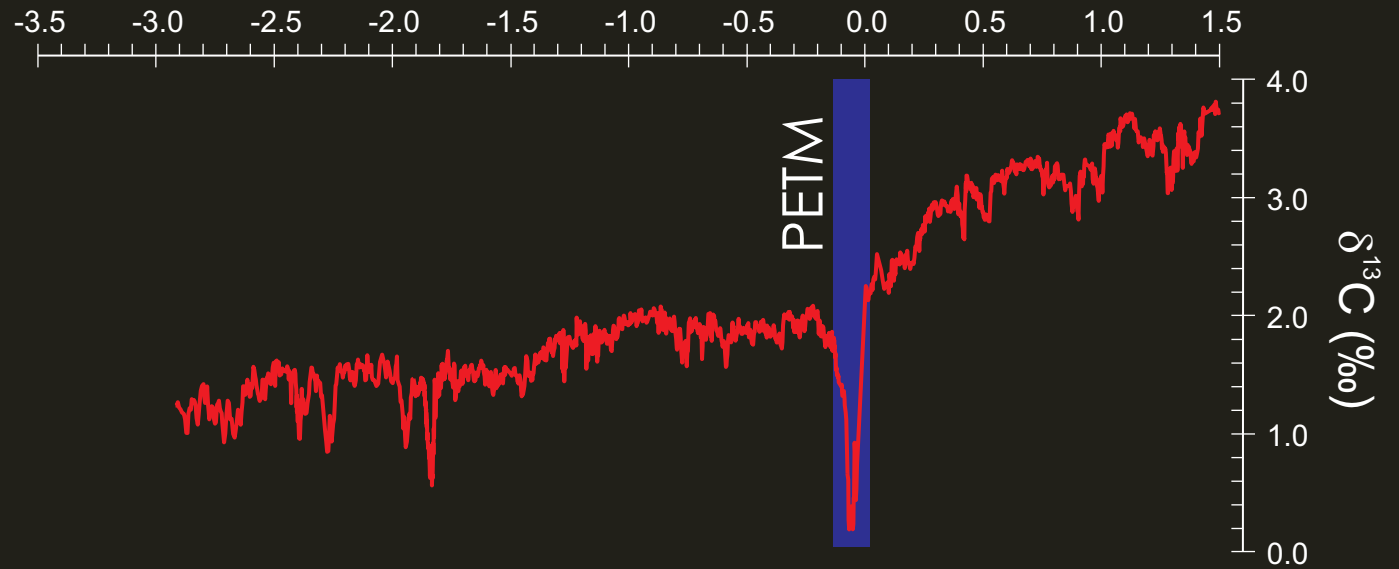


Impulse response function analysis of the 'long tail' of $\text{CO}_{2(\text{excess})}$



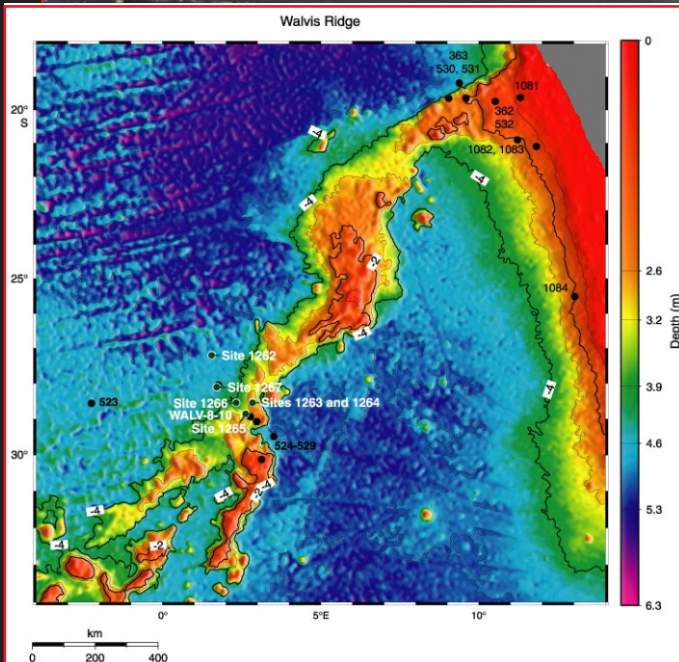
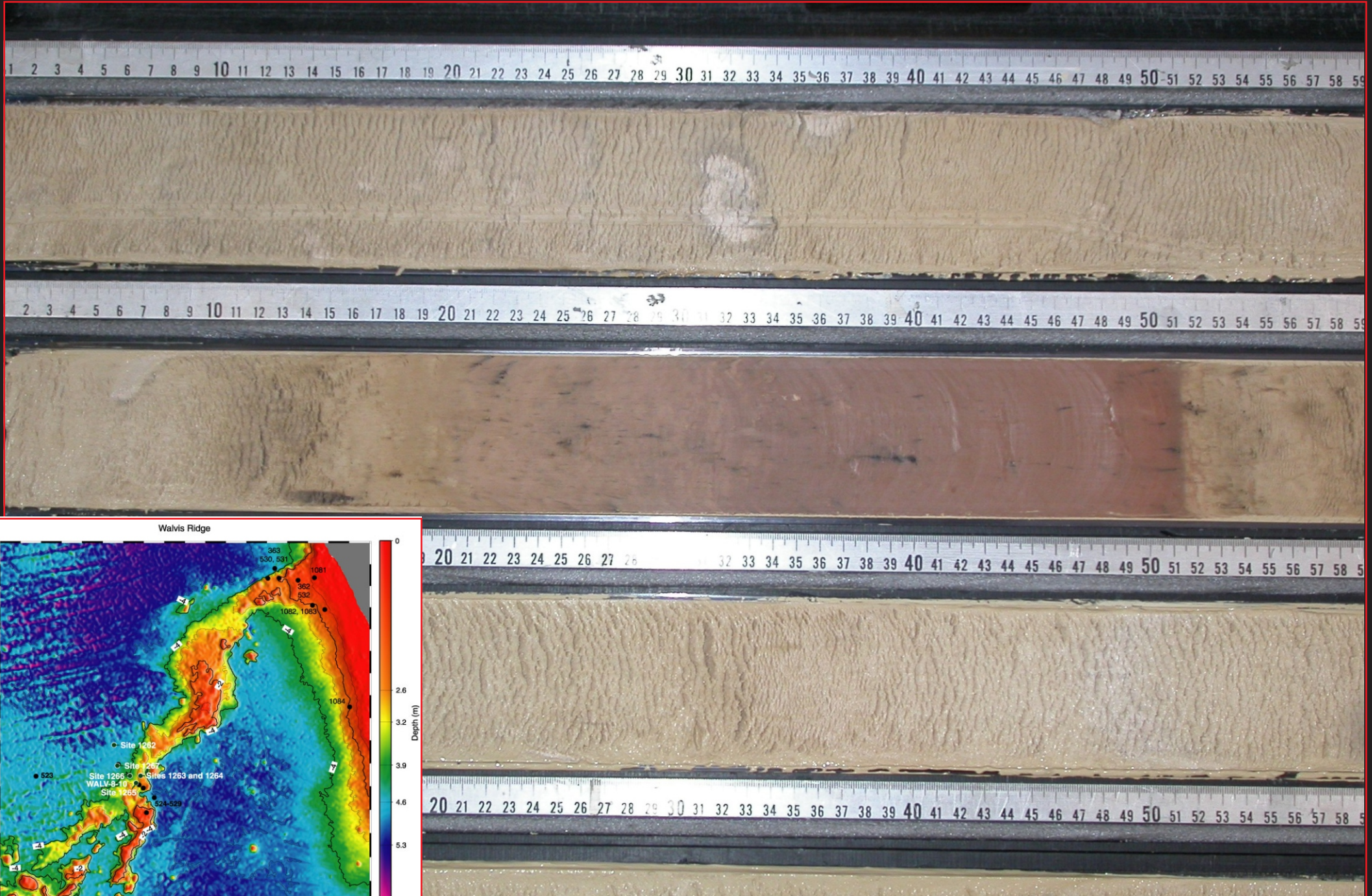
Zachos et al. [2010]
Lunt et al. [2011]

Age relative to the PETM (Ma)



Zachos et al. [2001, 2008]

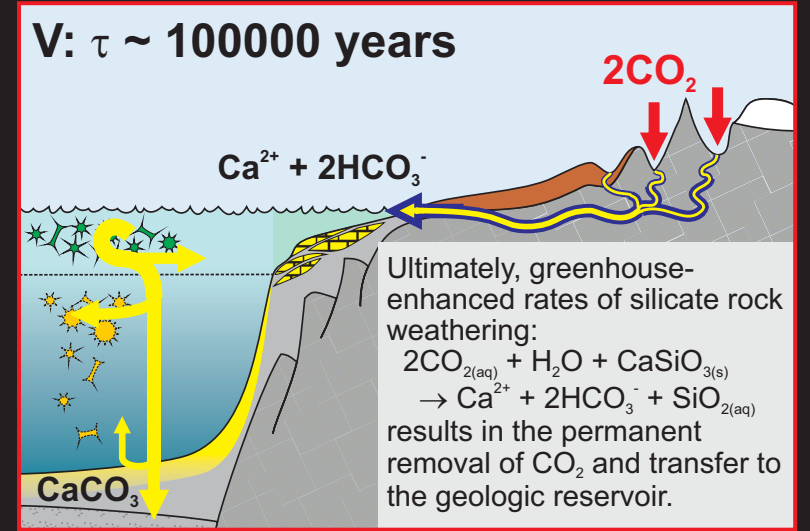
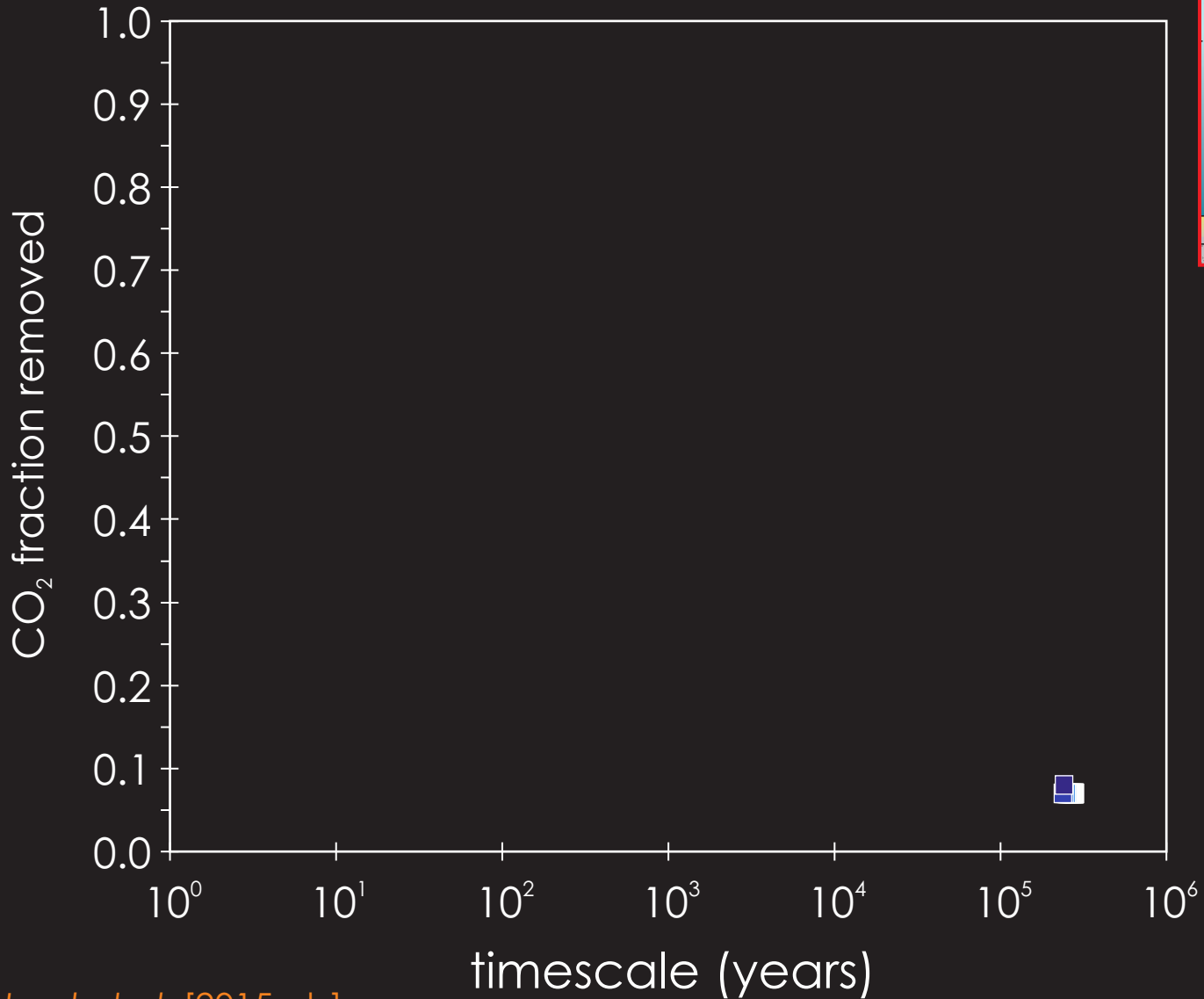
Impulse response function analysis of the 'long tail' of $\text{CO}_2(\text{excess})$



Sediments spanning the Palaeocene-Eocene boundary from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Dani Schmidt (University of Bristol)

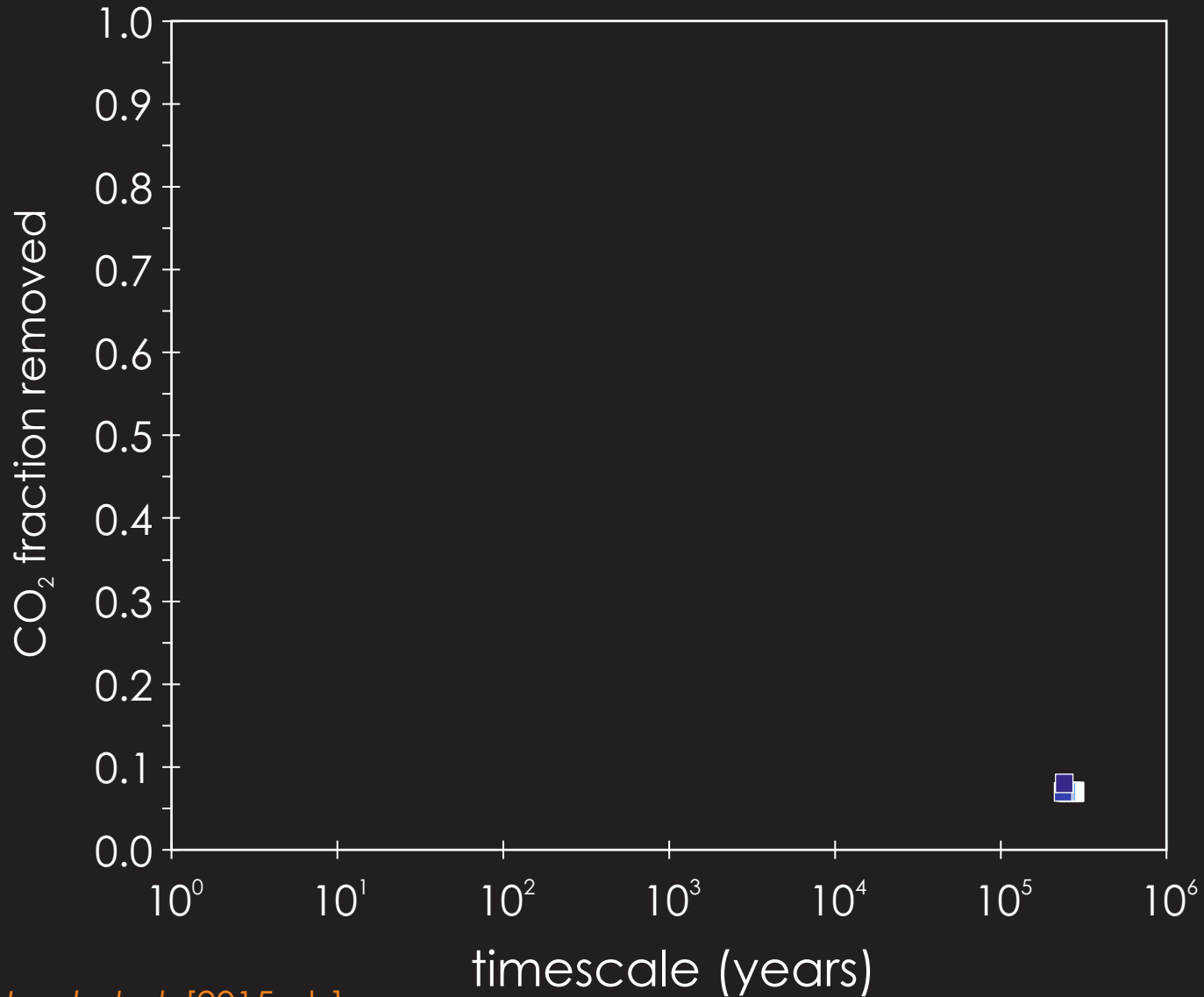


Silicate weathering (no time-scale response!).

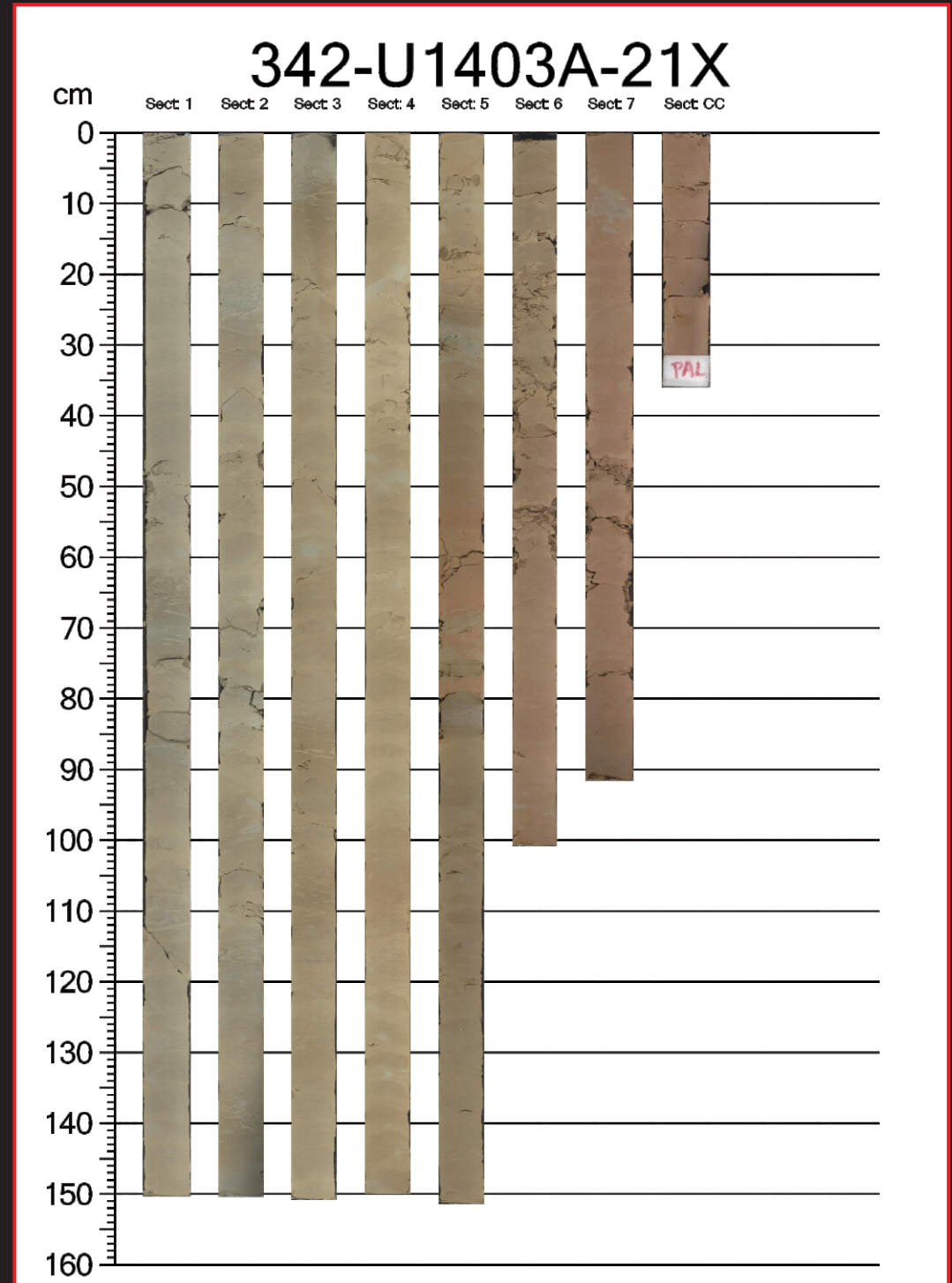
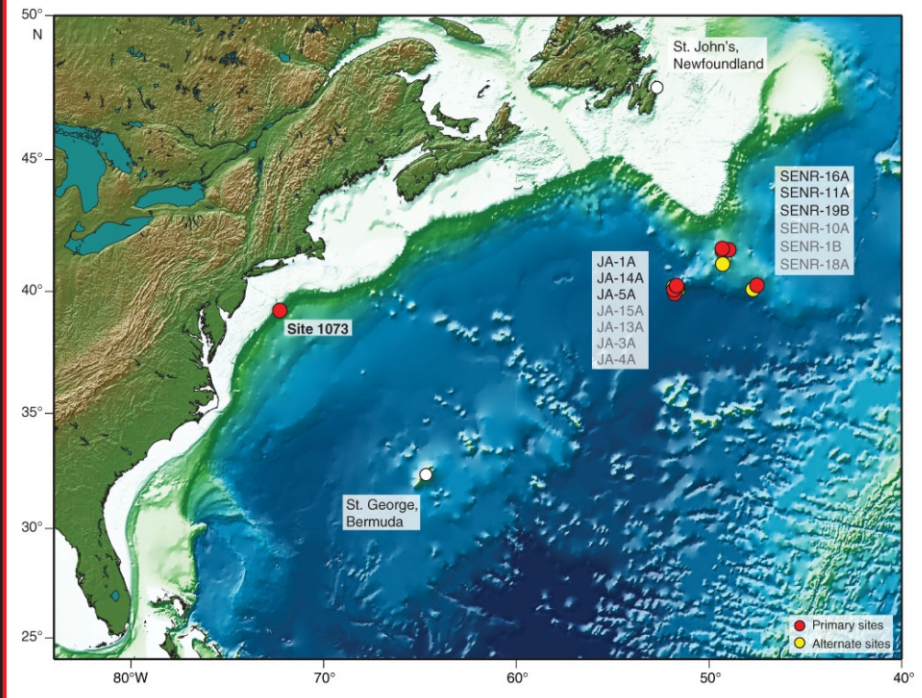


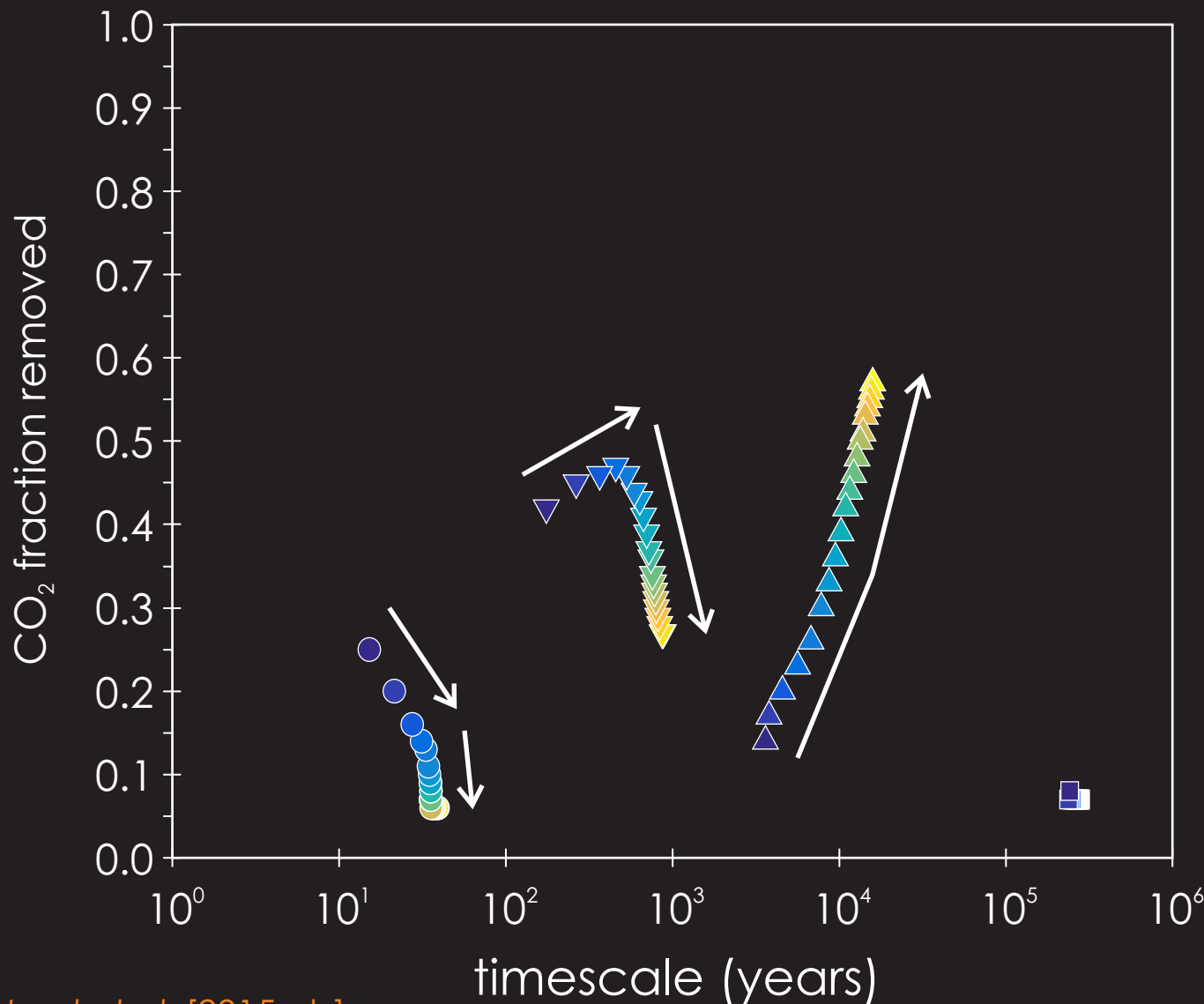


evidence?



Impulse response function analysis of the 'long tail' of CO_{2(excess)}





With increasing total CO_2 emissions, the response time of all sinks (bar silicate weathering) lengthen, and the shorter time-scale two weaken at the expense of the $\sim 10,000$ year CaCO_3 burial process.

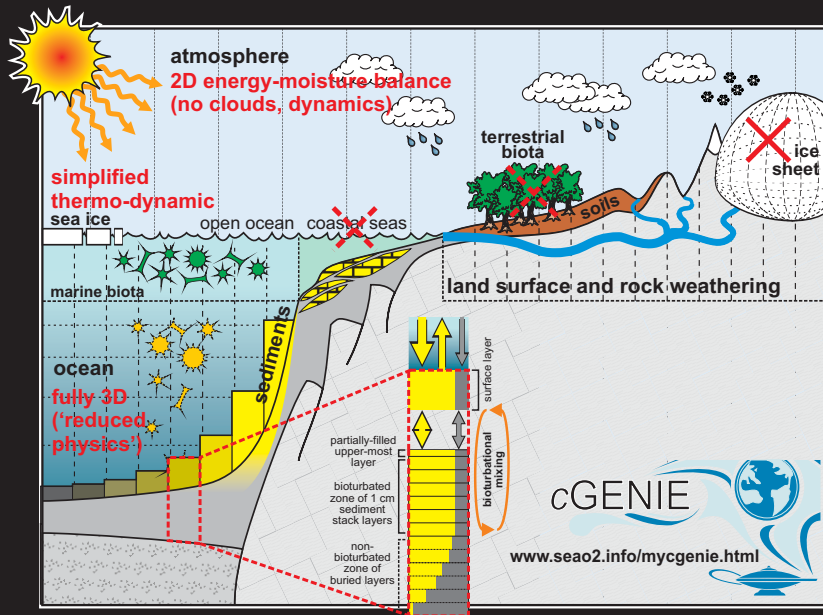
Elevated atmospheric $p\text{CO}_2$ hence becomes more persistent as the main short-term CO_2 feedbacks weaken.

The majority of carbon removal beyond $\sim 10,000$ PgC is removed only on time-scales exceeding 10,000 years.

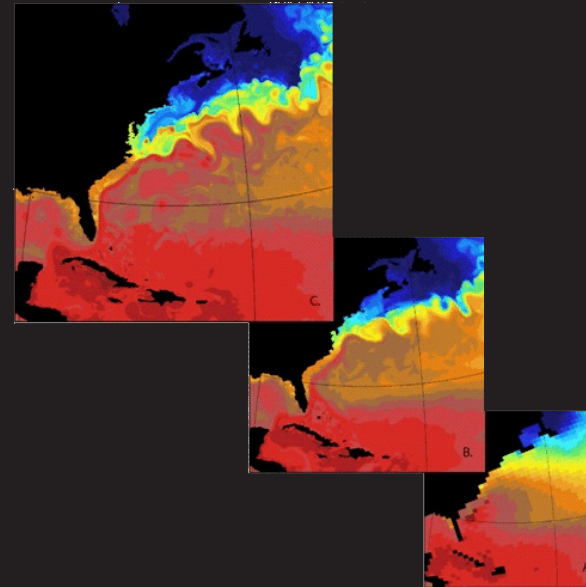
Melting Antarctica



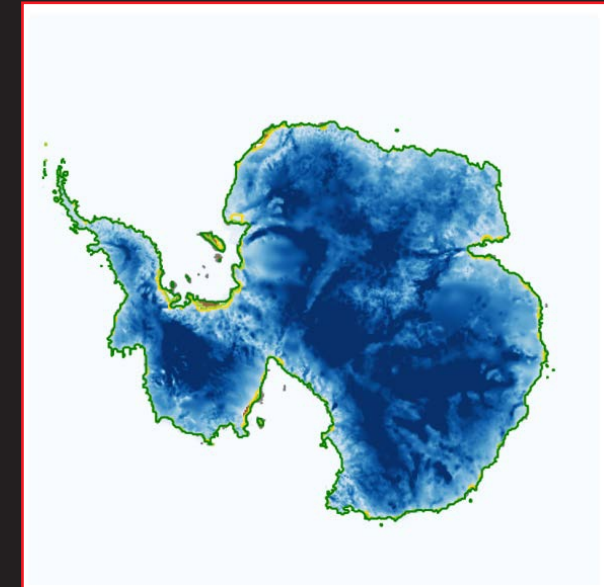
Melting Antarctica



Earth system model
(CO₂ and mean SST trajectories)

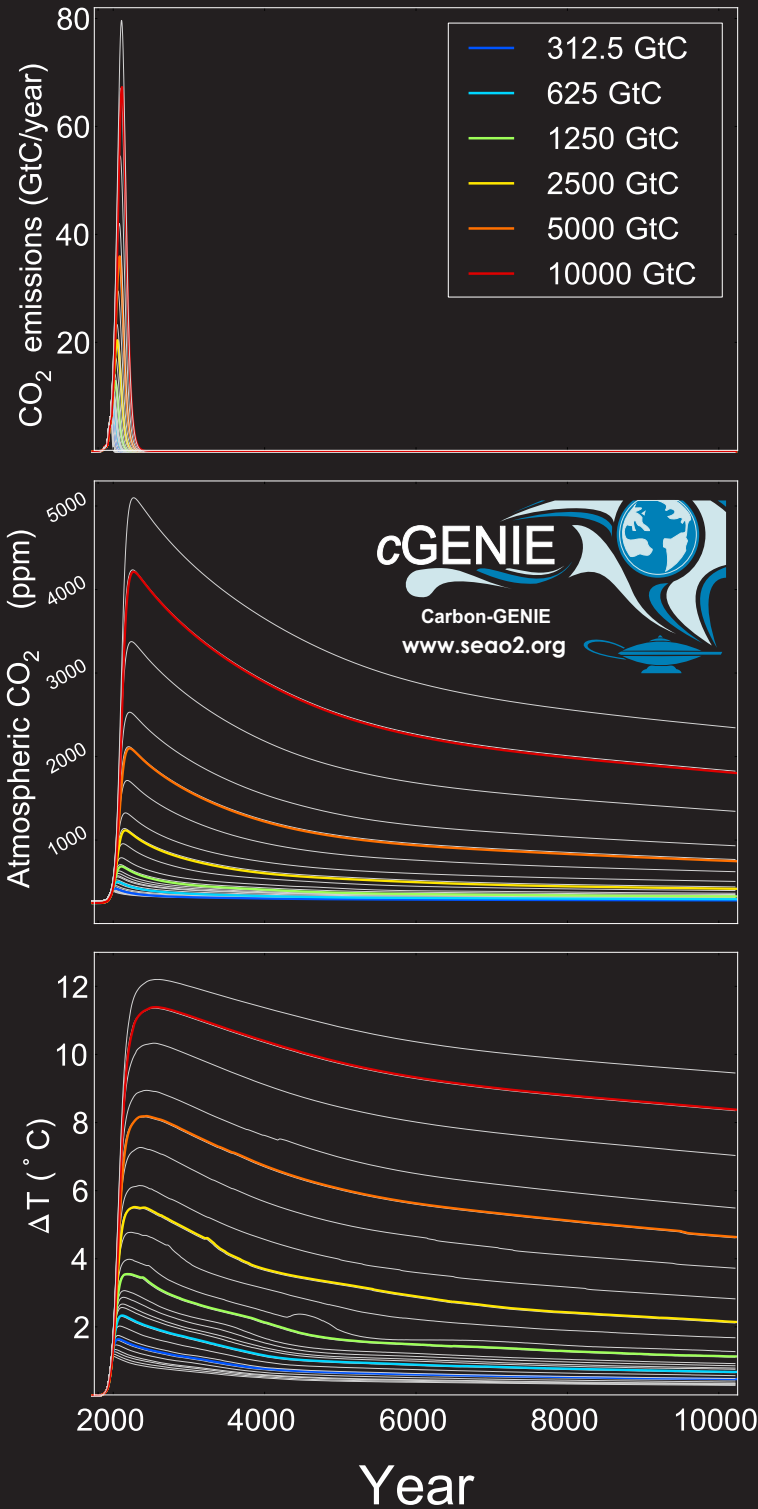


Downscaling
(50 SST and regional climate)

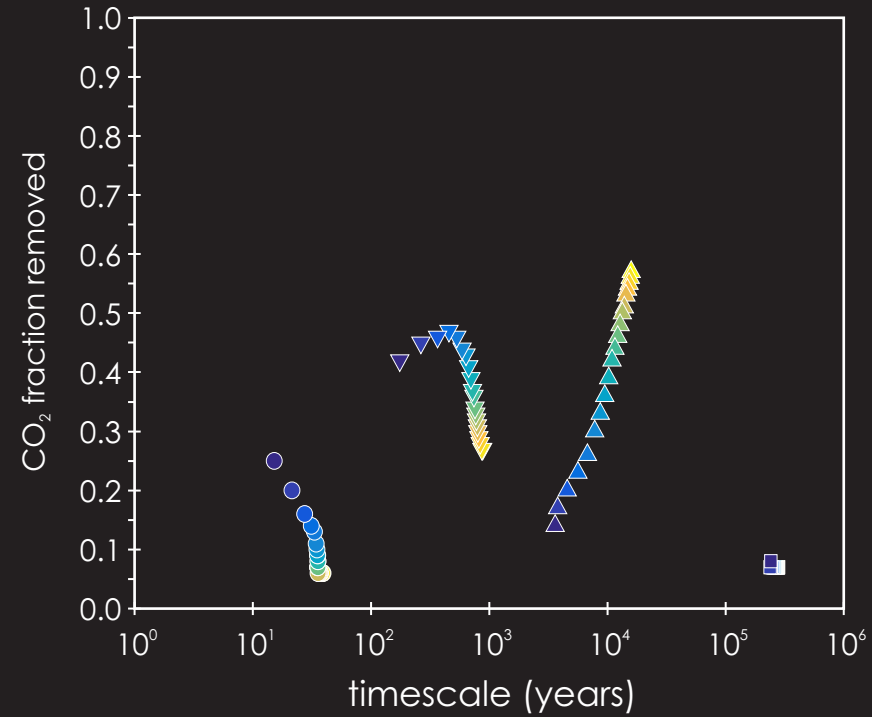
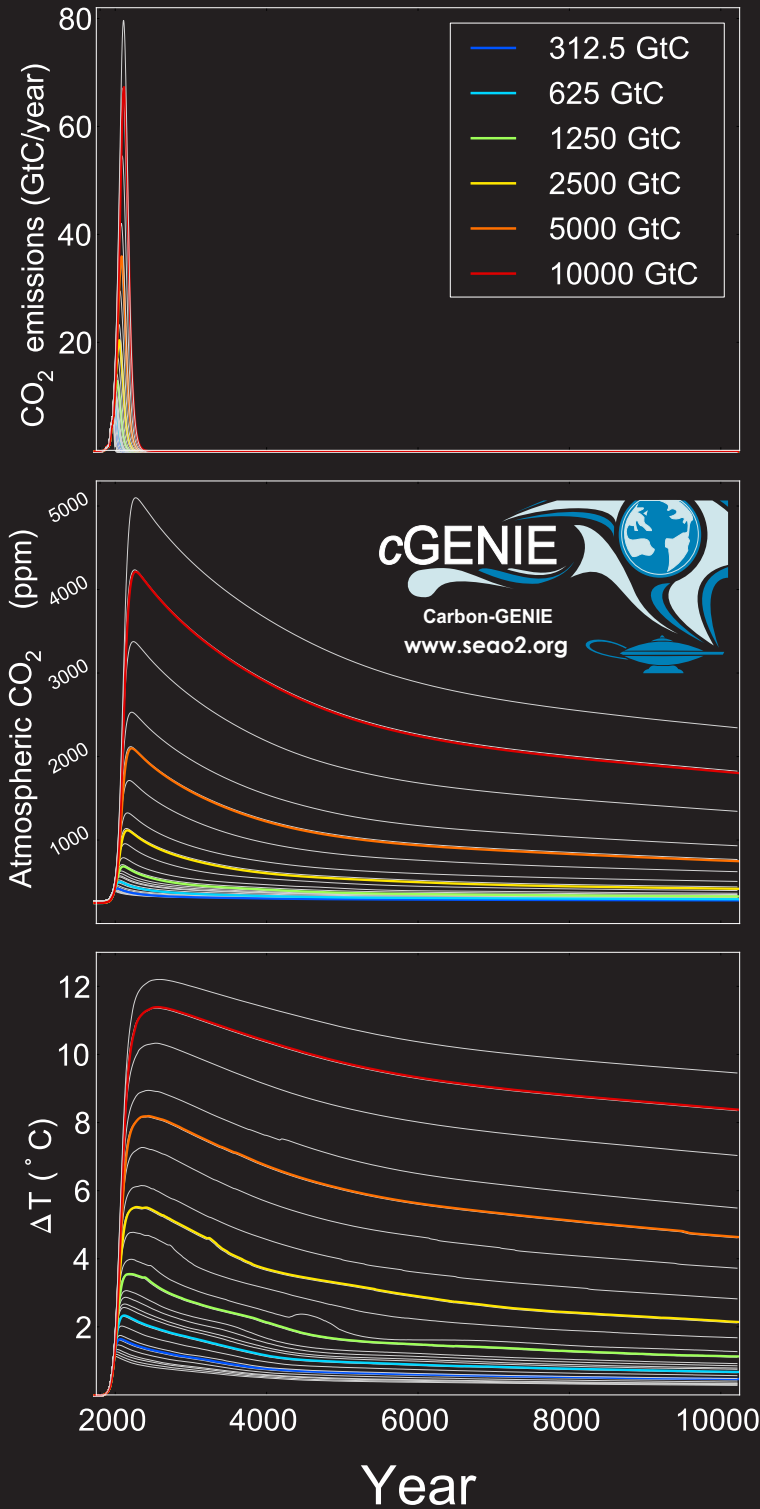


Ice sheet model

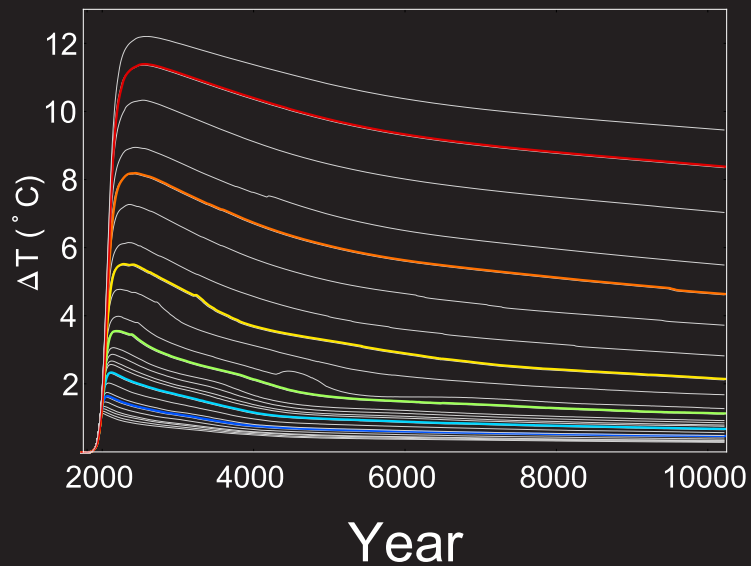
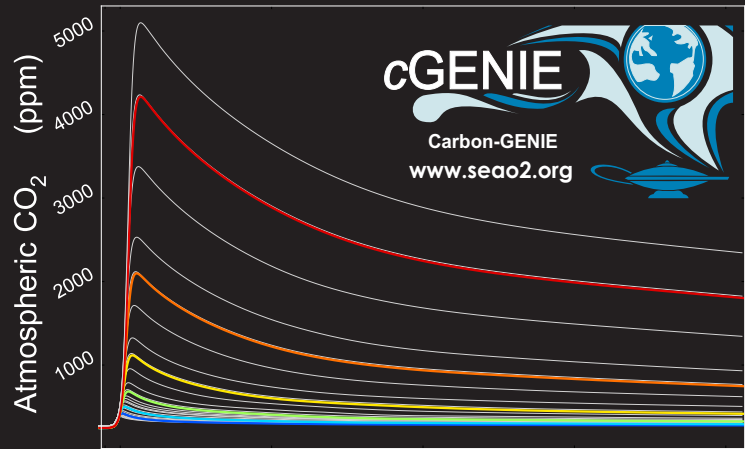
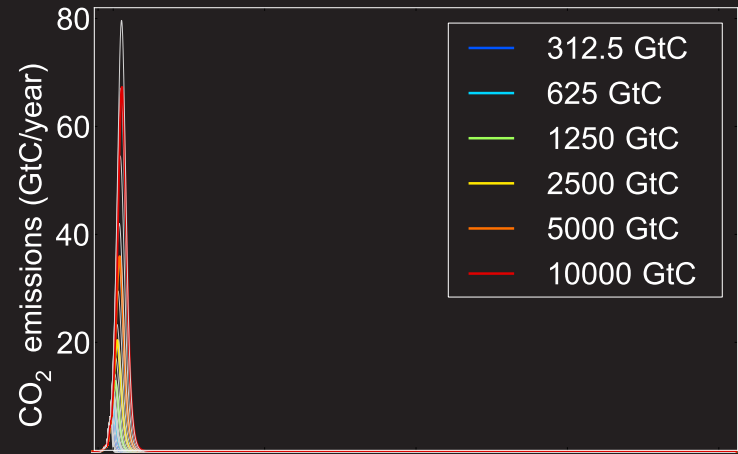
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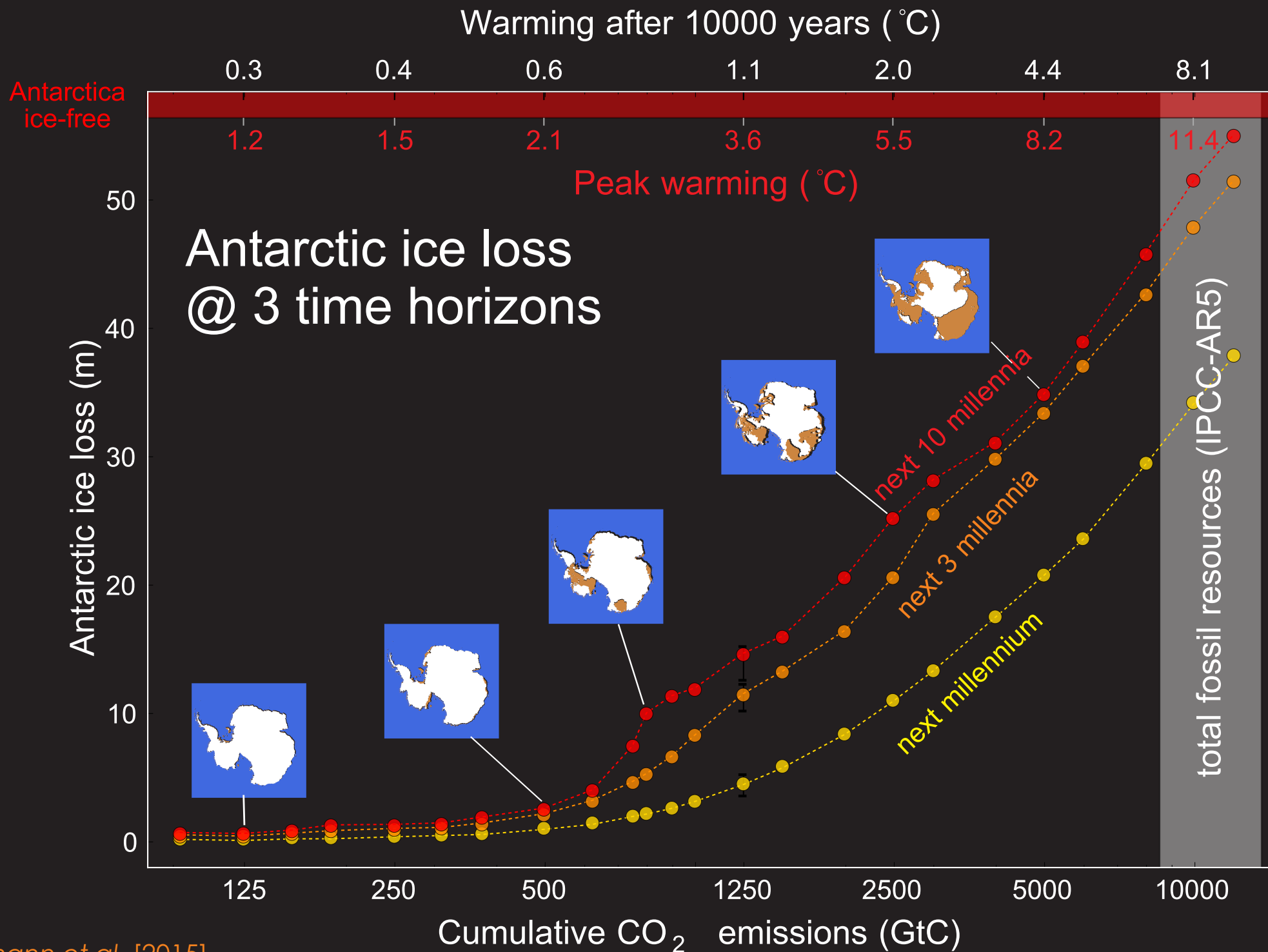


Melting Antarctica



↔ $\Delta F \propto \ln(C/C_0)$

Melting Antarctica



Enhanced weathering (CO₂ removal geoengineering)



Enhanced weathering (CO₂ removal geoengineering)



Enhanced weathering (CO₂ removal geoengineering)





granite ≈

SiO₂ = 72%

...

CaO = 1.8%

...

MgO = 0.7%

...

basalt ≈

SiO₂ = 50%

...

CaO = 10%

...

MgO = 10%

...

Enhanced weathering (CO₂ removal geoengineering)



~ plagioclase + pyroxene (+olivine)



Enhanced weathering (CO₂ removal geoengineering)



~ olivine + pyroxene

Harzburgite

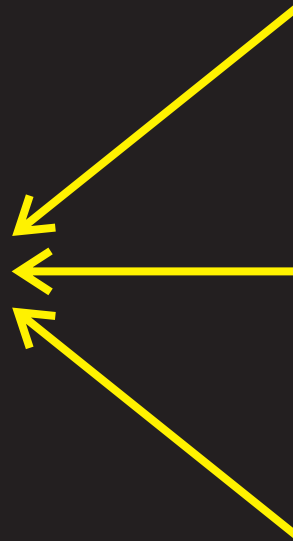


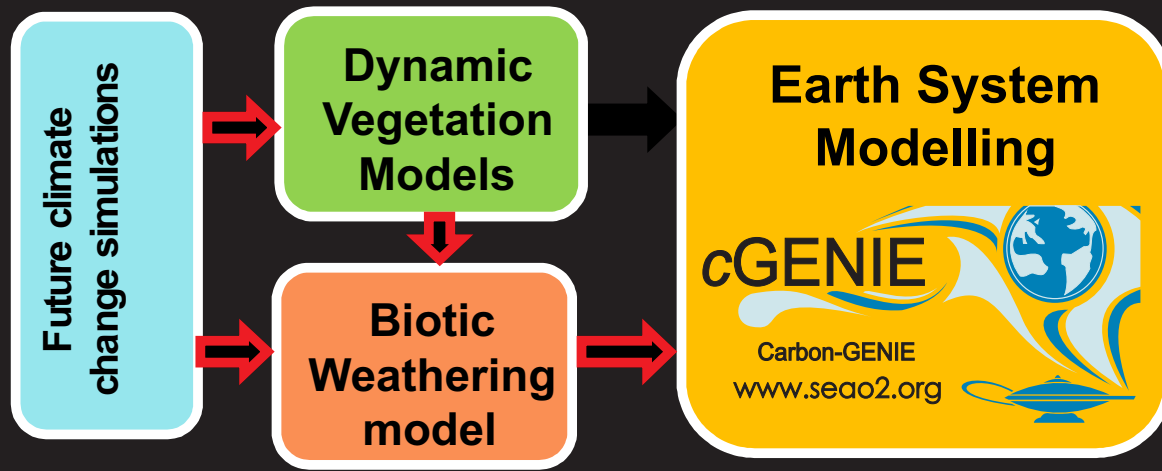
~ plagioclase + pyroxene (+olivine)



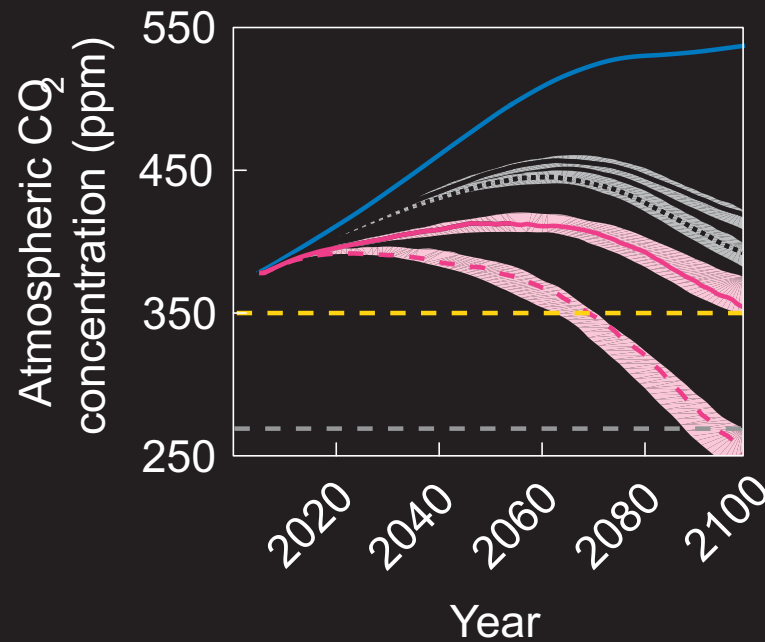
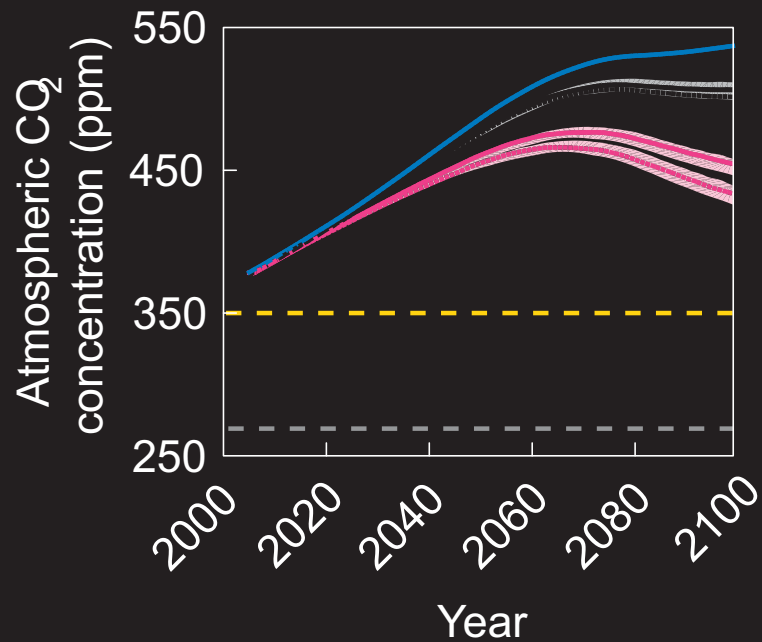
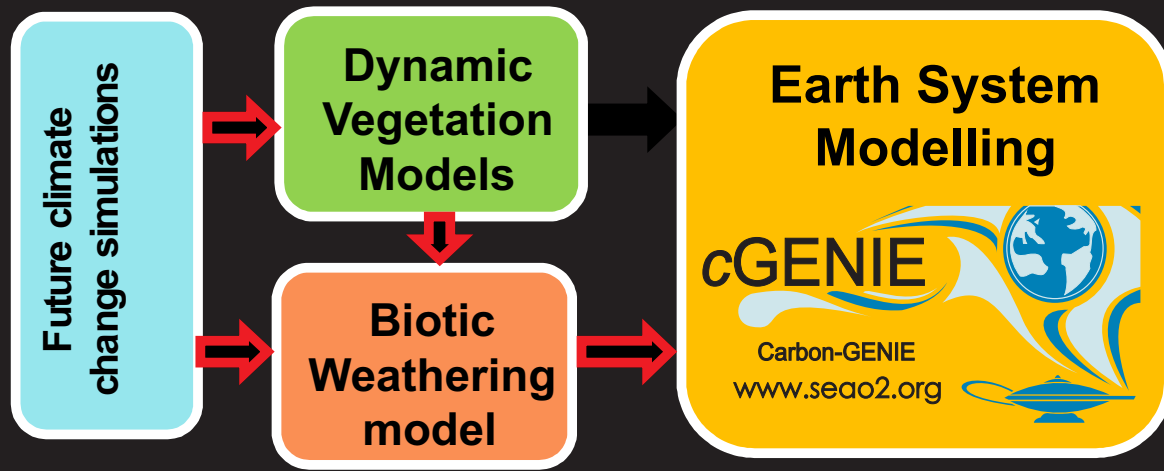
>90% olivine: $(\text{Mg}^{+2}, \text{Fe}^{+2})_2\text{SiO}_4$

Dunite



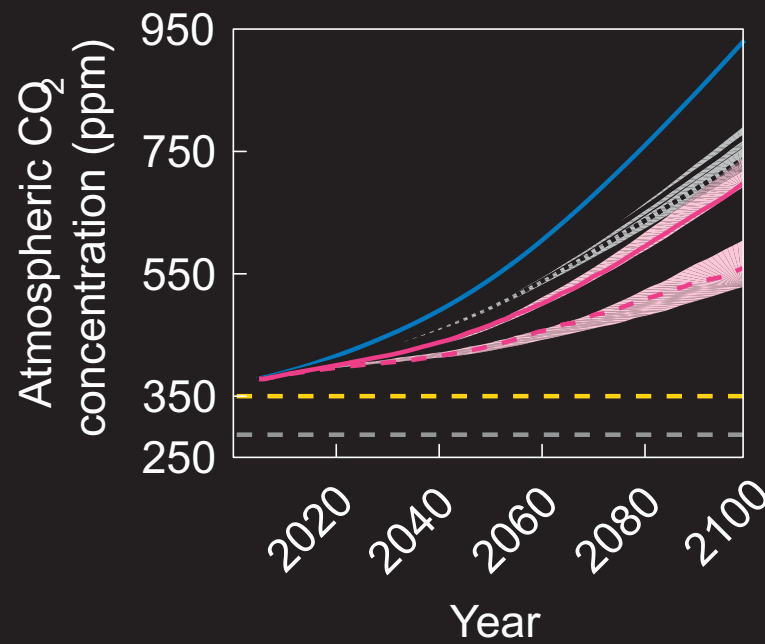
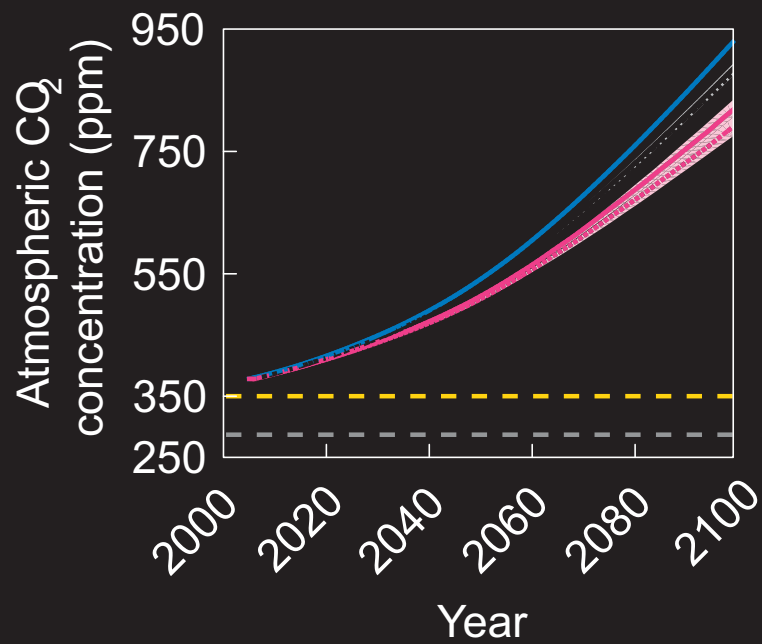
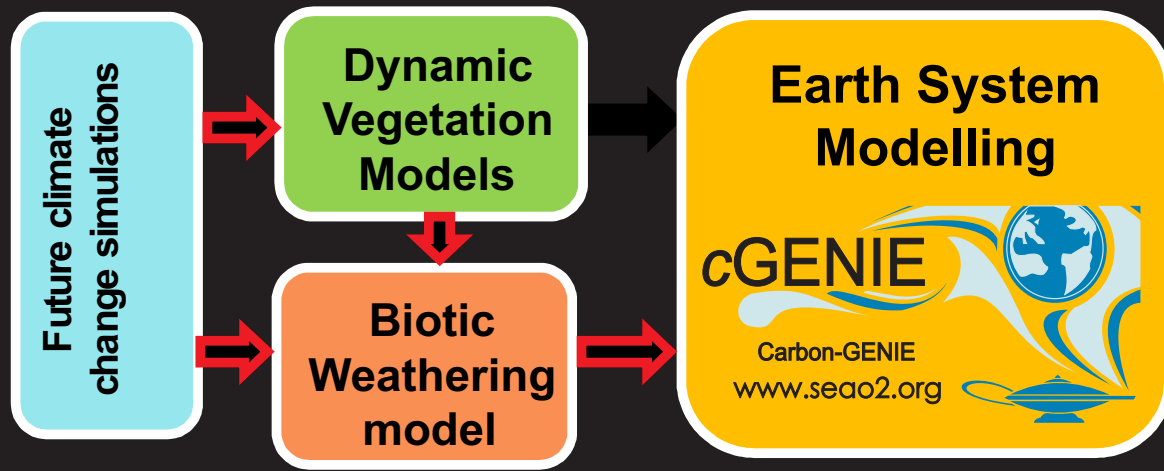


Enhanced weathering (CO₂ removal geoengineering)



- RCP scenario
- Basalt 10 cm
- Basalt 30 cm
- Harzburgite 10 cm
- Harzburgite 30 cm
- - - 350 ppm CO₂
- - - Pre-industrial CO₂

Enhanced weathering (CO₂ removal geoengineering)



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Current global oil
consumption =
90,136×10³ barrels per
day

$$\begin{aligned} 1.0 \text{ barrel} &= 159 \text{ l} \\ &= 159 \times 10^3 \text{ cm}^3 \end{aligned}$$

$$\begin{aligned} \Rightarrow \text{oil consumption} & \\ &= 5.23 \times 10^{15} \text{ cm}^3 \text{ year}^{-1} \\ &= \mathbf{5.23 \text{ km}^3 \text{ year}^{-1}} \end{aligned}$$

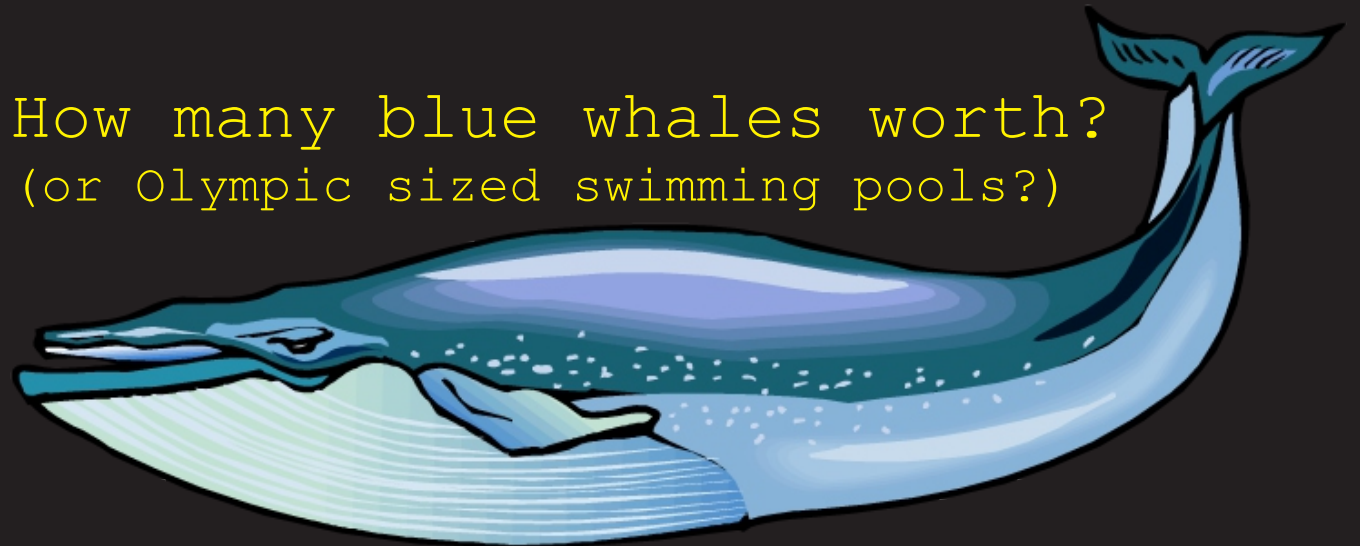


Current global oil
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1.0 barrel = 159 l
= 159×10³ cm³

⇒ oil consumption
= 5.23×10¹⁵ cm³ year⁻¹
= **5.23 km³ year⁻¹**

How many blue whales worth?
(or Olympic sized swimming pools?)





Current global oil
consumption =
90,136×10³ barrels per
day

1.0 barrel = 159 l
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= 5.23×10¹⁵ cm³ year⁻¹
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1.0E0 Avon Gorges





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Assume:

101 m deep \times 214 m
across (at Bridge),
2.5 km long

\Rightarrow

$$\begin{aligned} \text{volume} &= 2.5 \times 0.101 \times 0.214 \\ &= \mathbf{0.054 \text{ km}^3} \end{aligned}$$

(3.8 days worth of global
oil supply by volume)





Thanks to:

Natalie Lord and Dan Lunt [Bristol], Mike Thorne [Mike Thorne and Associates Limited]

Lyla Taylor and David Beerling [Sheffield], *et al.*

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AMEC and Quintessa (results part of Working Group 6 of the IAEA-sponsored MODARIA Programme)

