A Long Tale of CO_2

Andy Ridgwell

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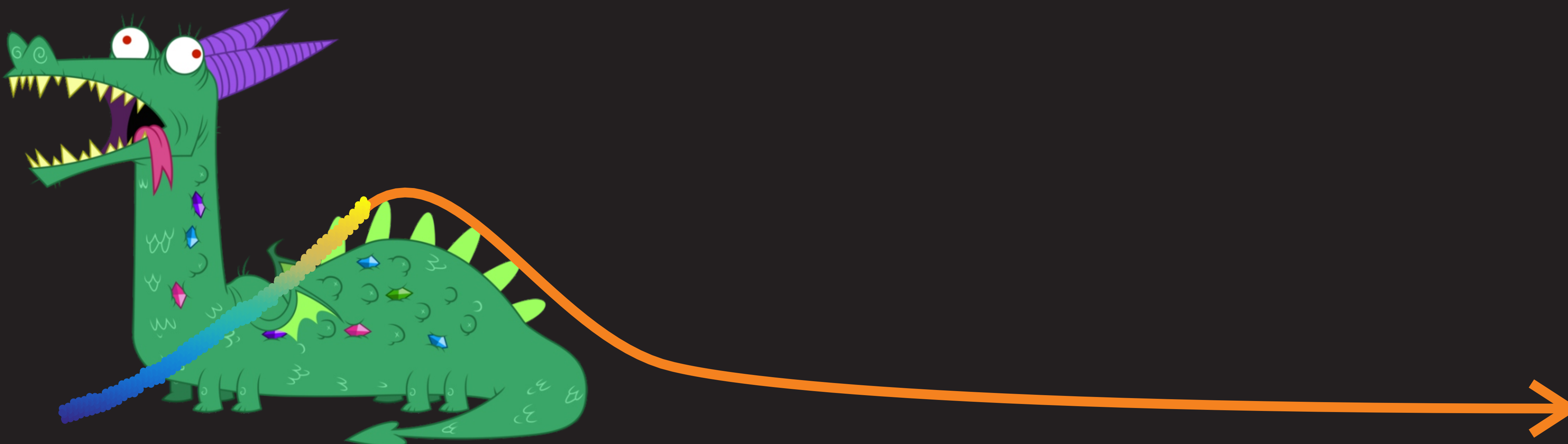
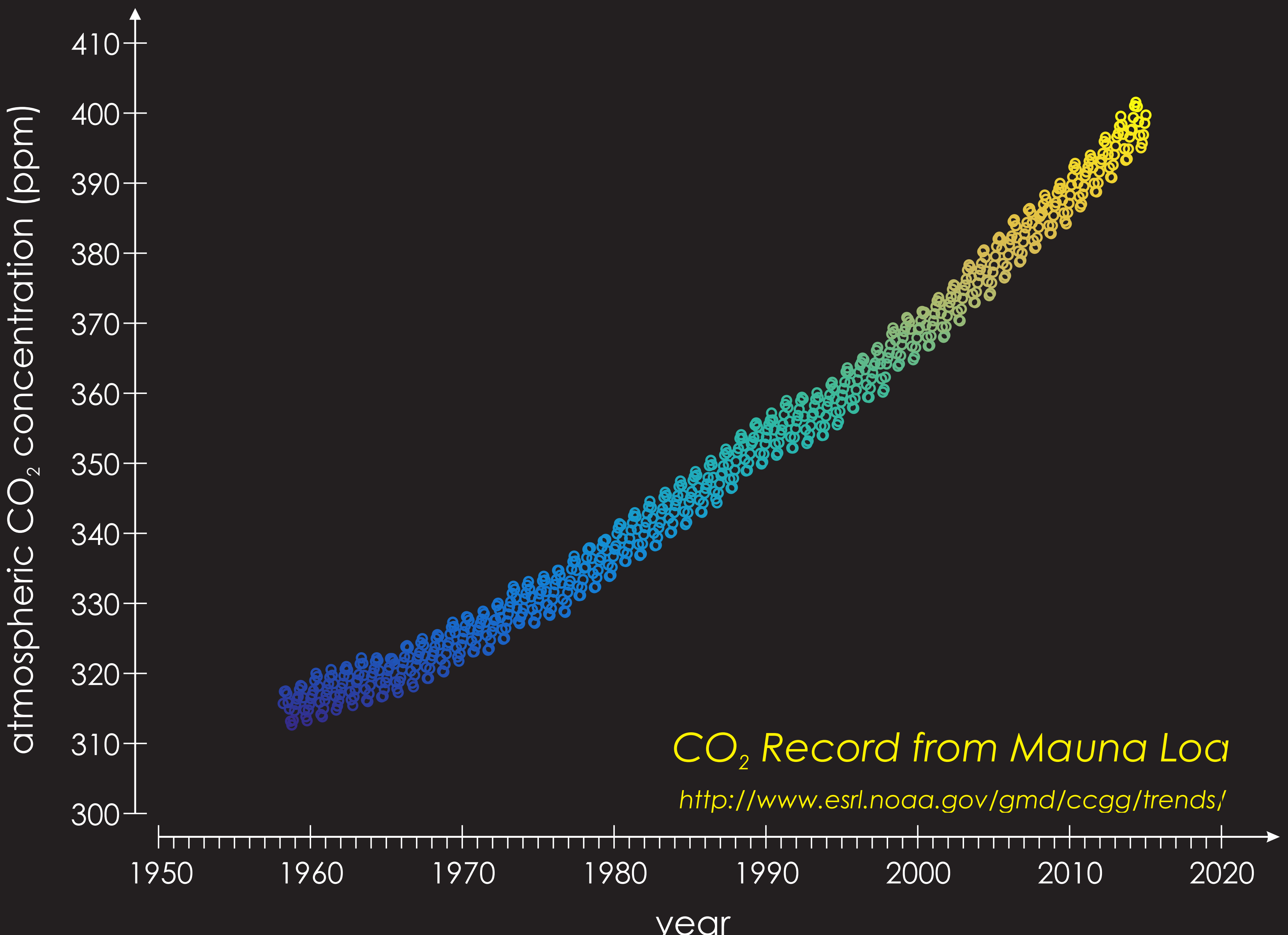
European Research Council
Established by the European Commission
UCR



Introduction (1): The fate of (fossil fuel) CO_2 emissions

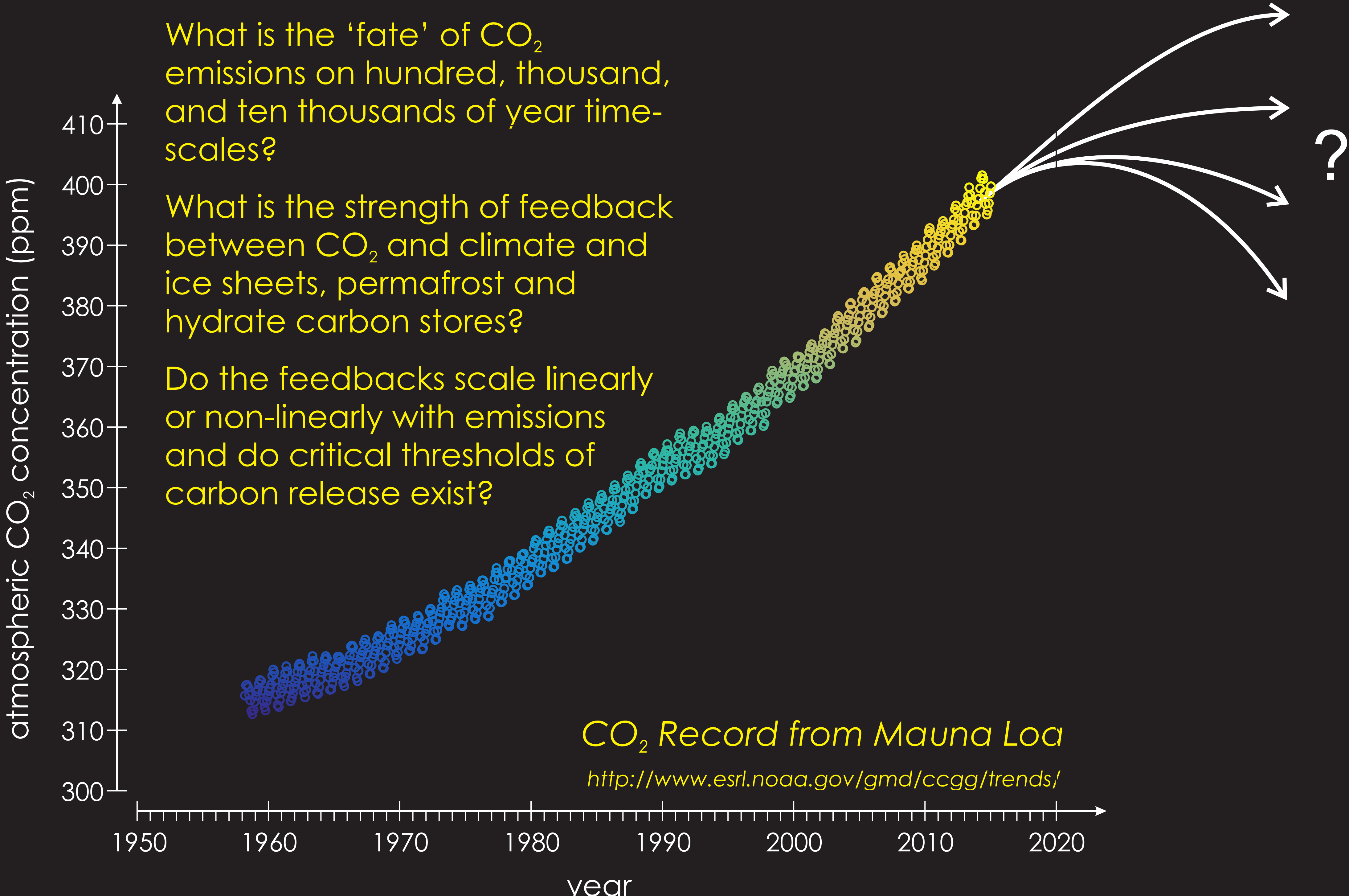


Introduction (1): The fate of (fossil fuel) CO_2 emissions

What is the 'fate' of CO_2 emissions on hundred, thousand, and ten thousands of year time-scales?

What is the strength of feedback between CO_2 and climate and ice sheets, permafrost and hydrate carbon stores?

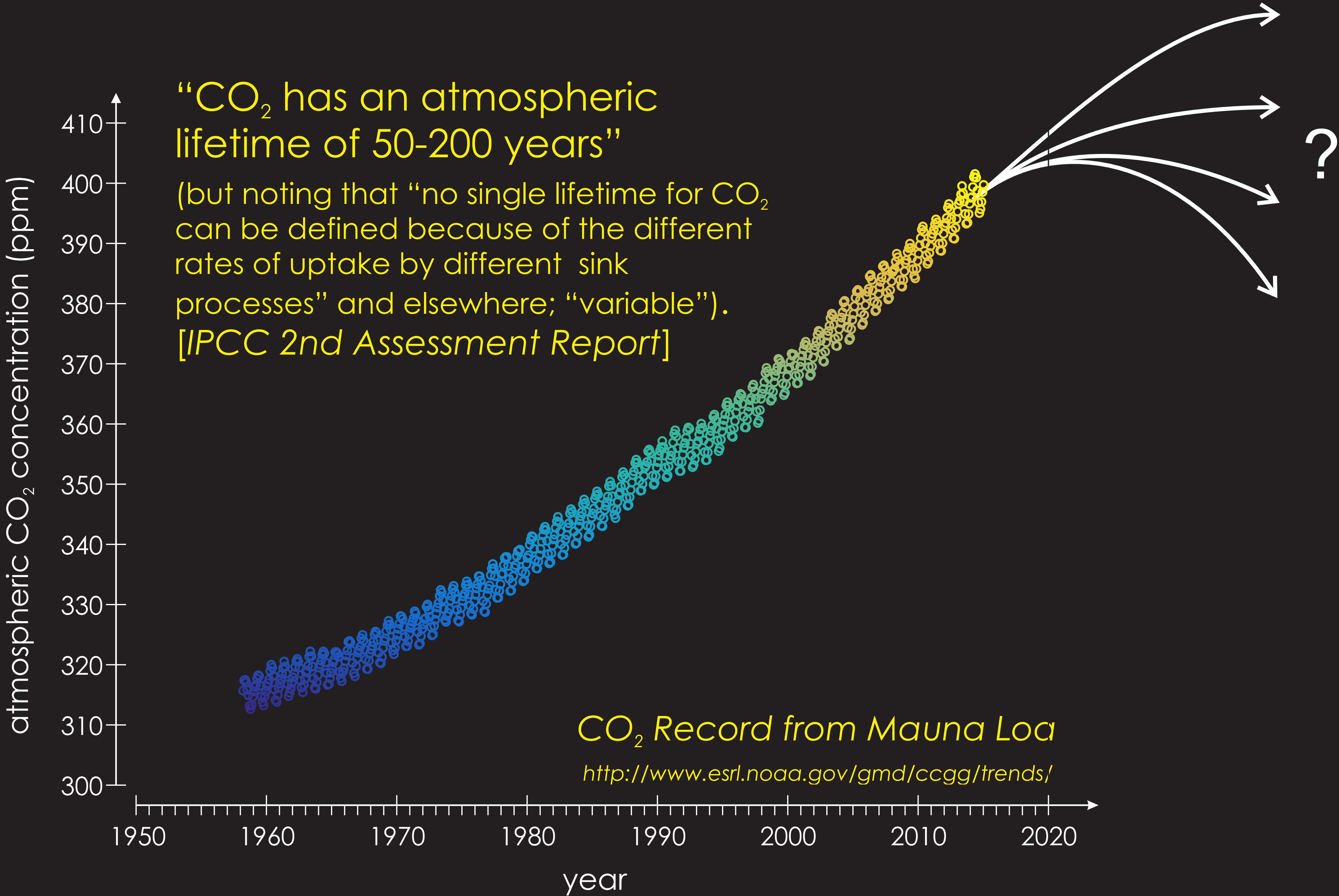
Do the feedbacks scale linearly or non-linearly with emissions and do critical thresholds of carbon release exist?



Introduction (1): The fate of (fossil fuel) CO_2 emissions

"CO_2 has an atmospheric lifetime of 50-200 years"

(but noting that "no single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes" and elsewhere; "variable"). [*IPCC 2nd Assessment Report*]



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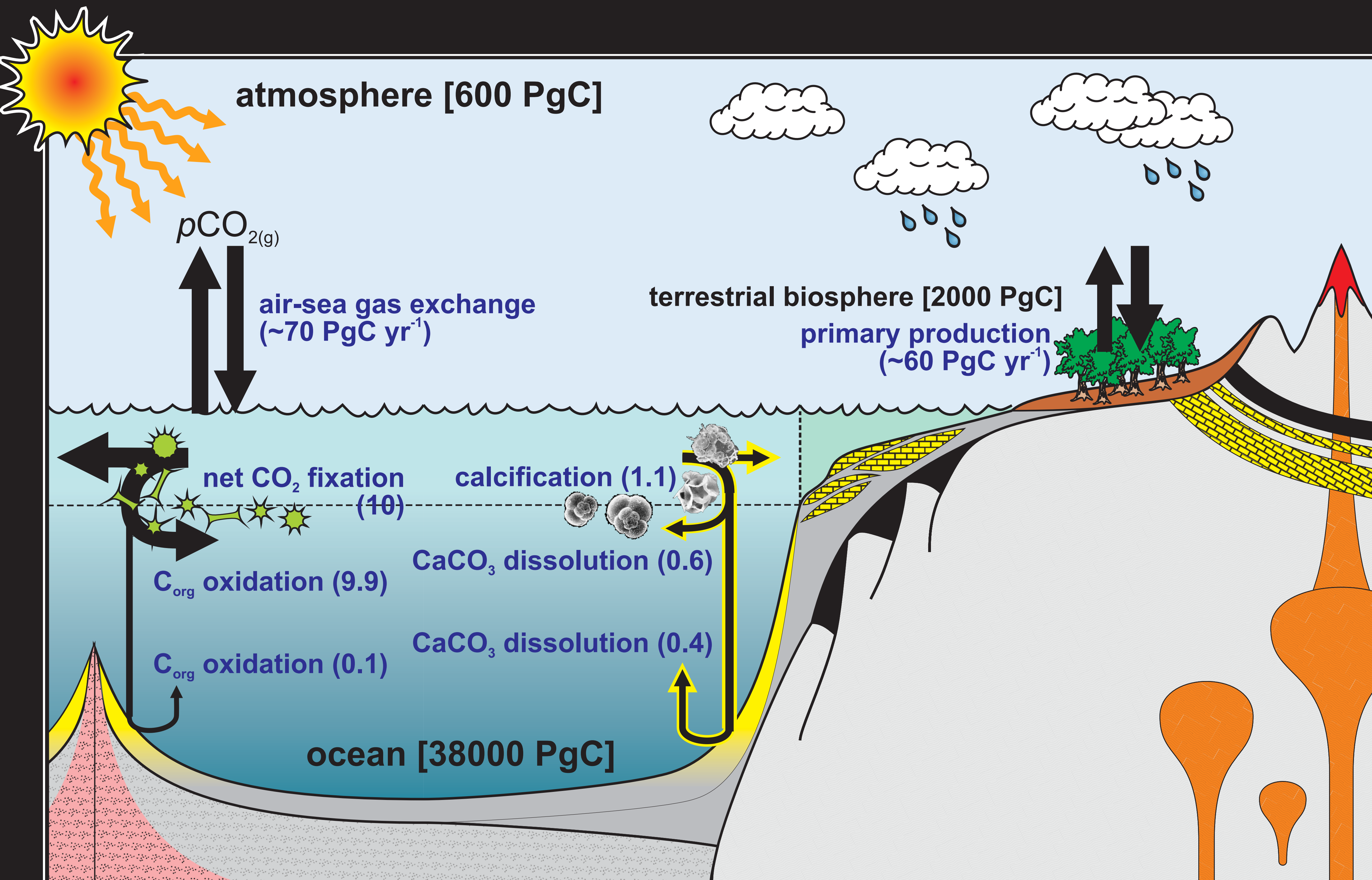
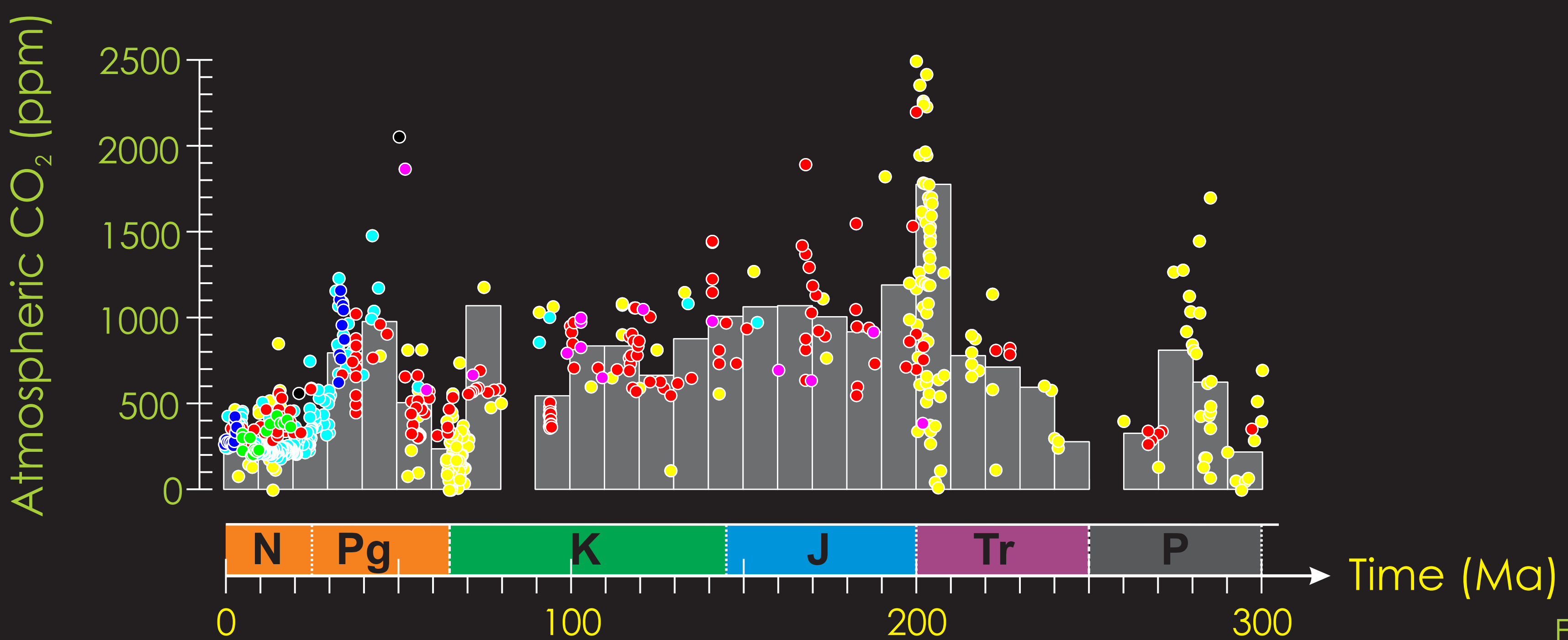
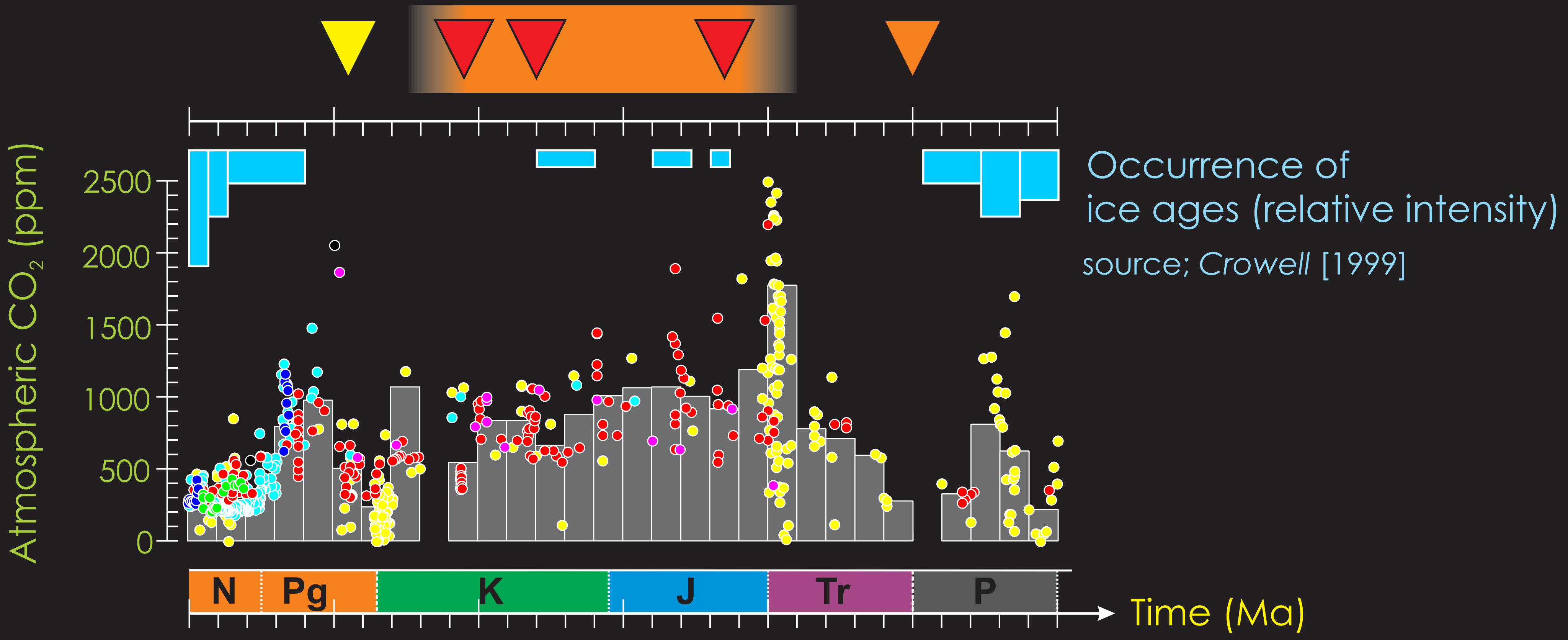


Introduction (2): paleo pCO_2



From: *Hönisch et al.* [2012]

Introduction (2): paleo pCO_2



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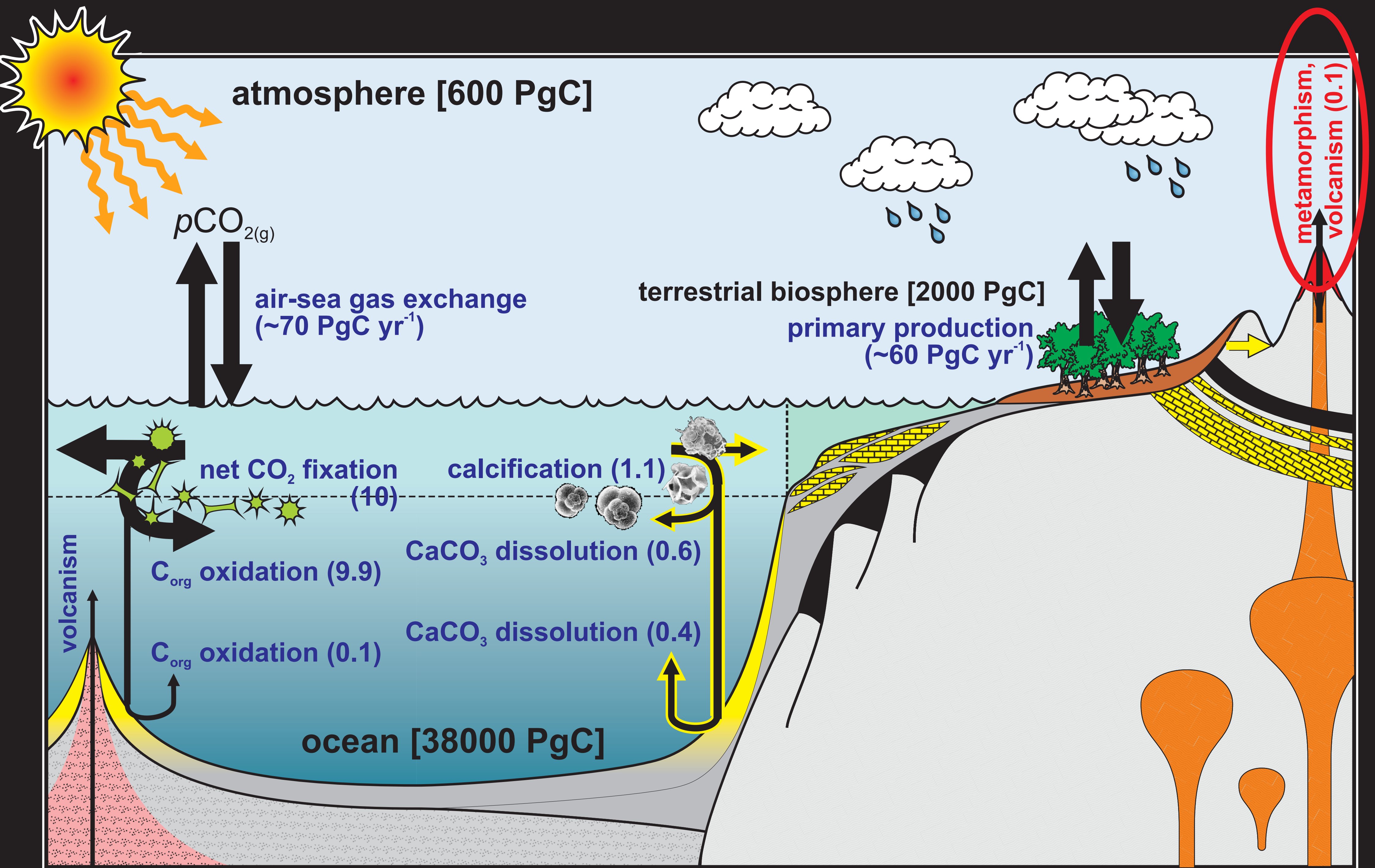
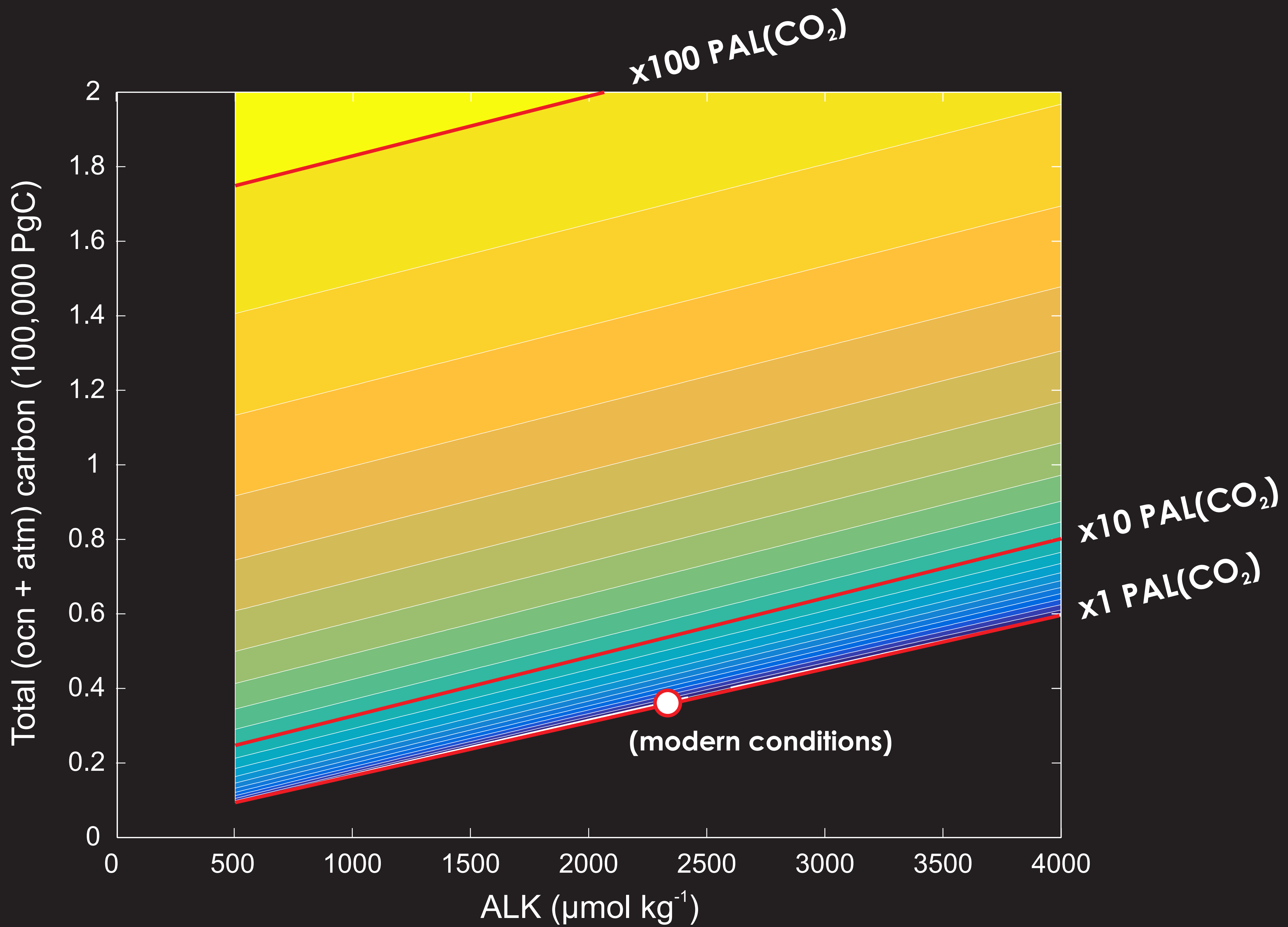
Introduction (2): paleo pCO_2



Introduction (2): paleo pCO_2



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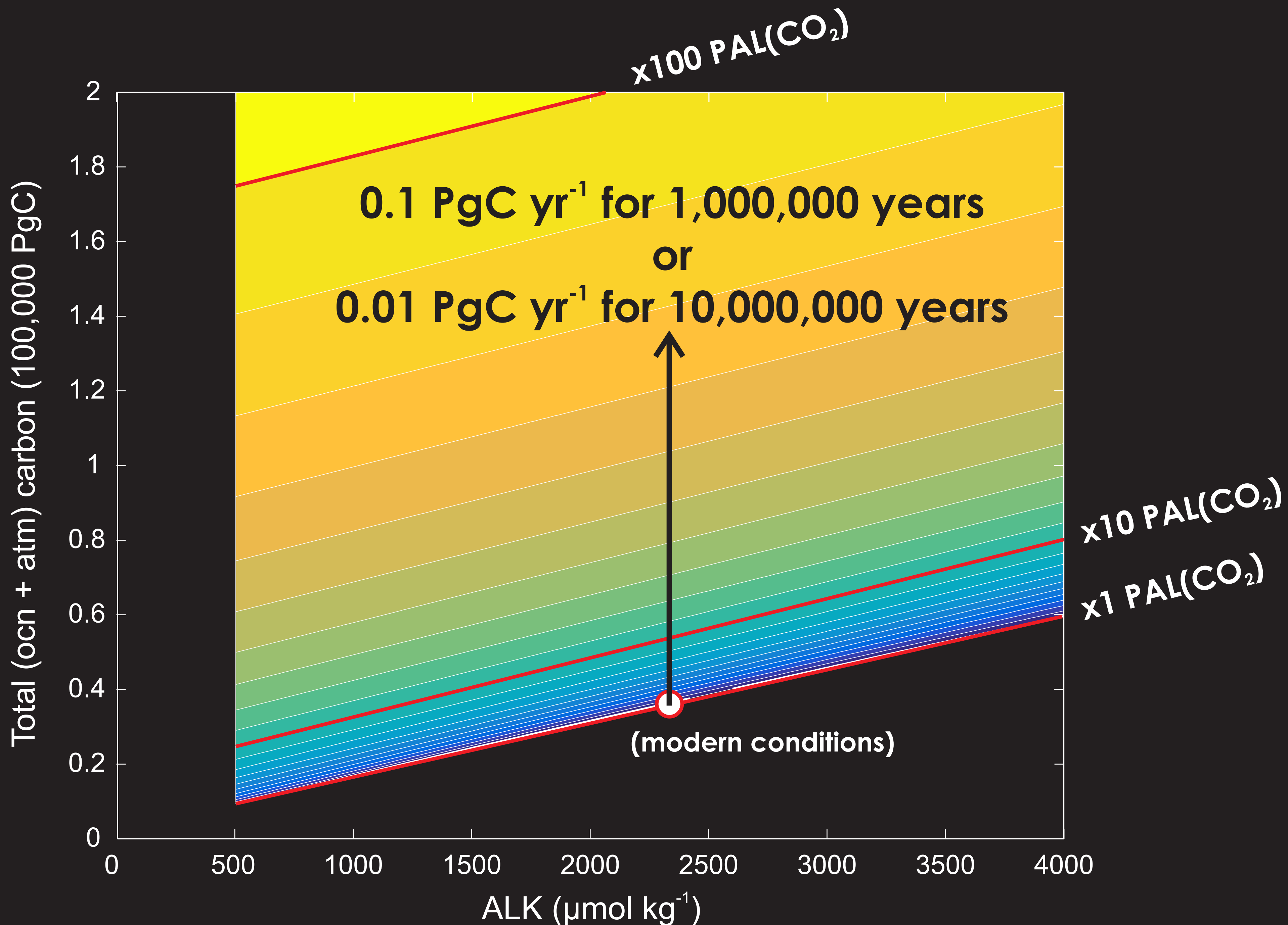

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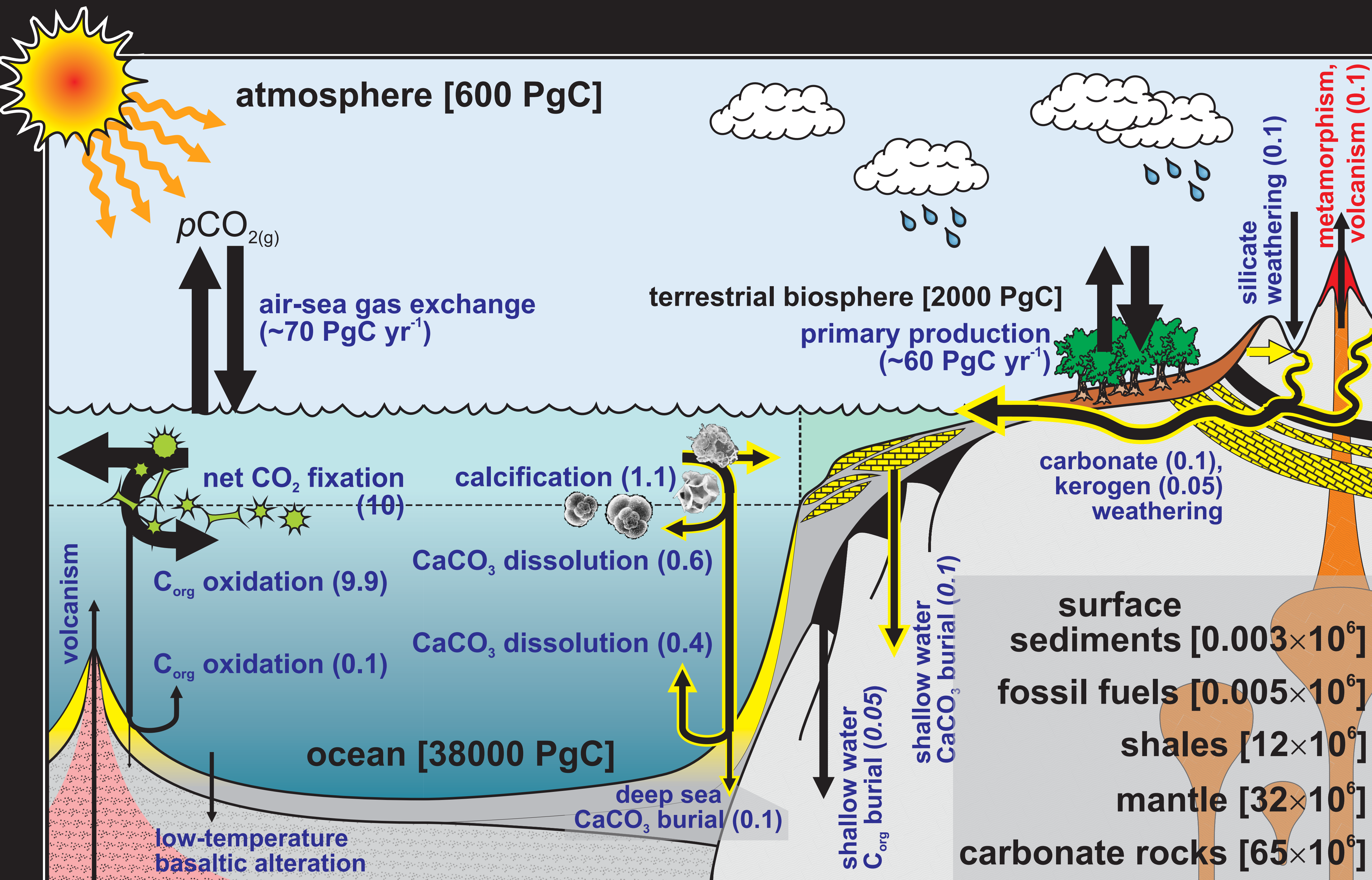


Introduction (3): The long tail of CO_2

Introduction (3): The long tail of CO_2

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

(1) $2CO_{2(aq)} + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$

(2) $CO_{2(aq)} + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

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

(3) $Ca^{2+} + 2HCO_3^- \rightarrow CO_{2(aq)} + H_2O + CaCO_3$

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.

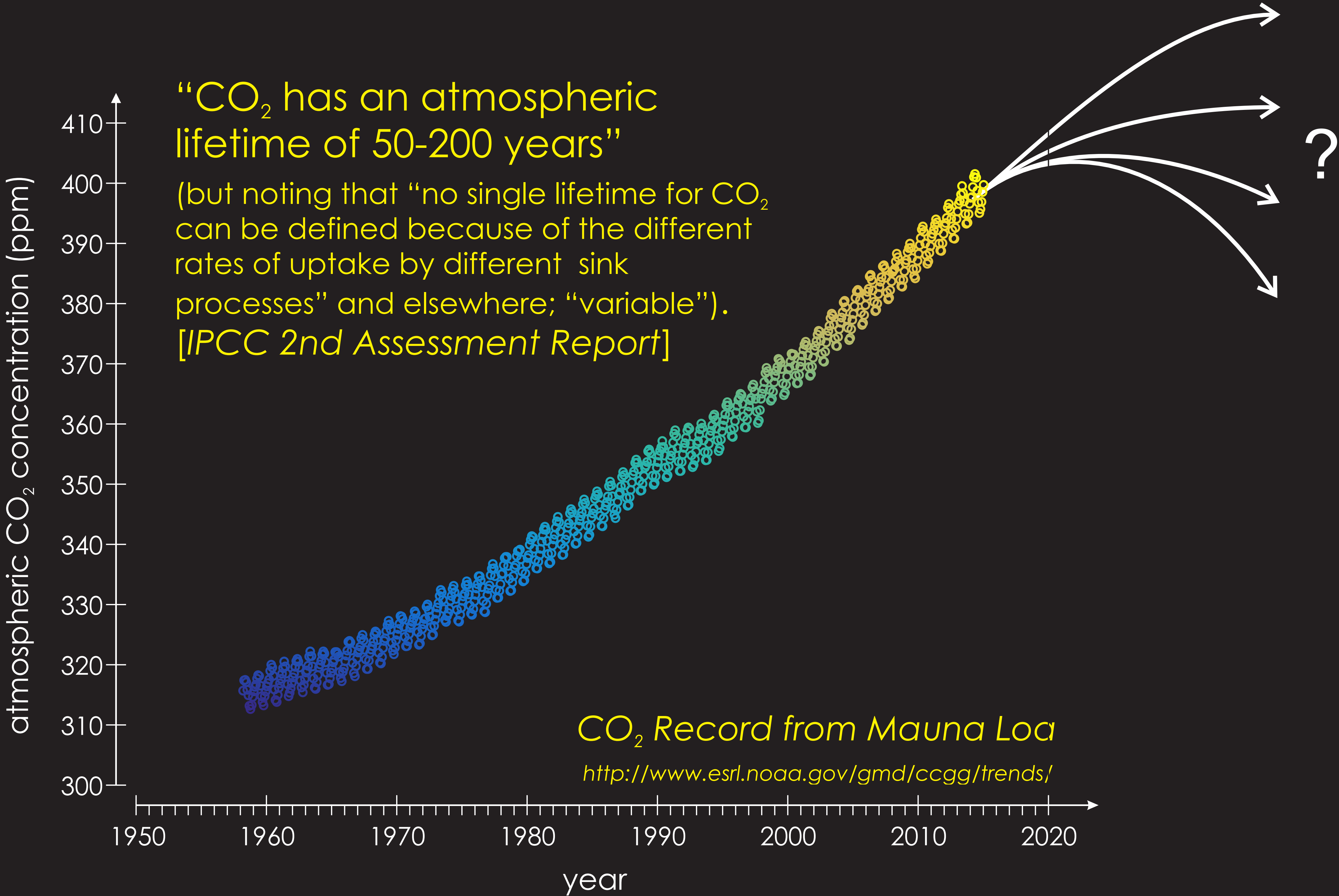
Introduction (3): The long tail of CO_2

Furthermore, the rate of silicate weathering should scale with climate.

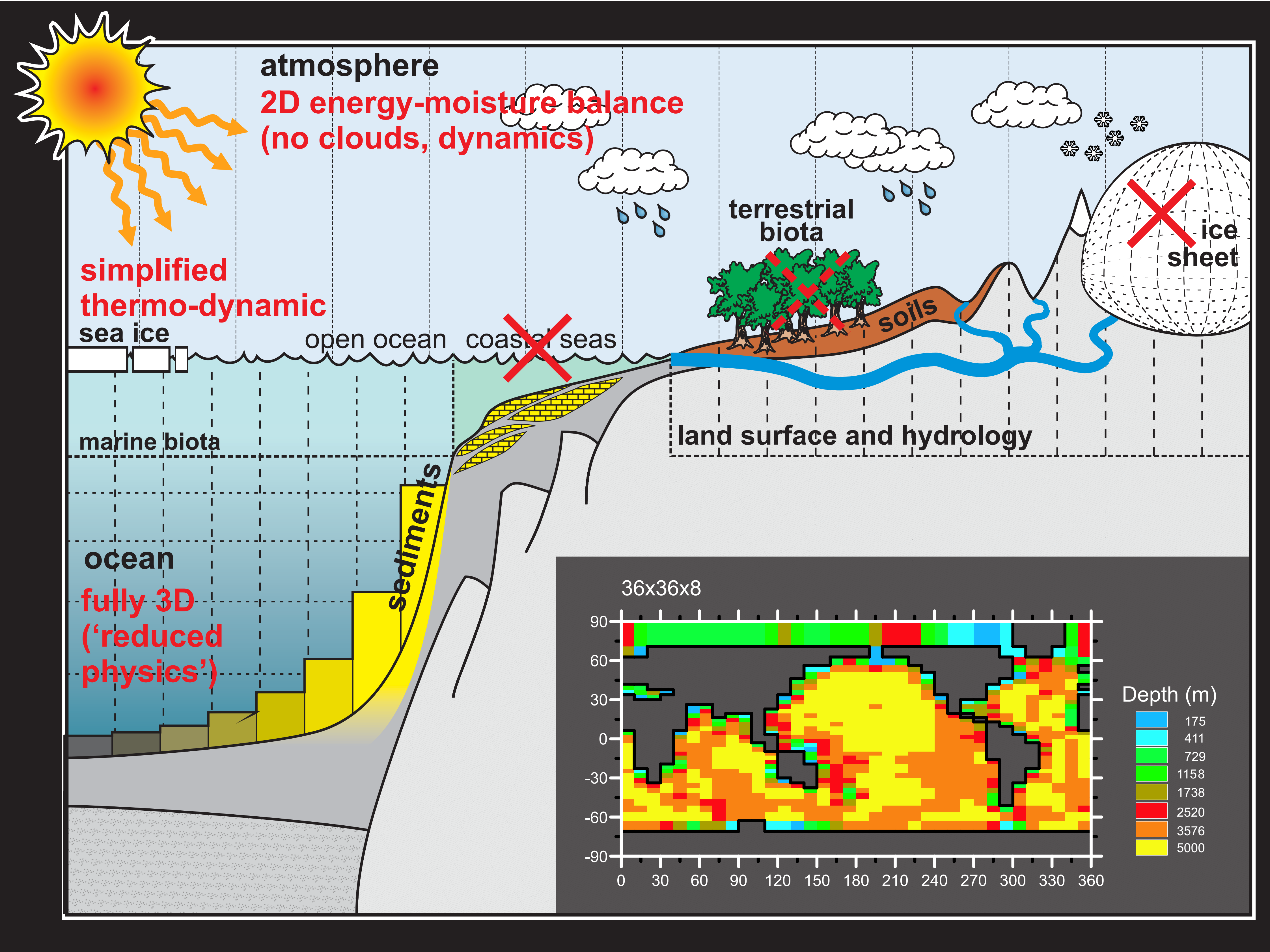
Hence the **silicate weathering feedback** is formed:

higher pCO_2 → higher temperatures (& rainfall) → higher weathering rates → lower pCO_2

lies, damn lies, and computer models

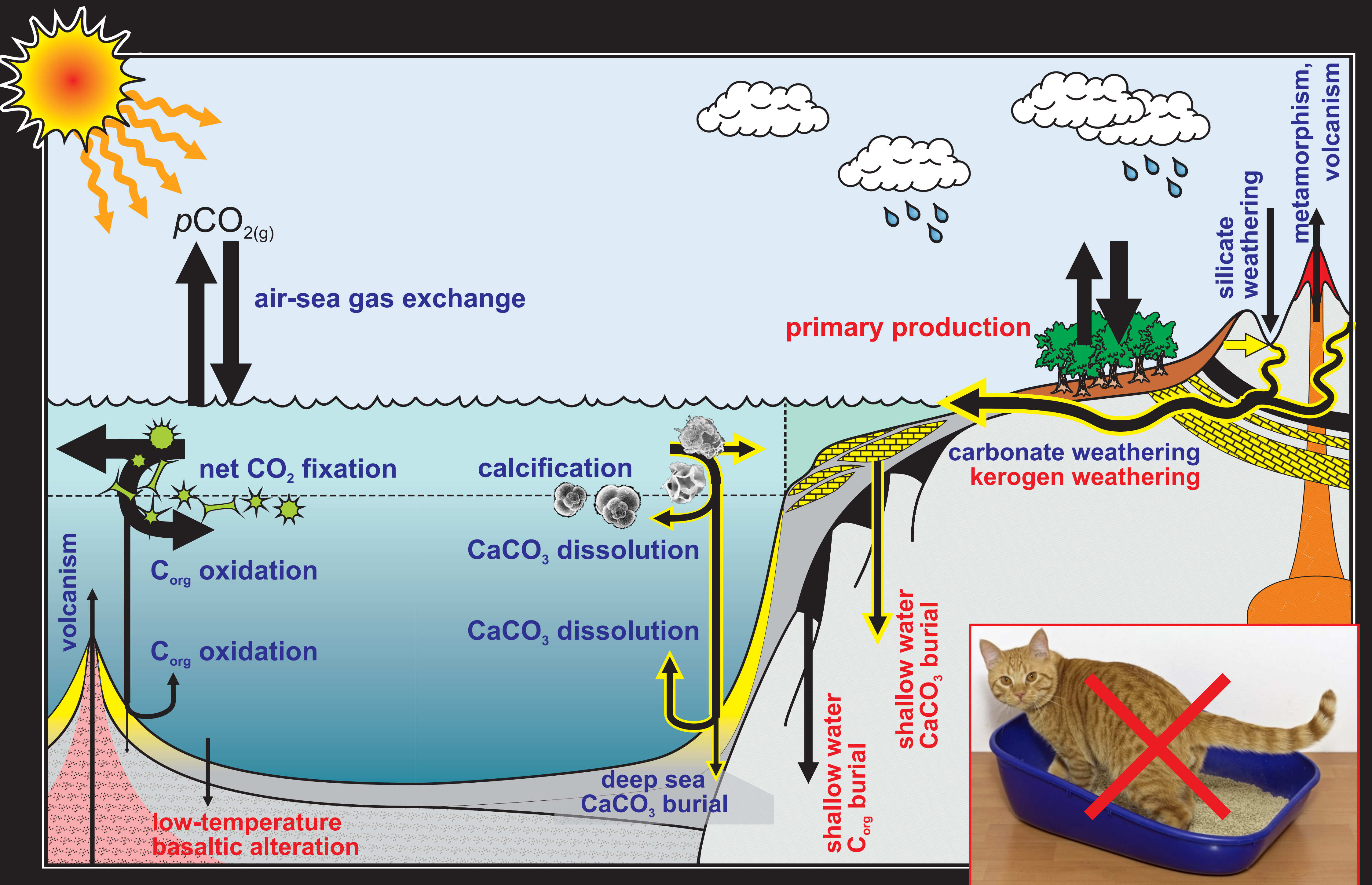


```
! calculate carbonate alkalinity

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
```



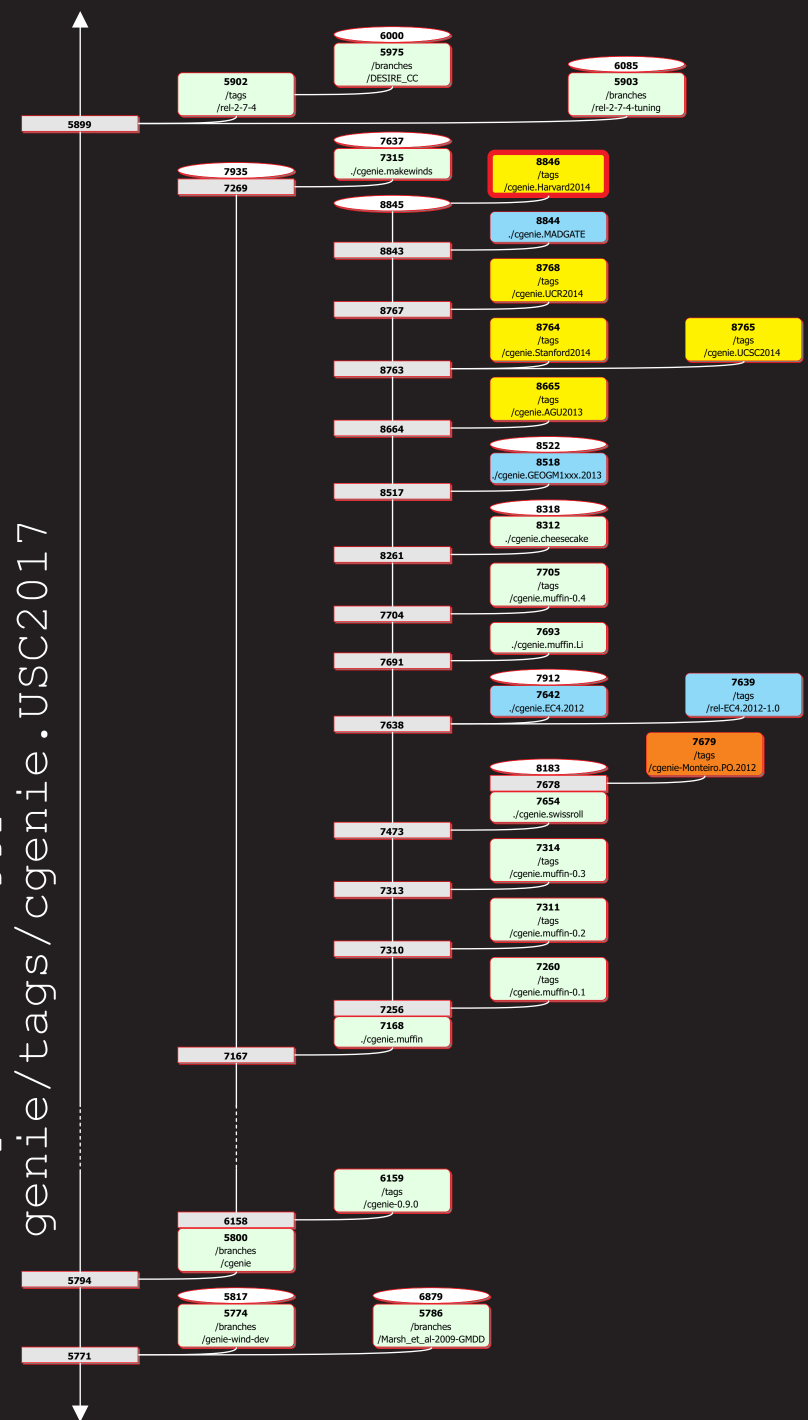
atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
coastal seas
terrestrial
biota
soils
ice
sheet
marine biota
sediments
land surface and hydrology
ocean
fully 3D
('reduced
physics')
36x36x8
Depth (m)
175
411
729
1158
1738
2520
3576
5000

lies, damn lies, and computer models



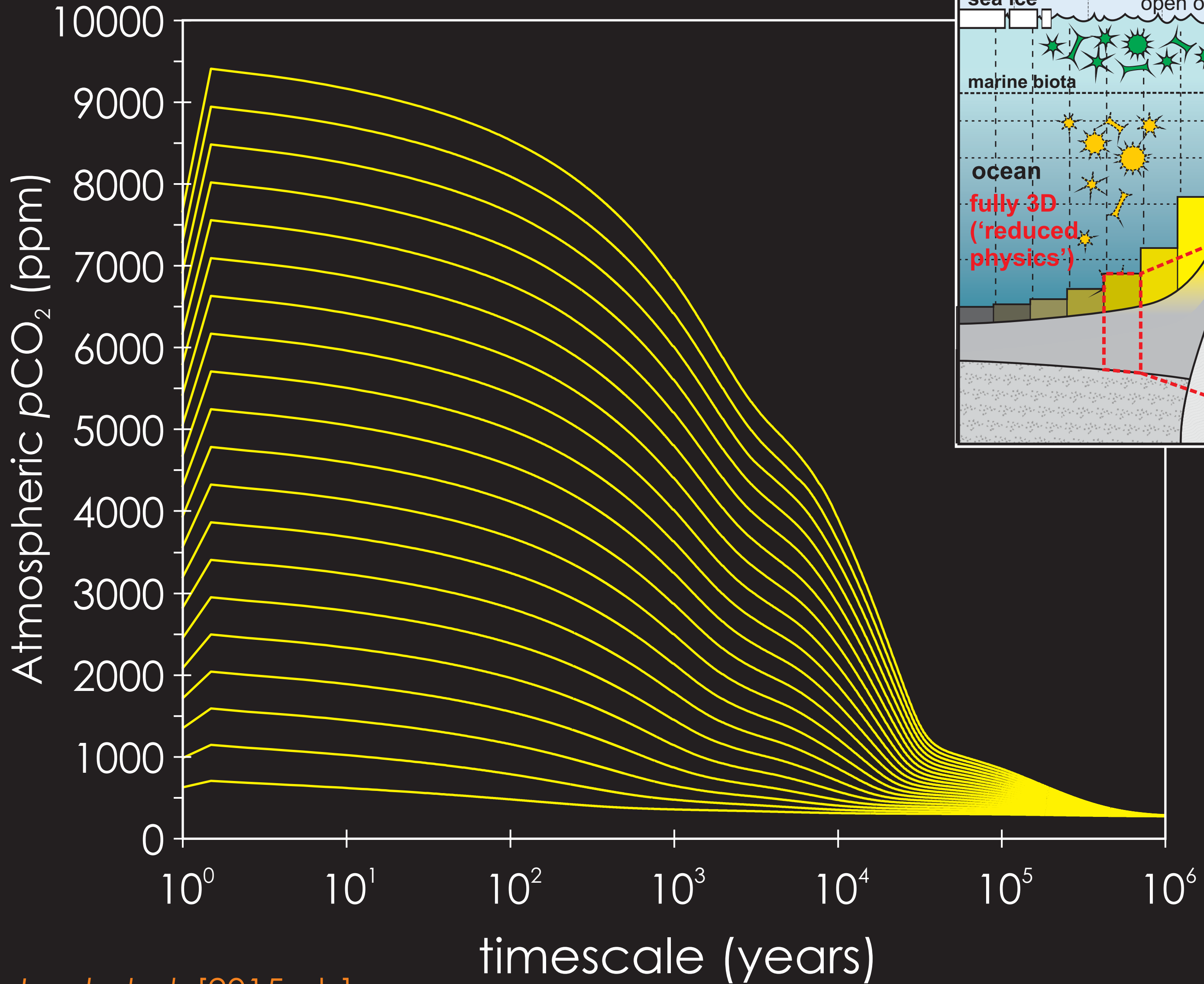
lies, damn lies, and computer models

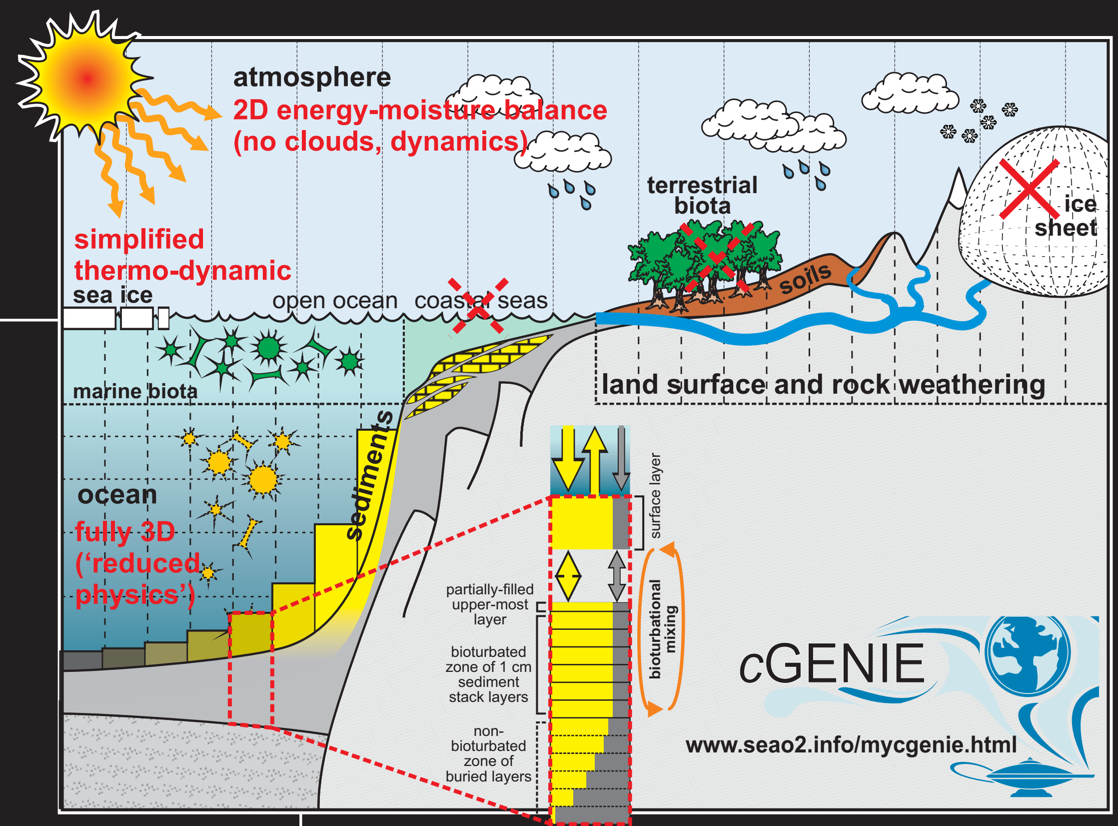
https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.USC2017



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

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





Lord et al. [2015a,b]

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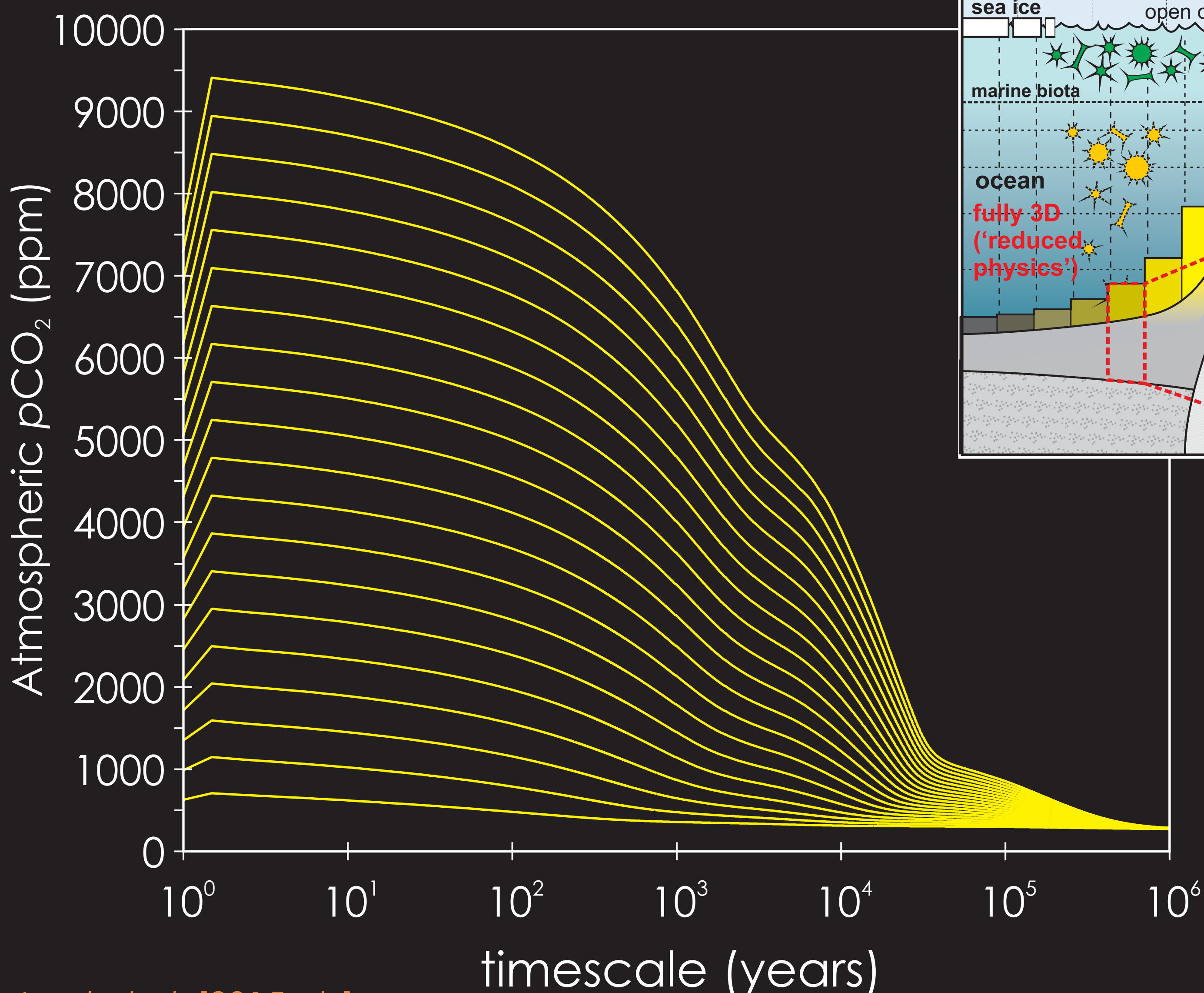
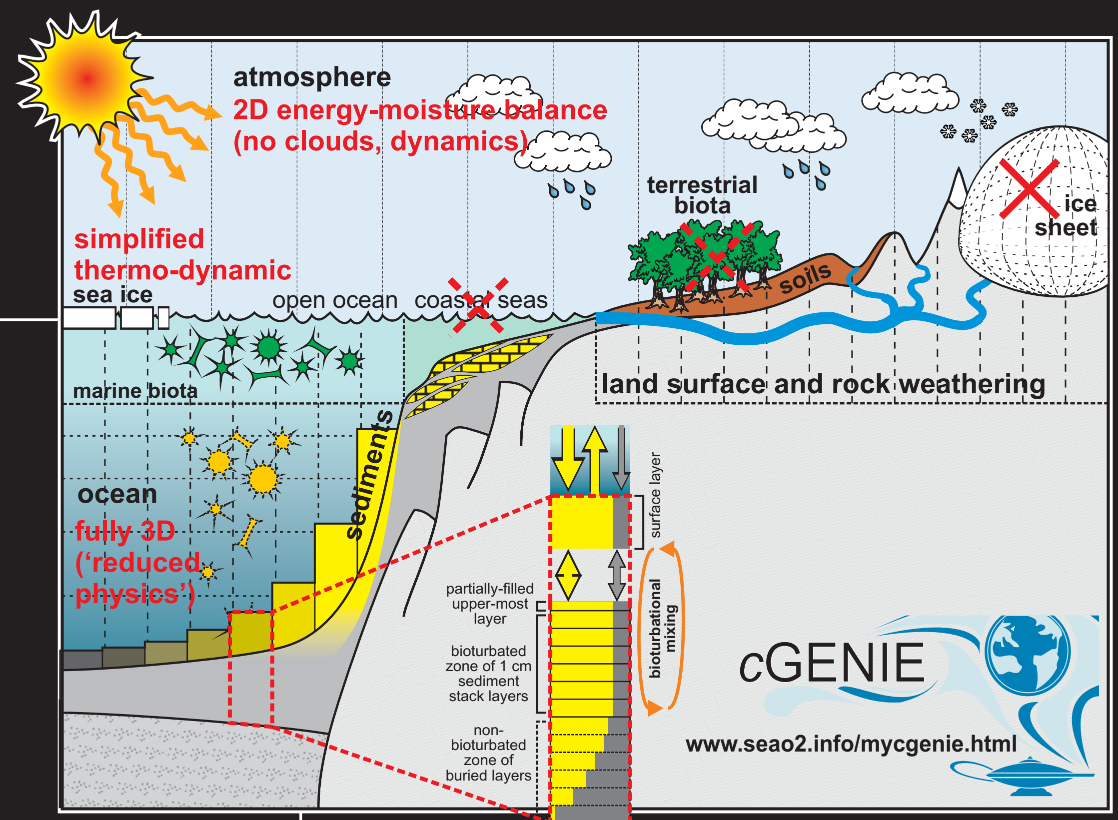




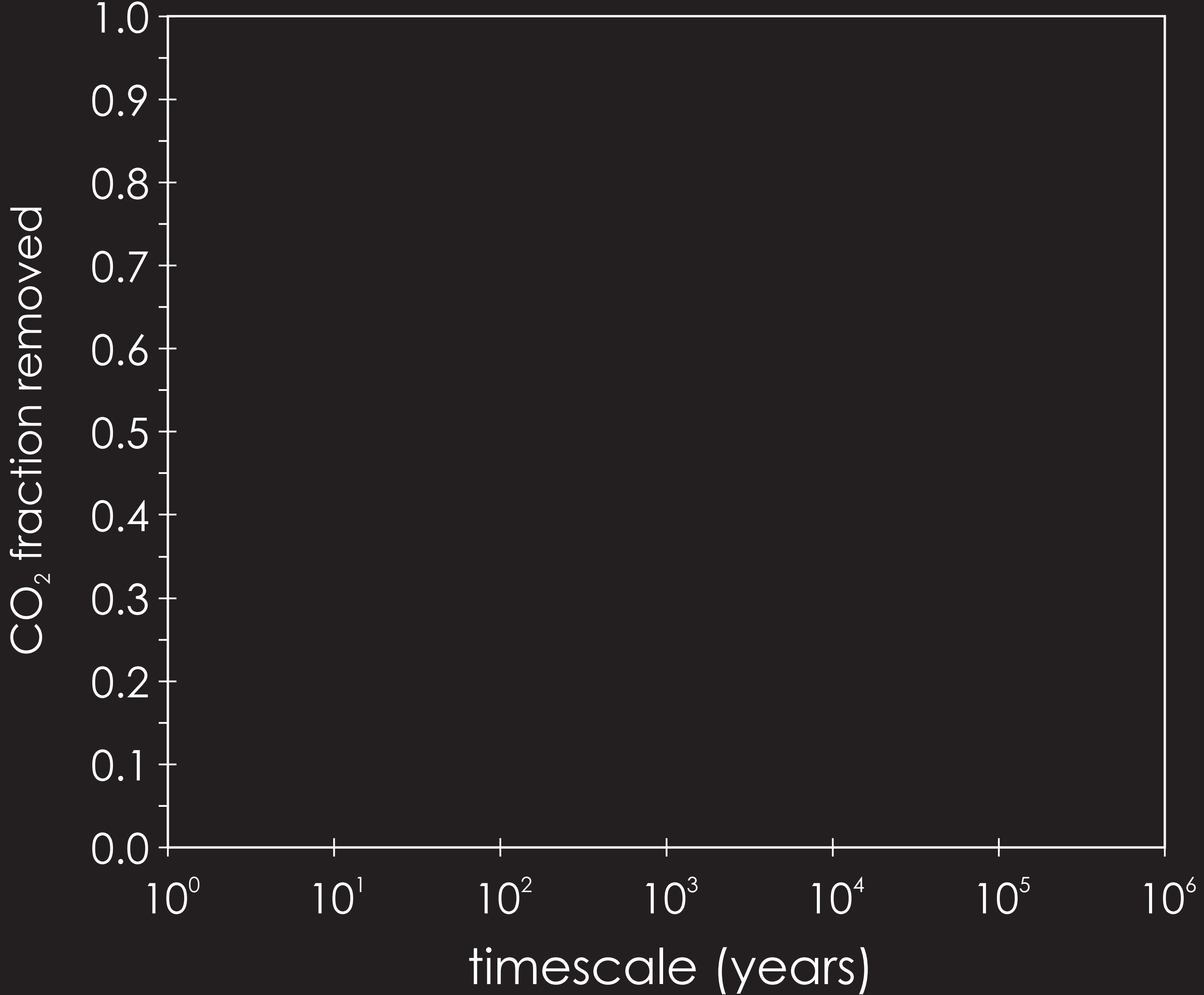
(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

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

Lord et al. [2015a,b]

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

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).



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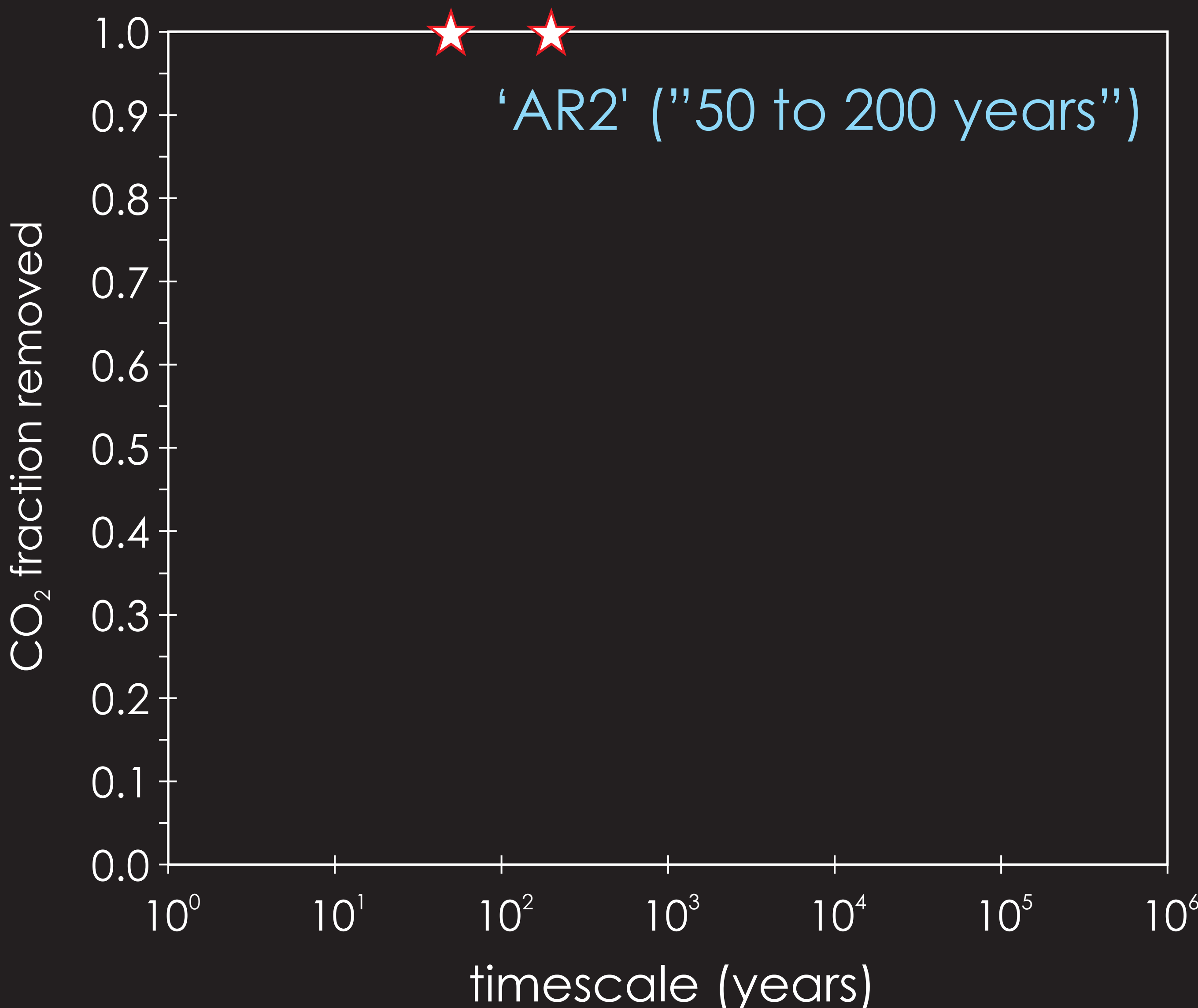

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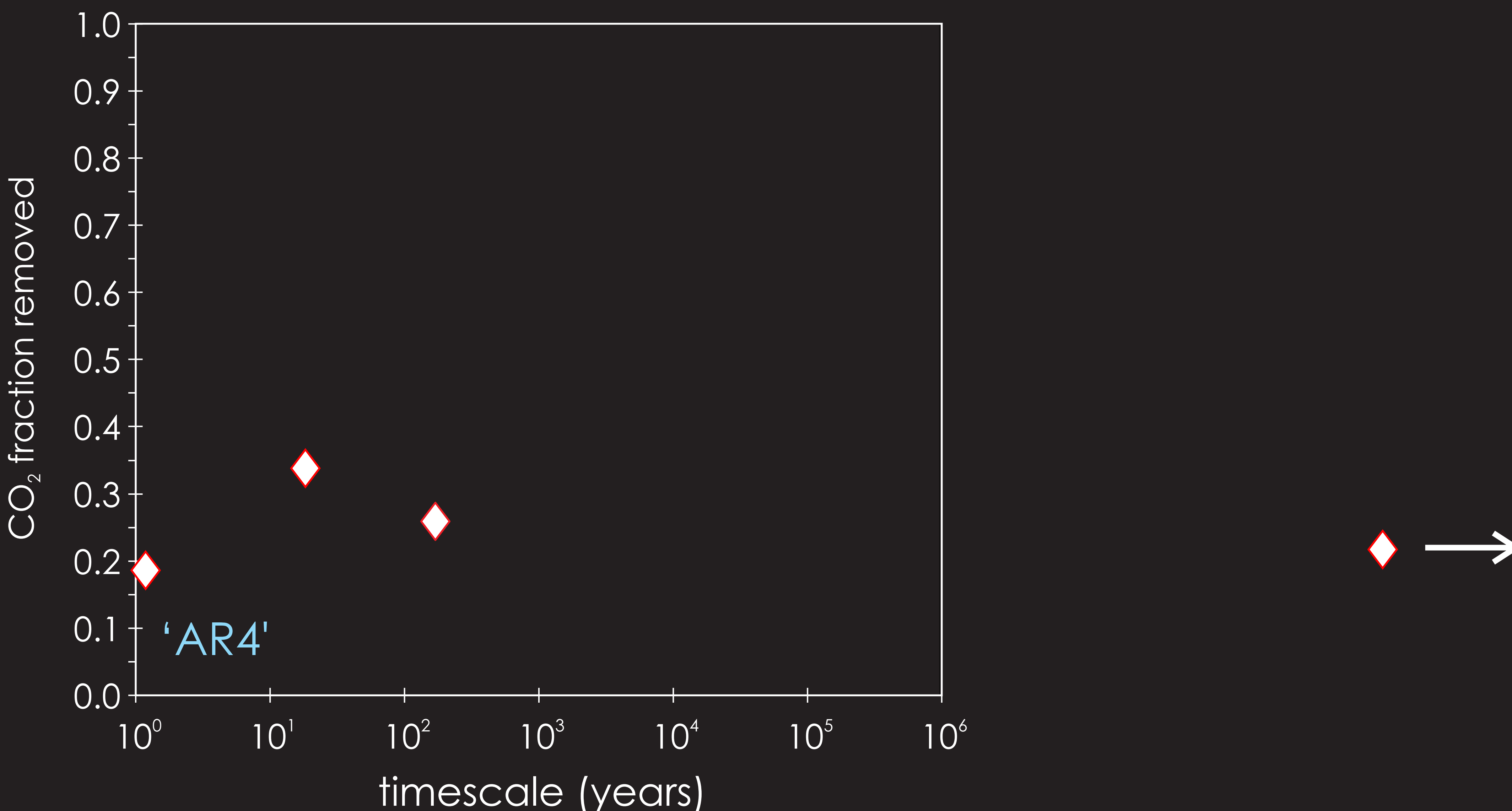
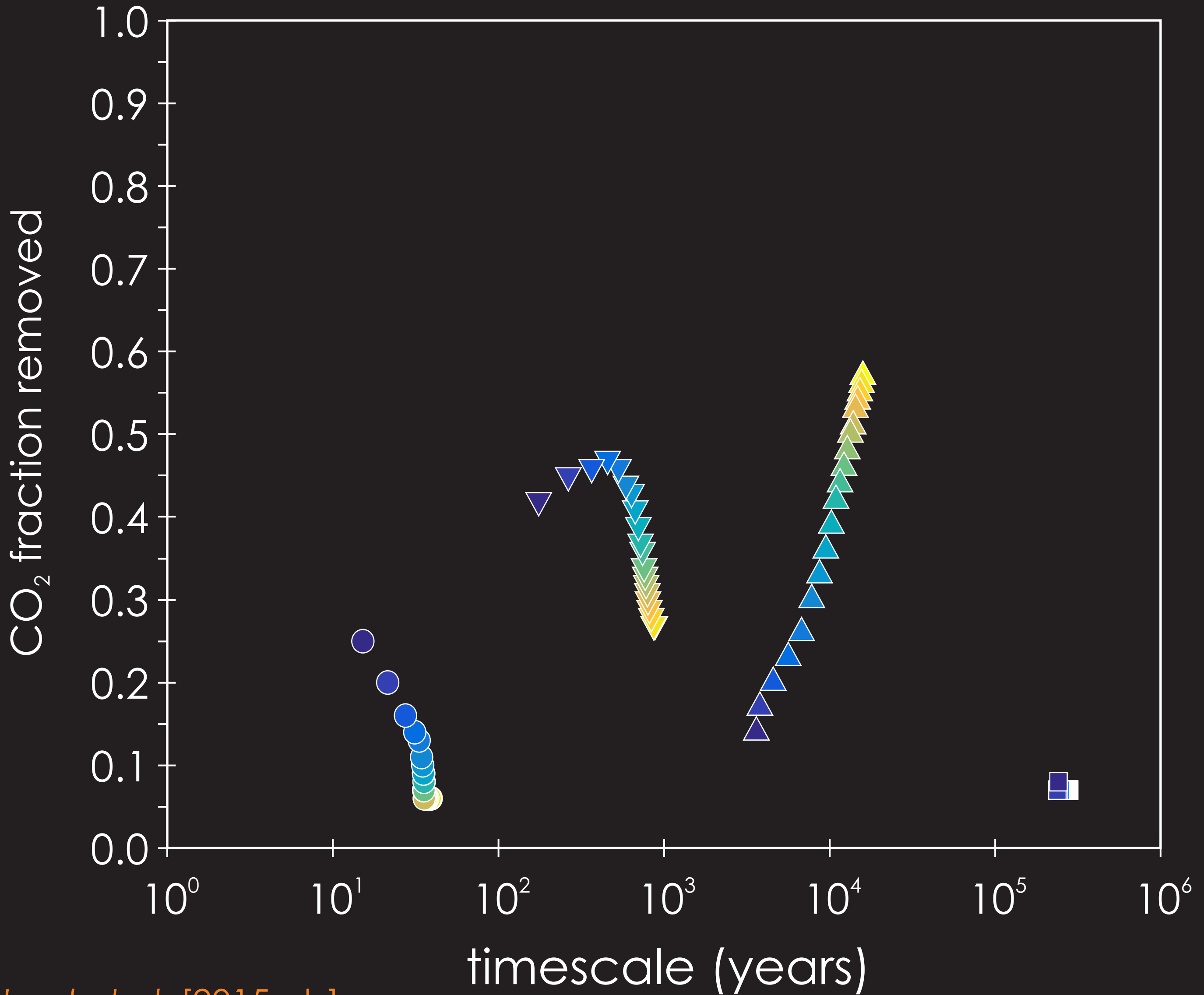


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

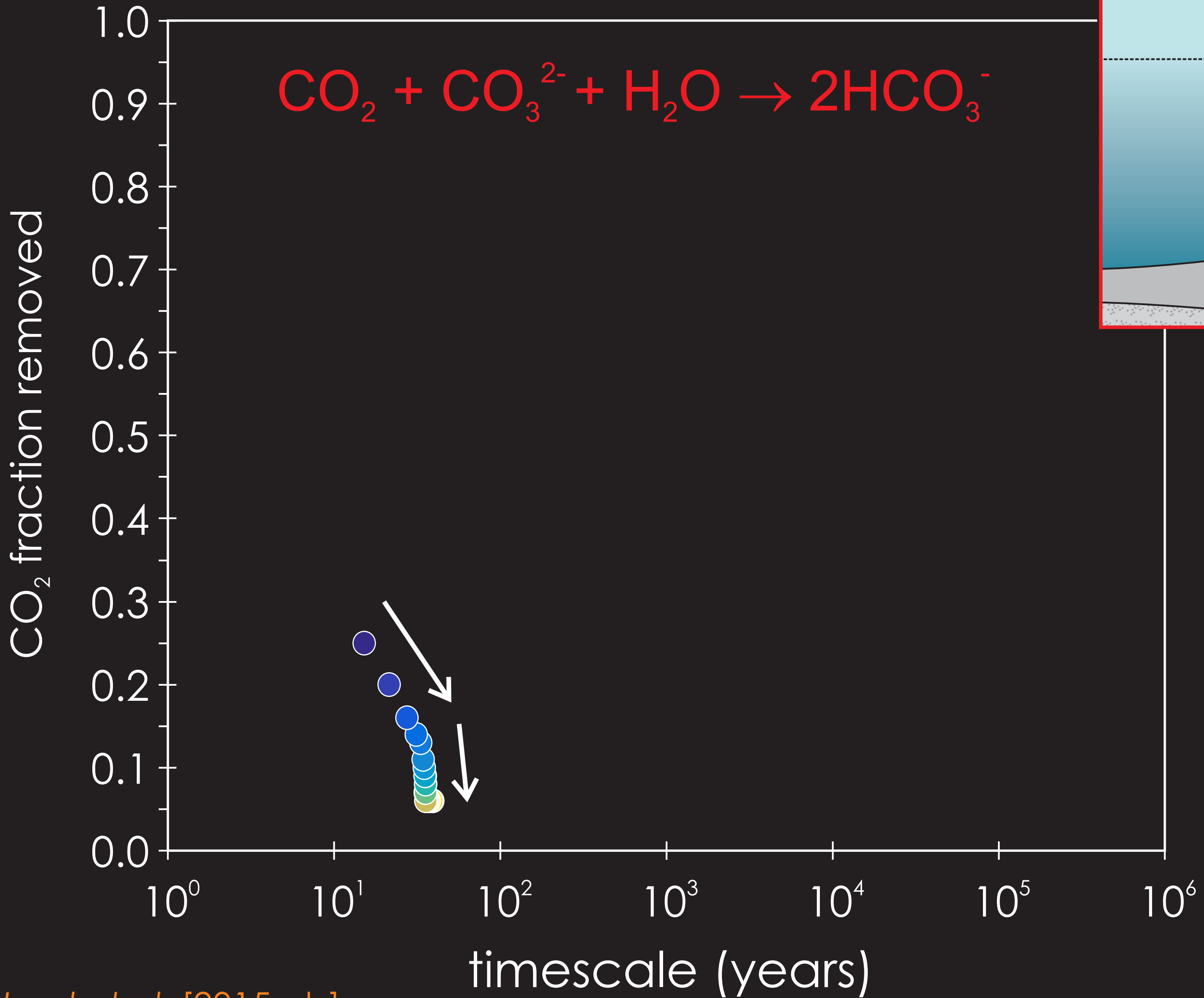
Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).

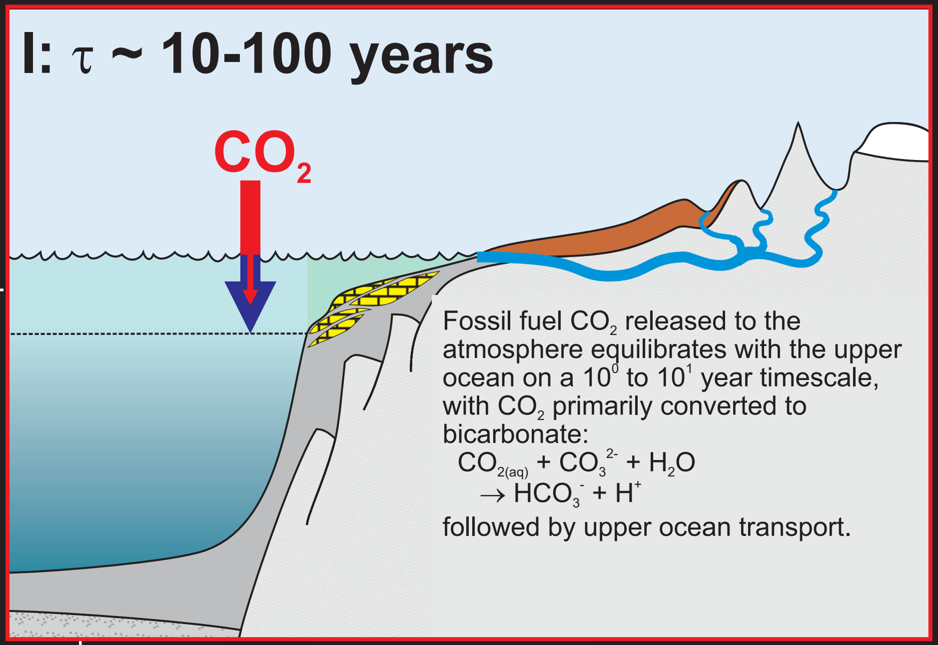


Lord et al. [2015a,b]

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

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

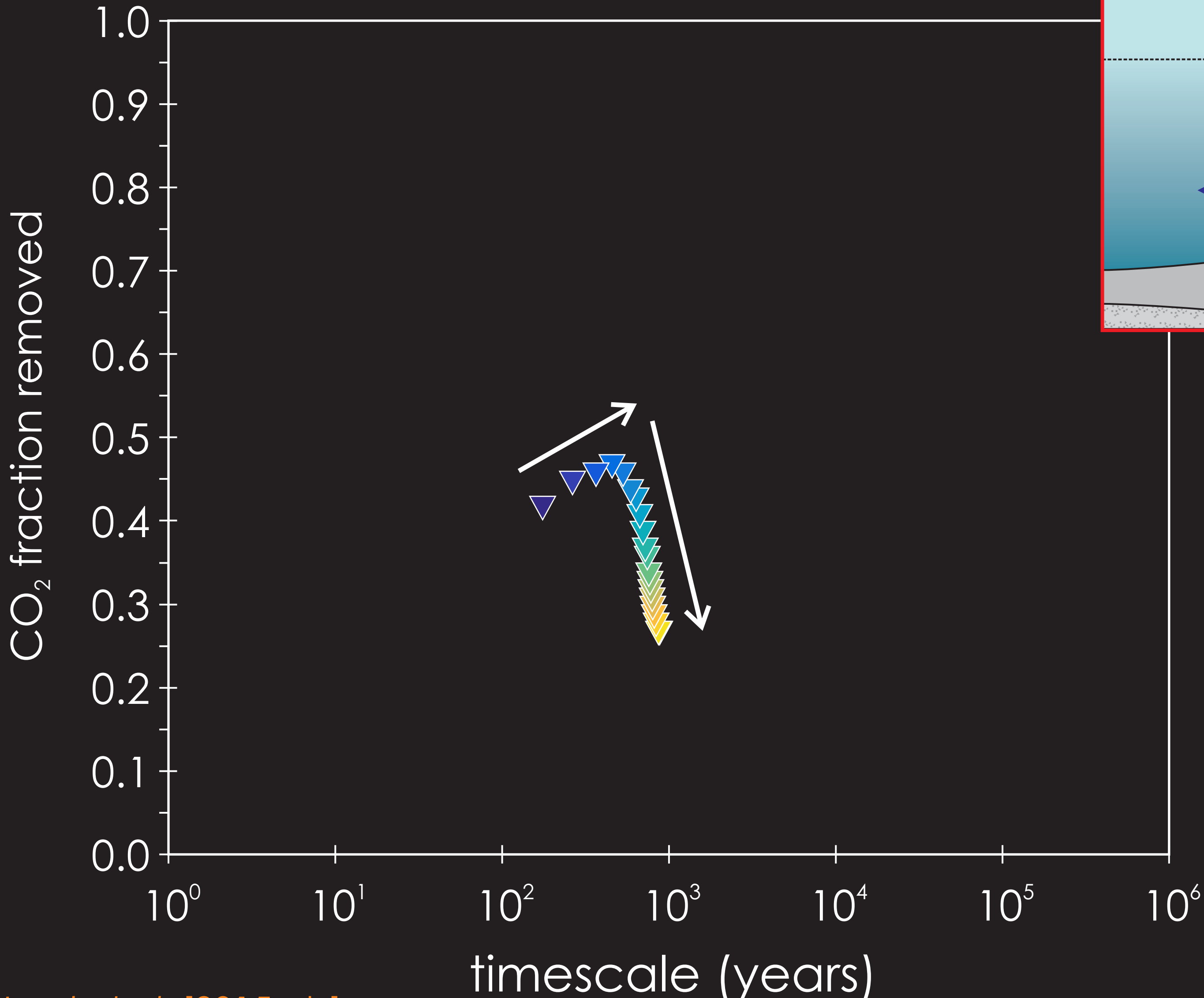


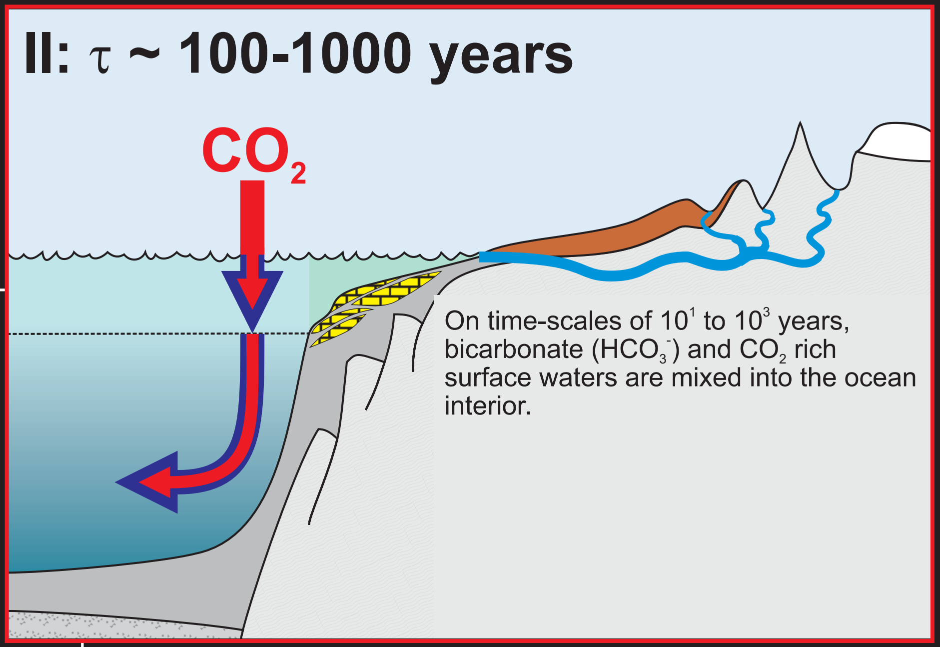


Lord et al. [2015a,b]

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

Ocean stratification and collapse of the AMOC (in this particular model). Threshold reached @ ~4000 PgC?

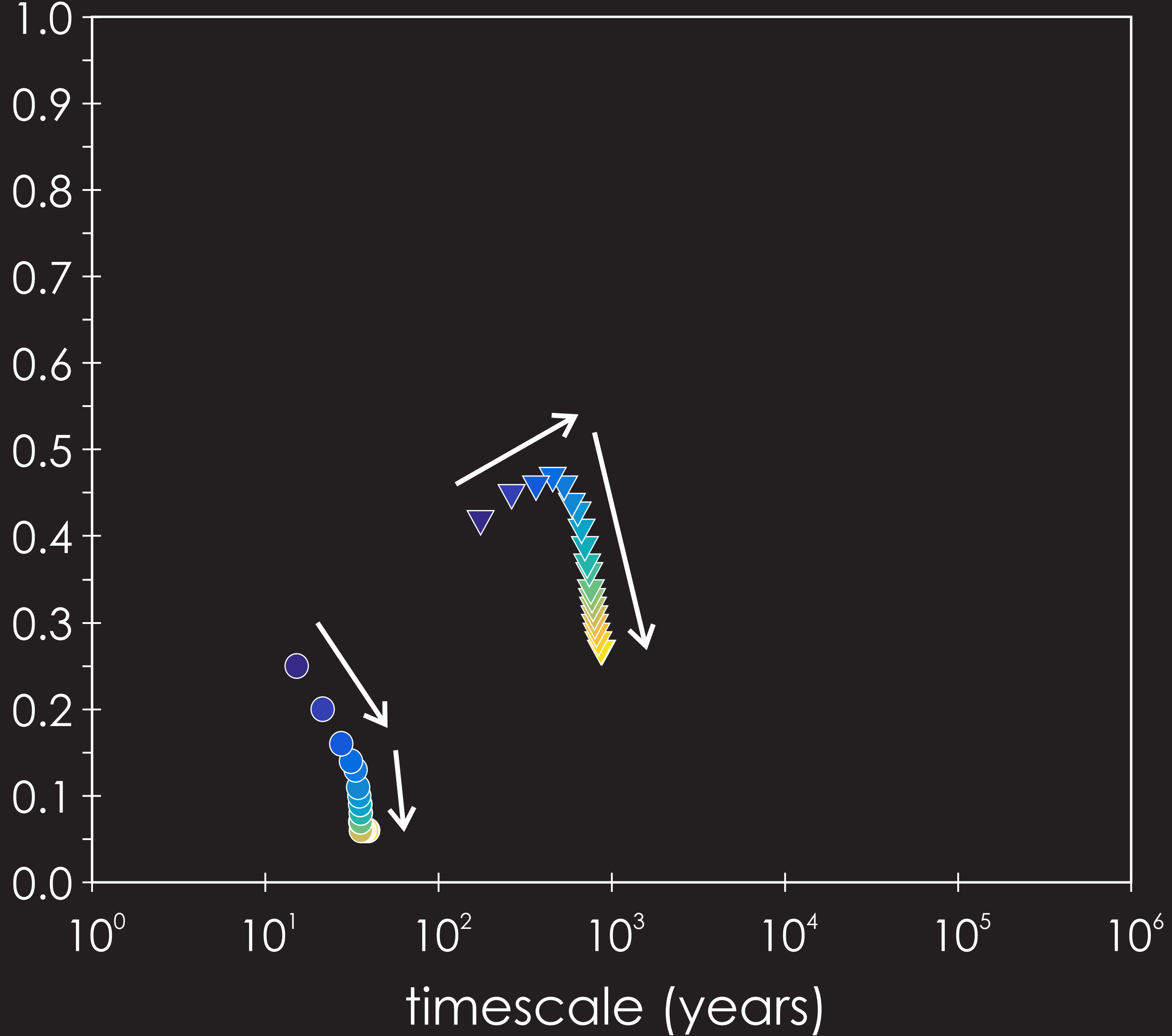




Lord et al. [2015a,b]

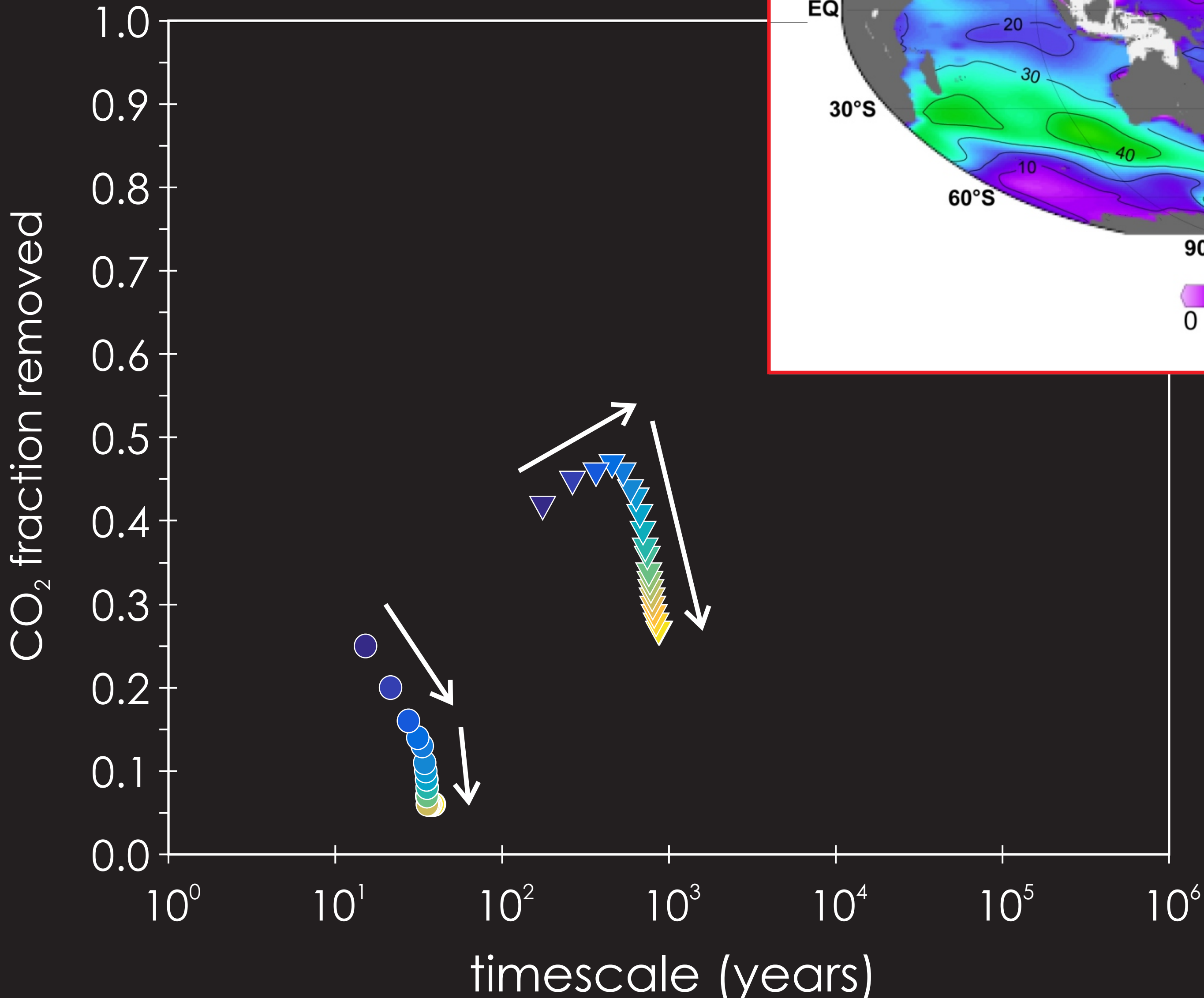
Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

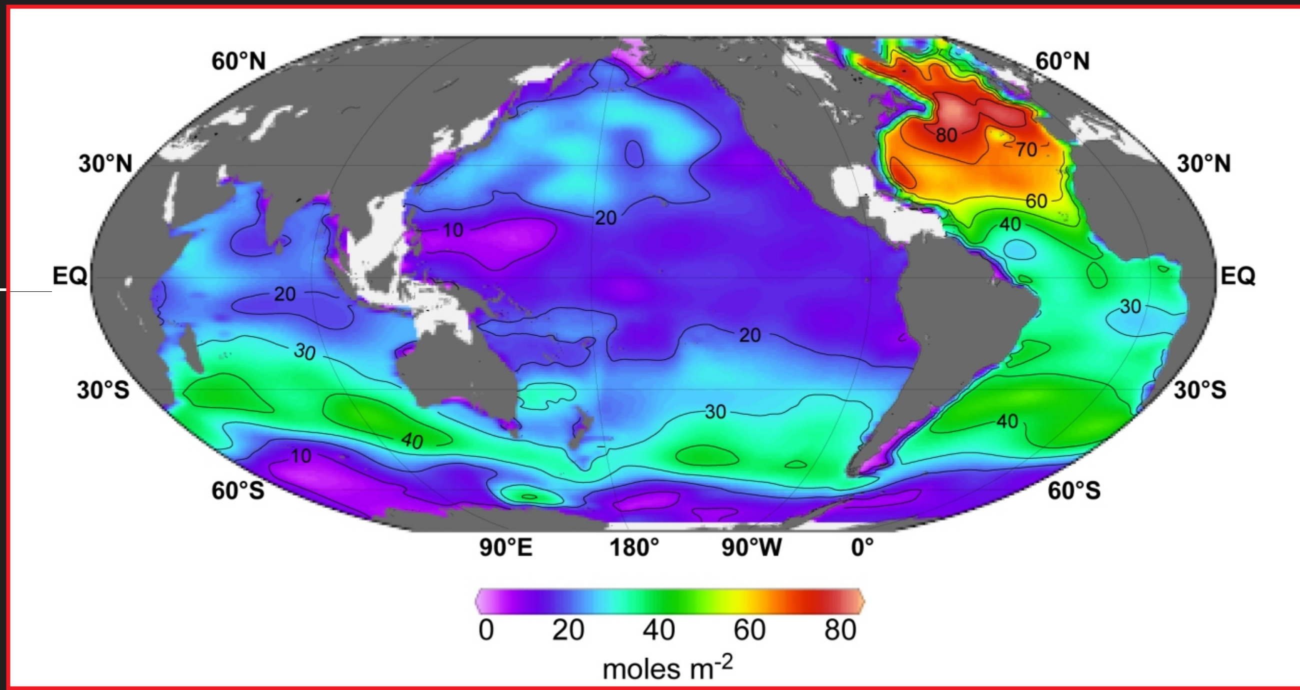
evidence?



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

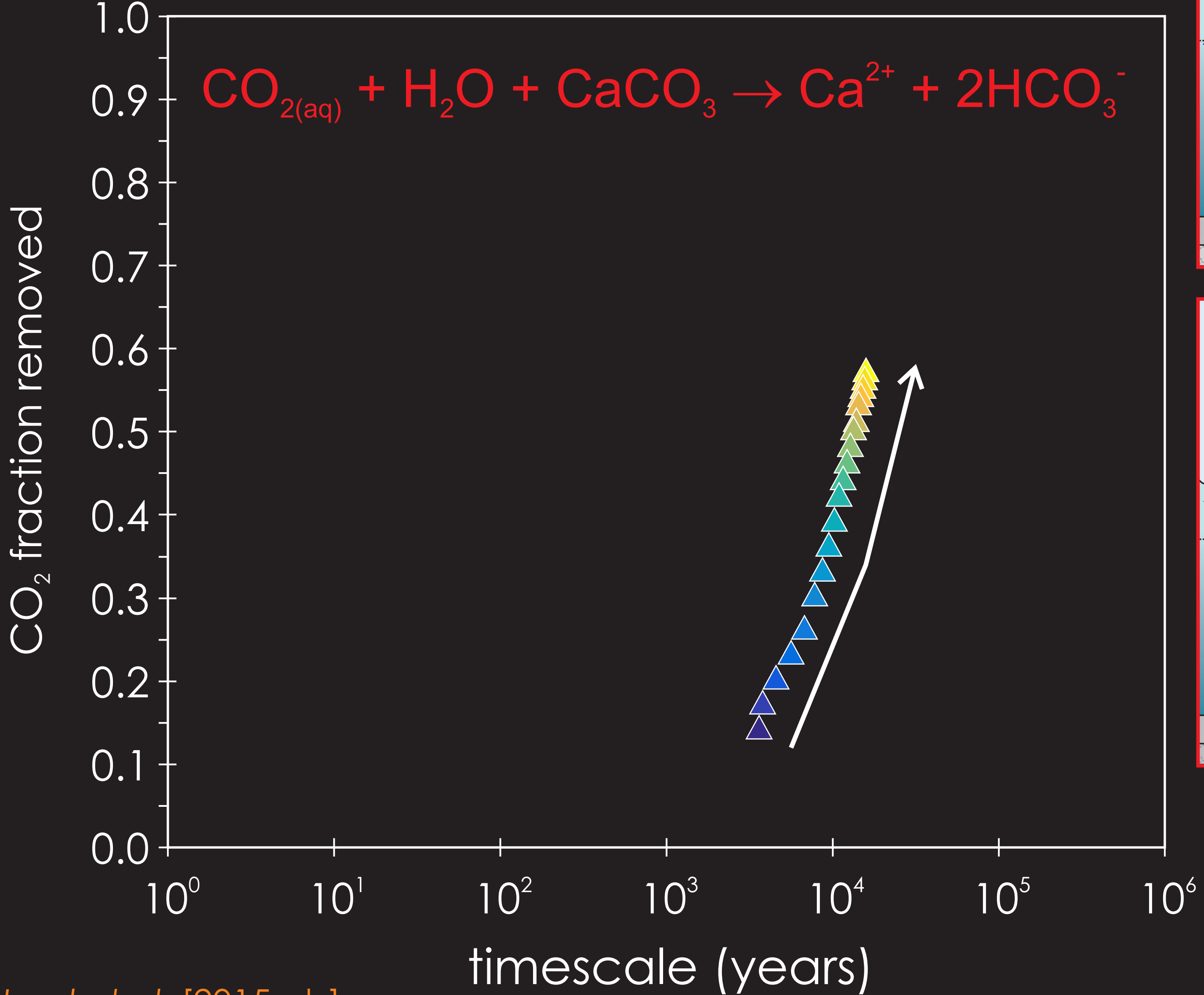
evidence?

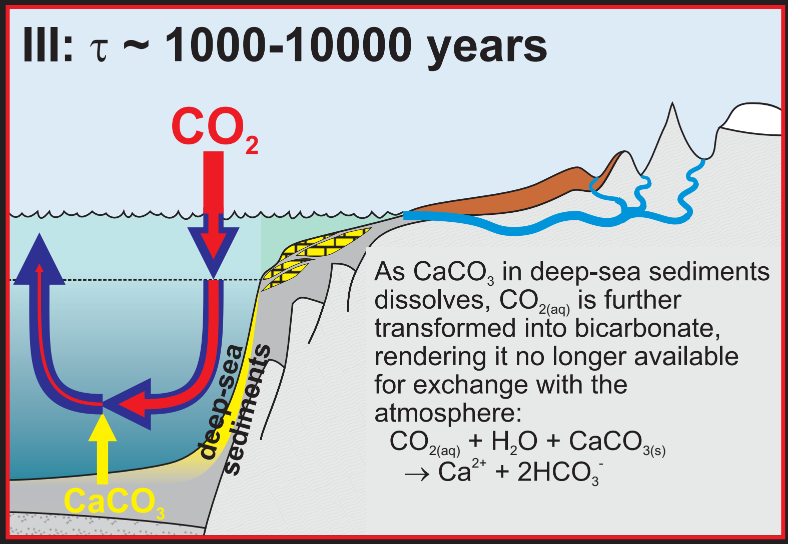


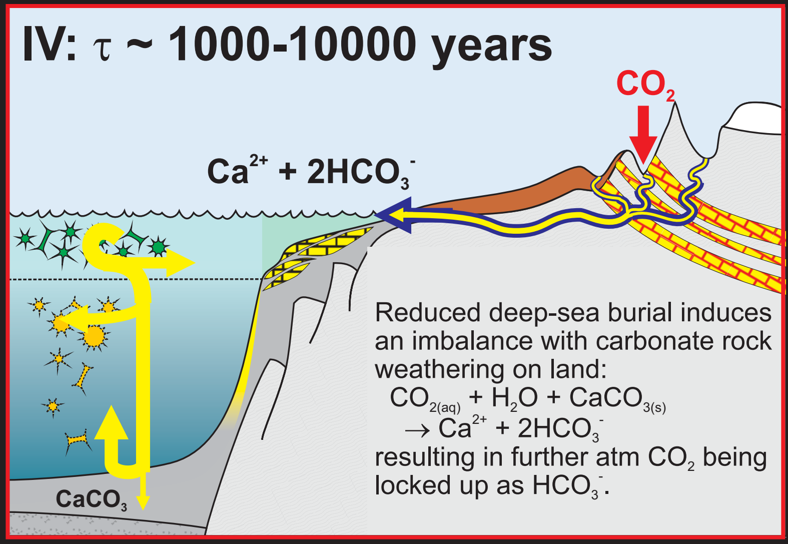


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

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



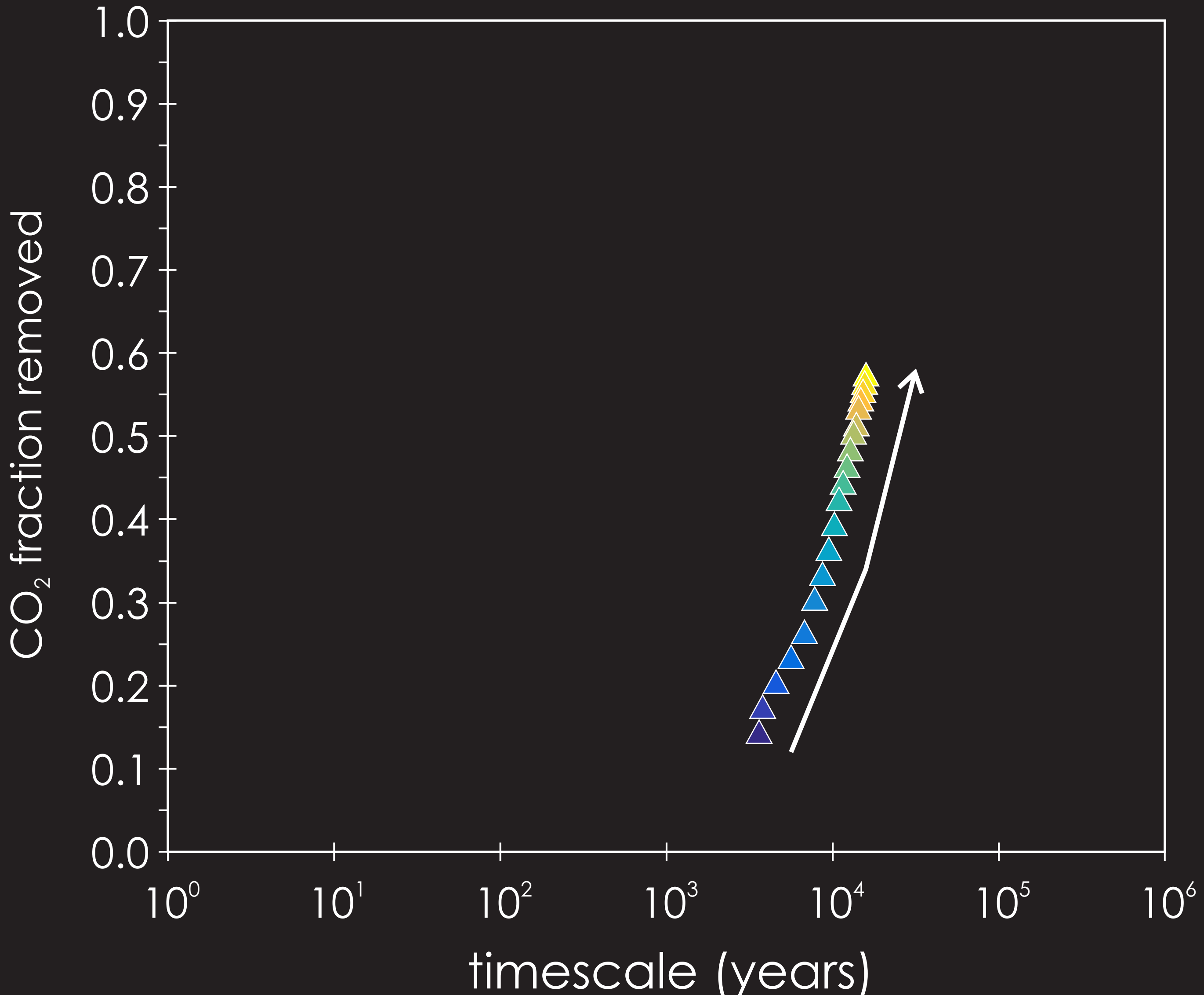




Lord et al. [2015a,b]

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

evidence?



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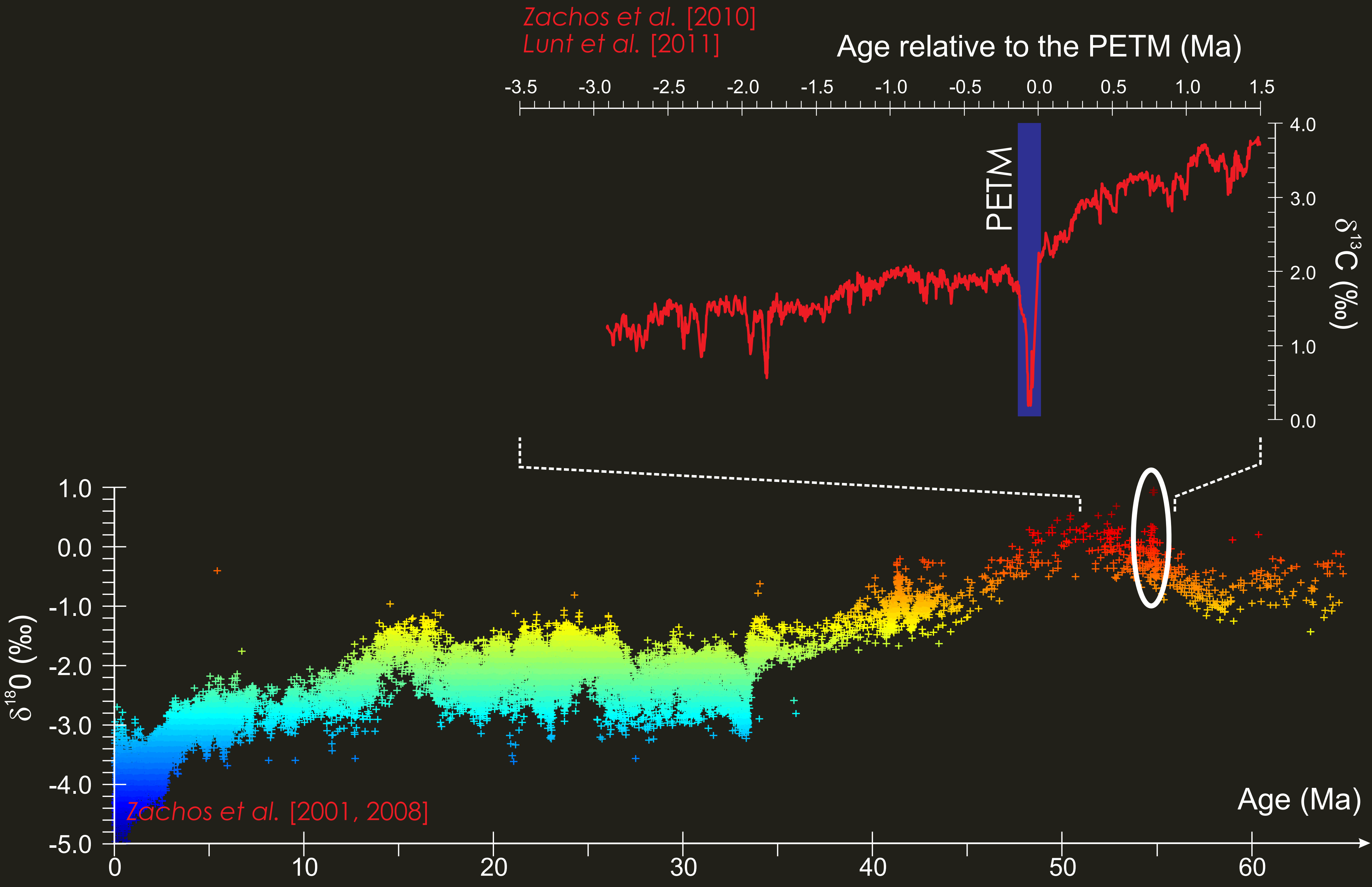

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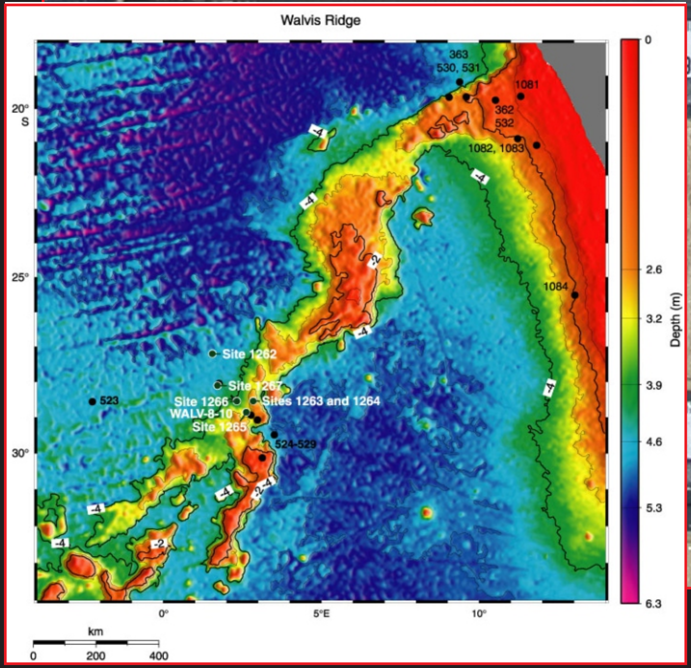
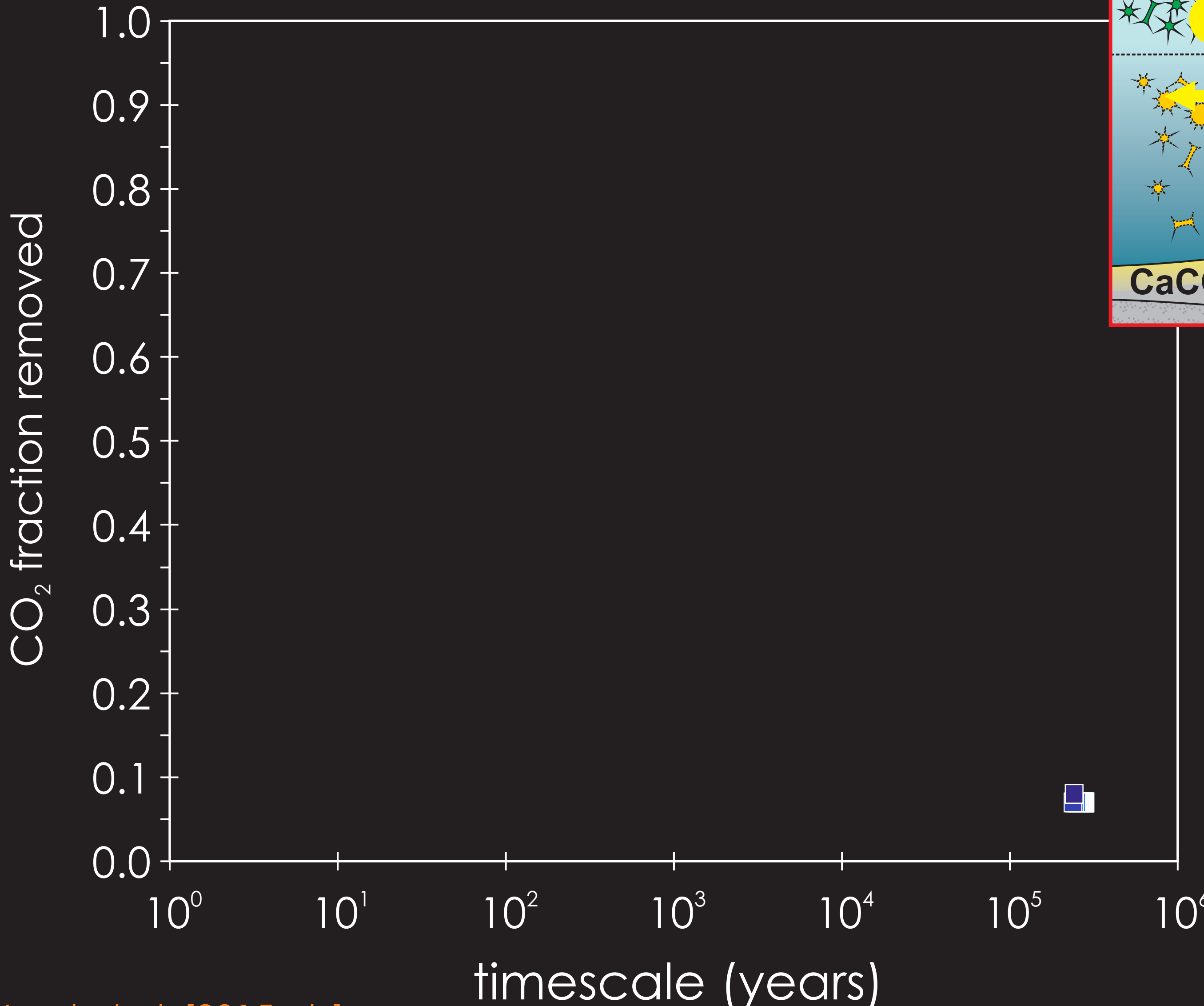
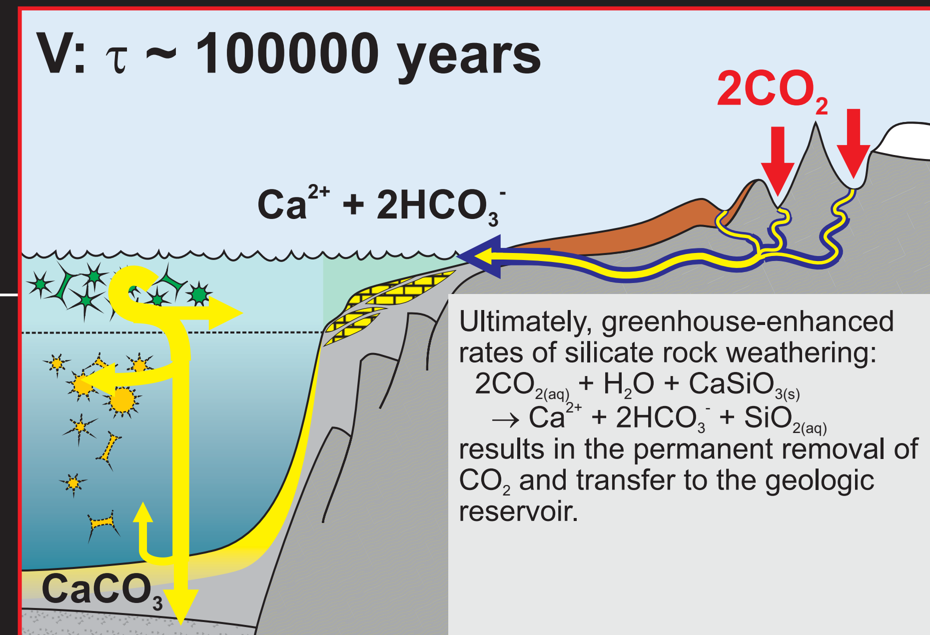


Sediments spanning the Palaeocene-Eocene boundary from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Dani Schmidt (University of Bristol)

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

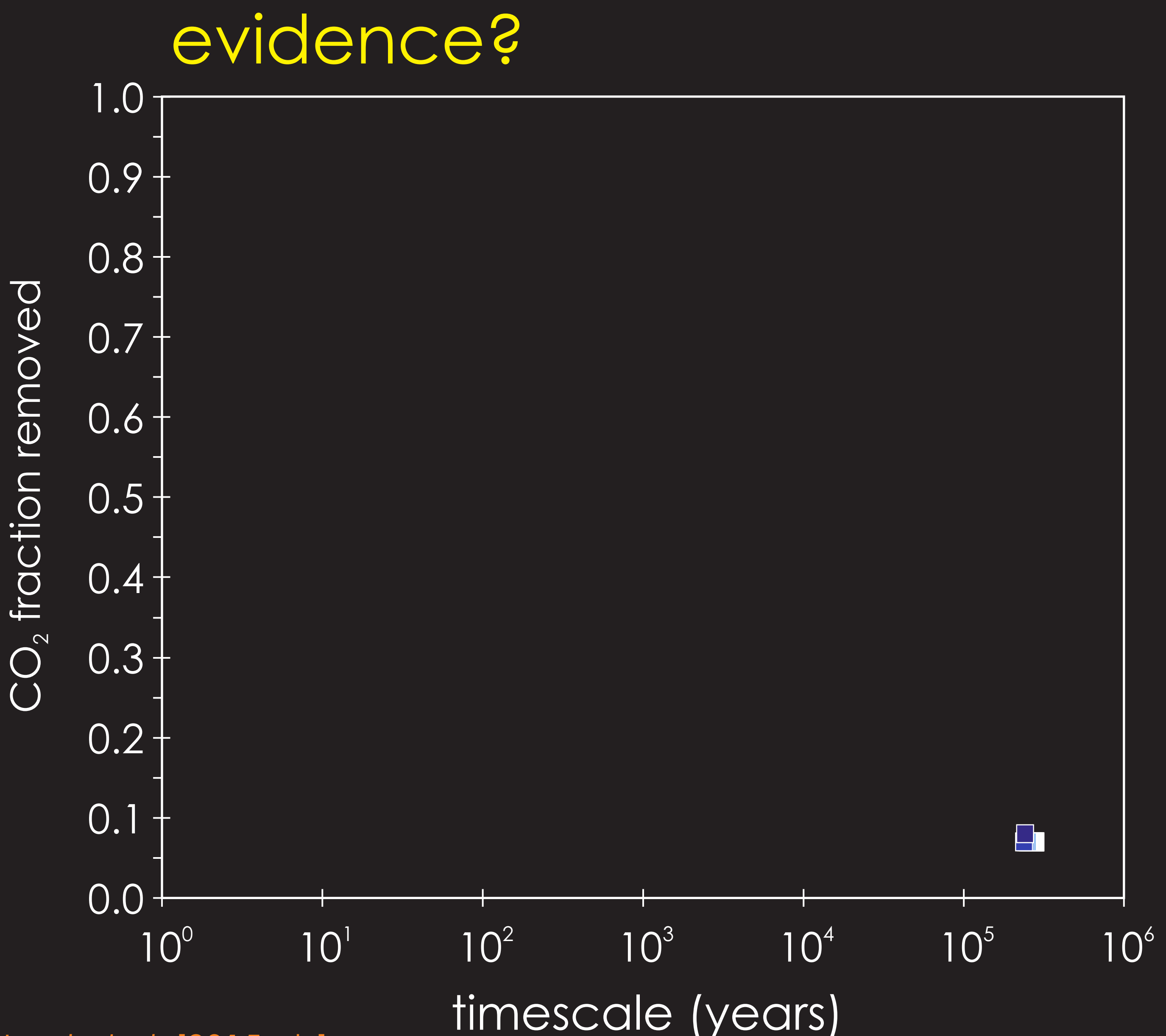
Silicate weathering (no time-scale response!).





Lord et al. [2015a,b]

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



Lord et al. [2015a,b]

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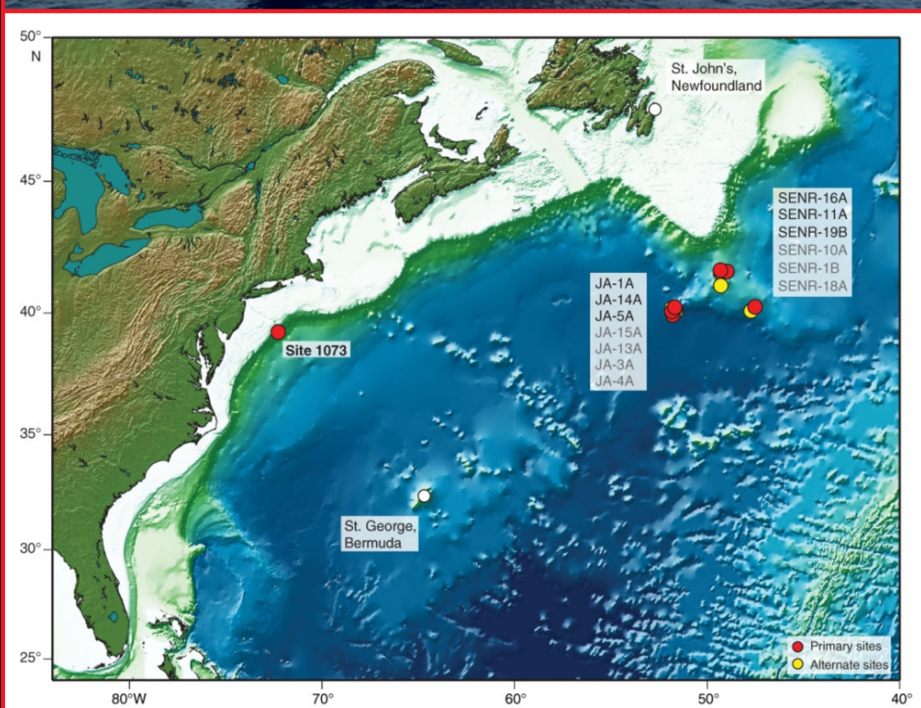
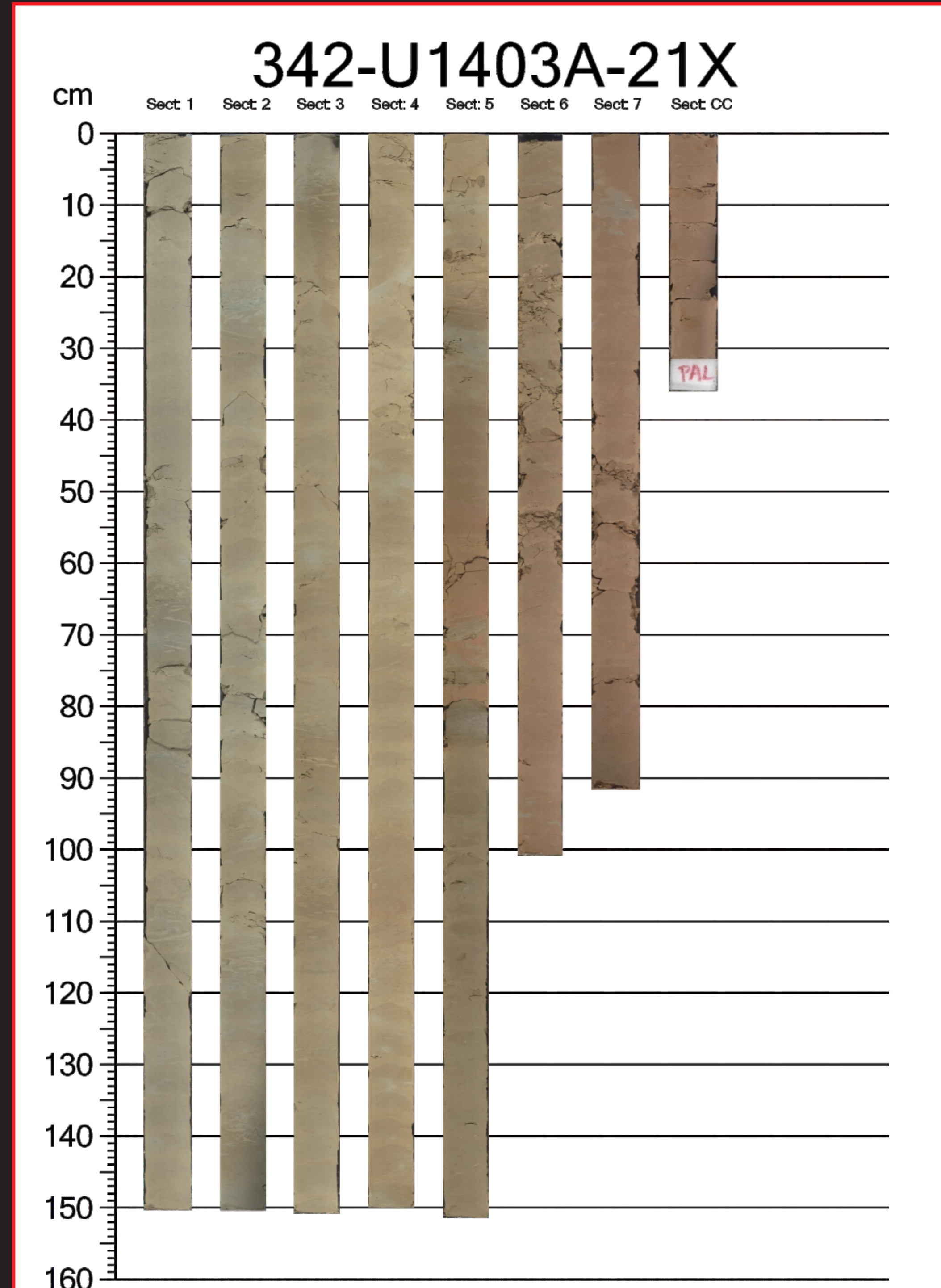
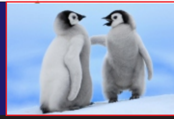
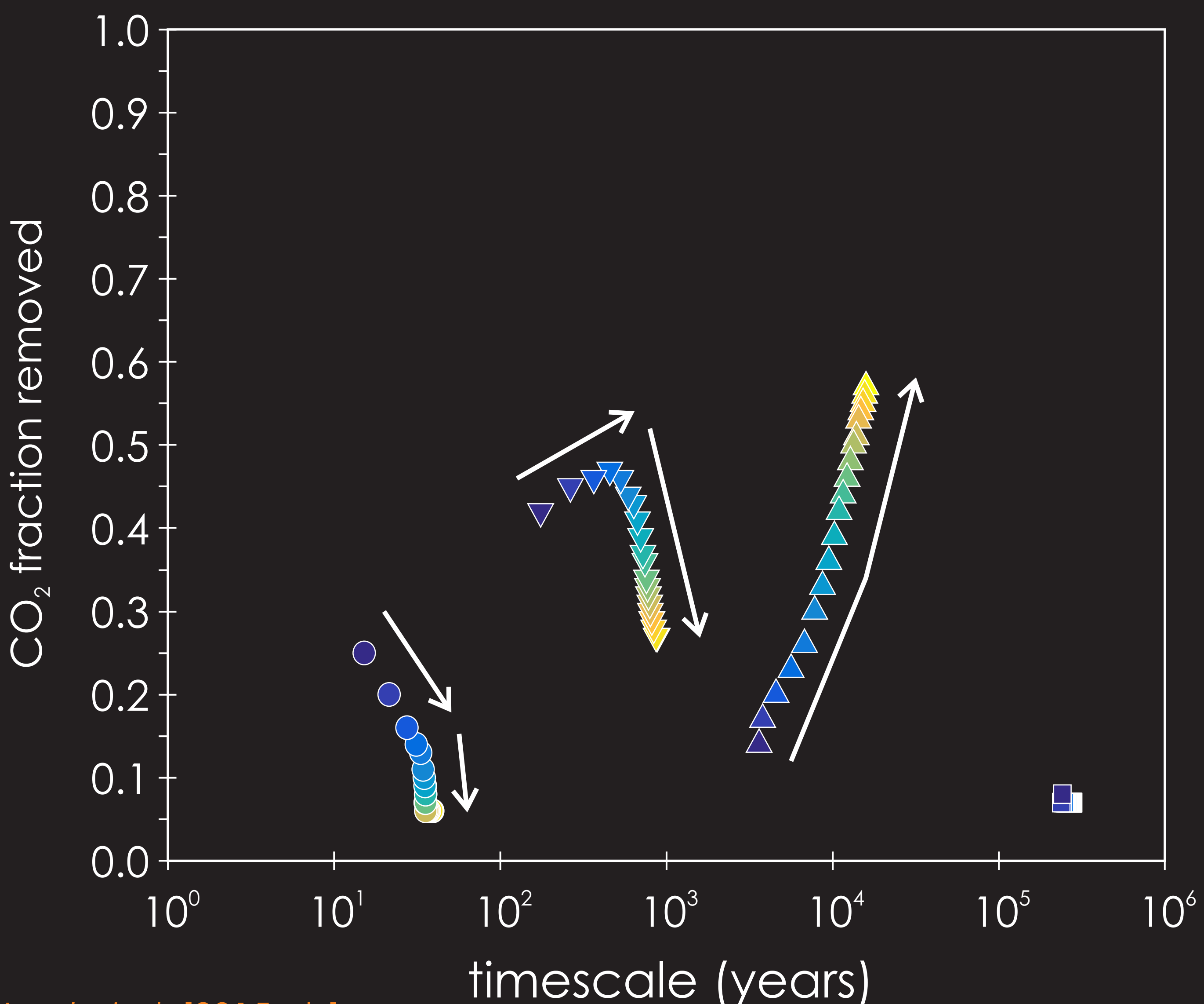




An impulse response function for the 'long tail' of $CO_{2(excess)}$ – IMPLICATIONS





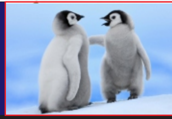
With increasing total CO_2 emissions, the response time of all sinks (bar silicate weathering) lengthen, and the shorter time-scale two weaken at the expense of the ~10,000 year $CaCO_3$ burial process.

Elevated atmospheric pCO_2 hence becomes more persistent as the main short-term CO_2 feedbacks weaken.

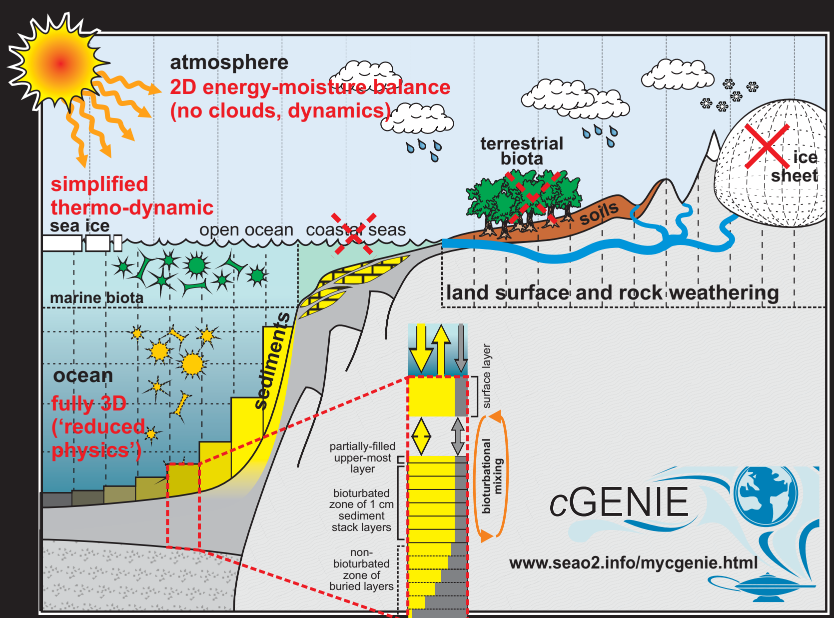
The majority of carbon removal beyond ~10,000 PgC emitted, is removed only on time-scales exceeding 10,000 years.

Lord et al. [2015a,b]

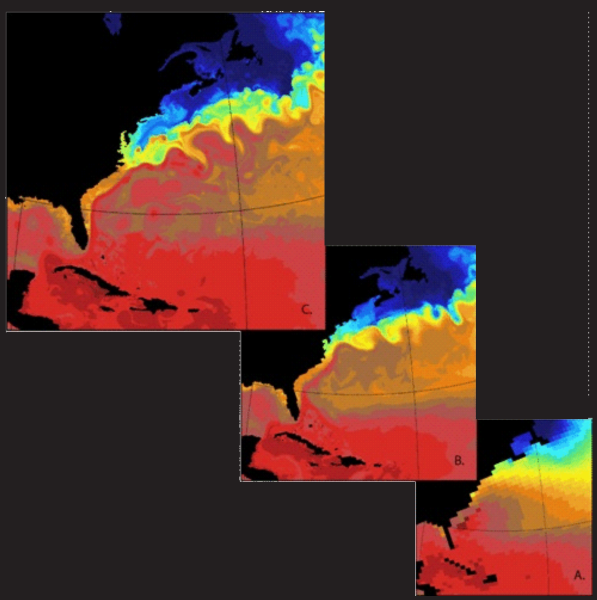
Melting Antarctica



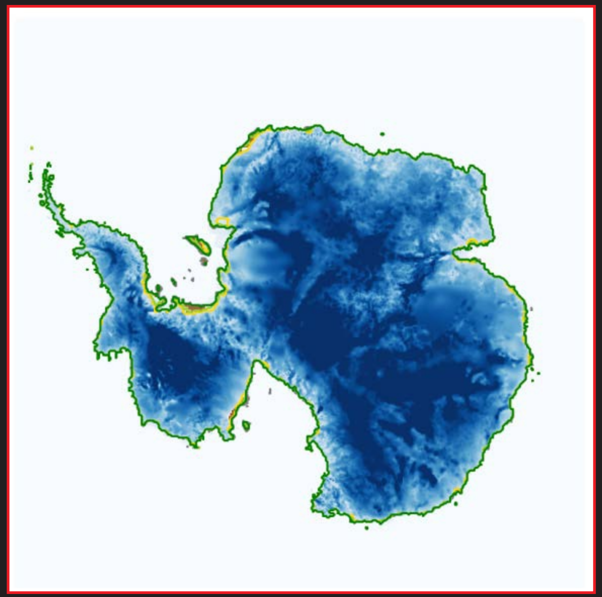
Melting Antarctica



Earth system model
(CO_2 and mean SST trajectories)



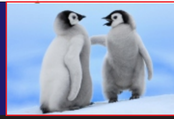
Downscaling
(SO SST and regional climate)

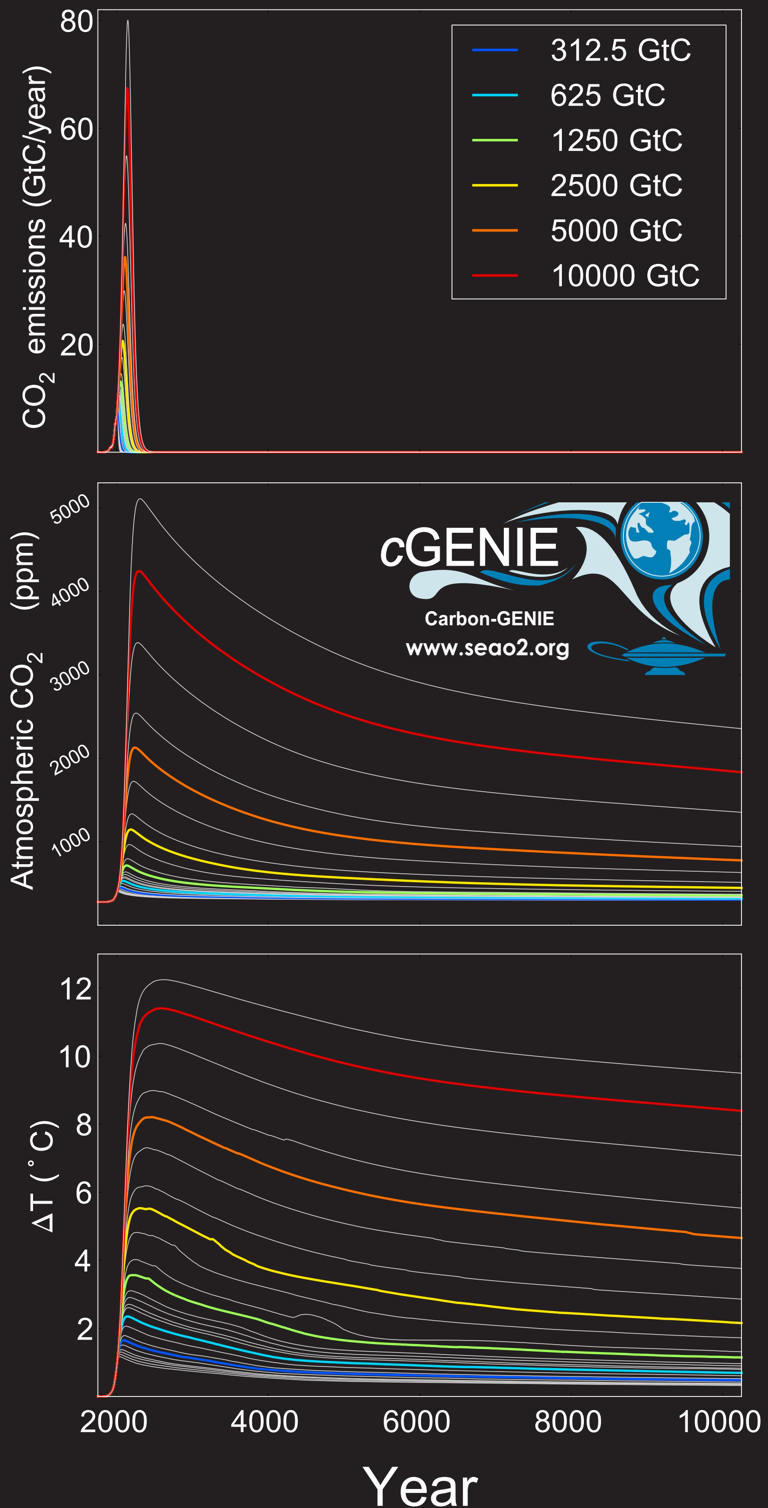


Ice sheet model

Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica





Winkelmann et al. [2015] (*Science Advances*)

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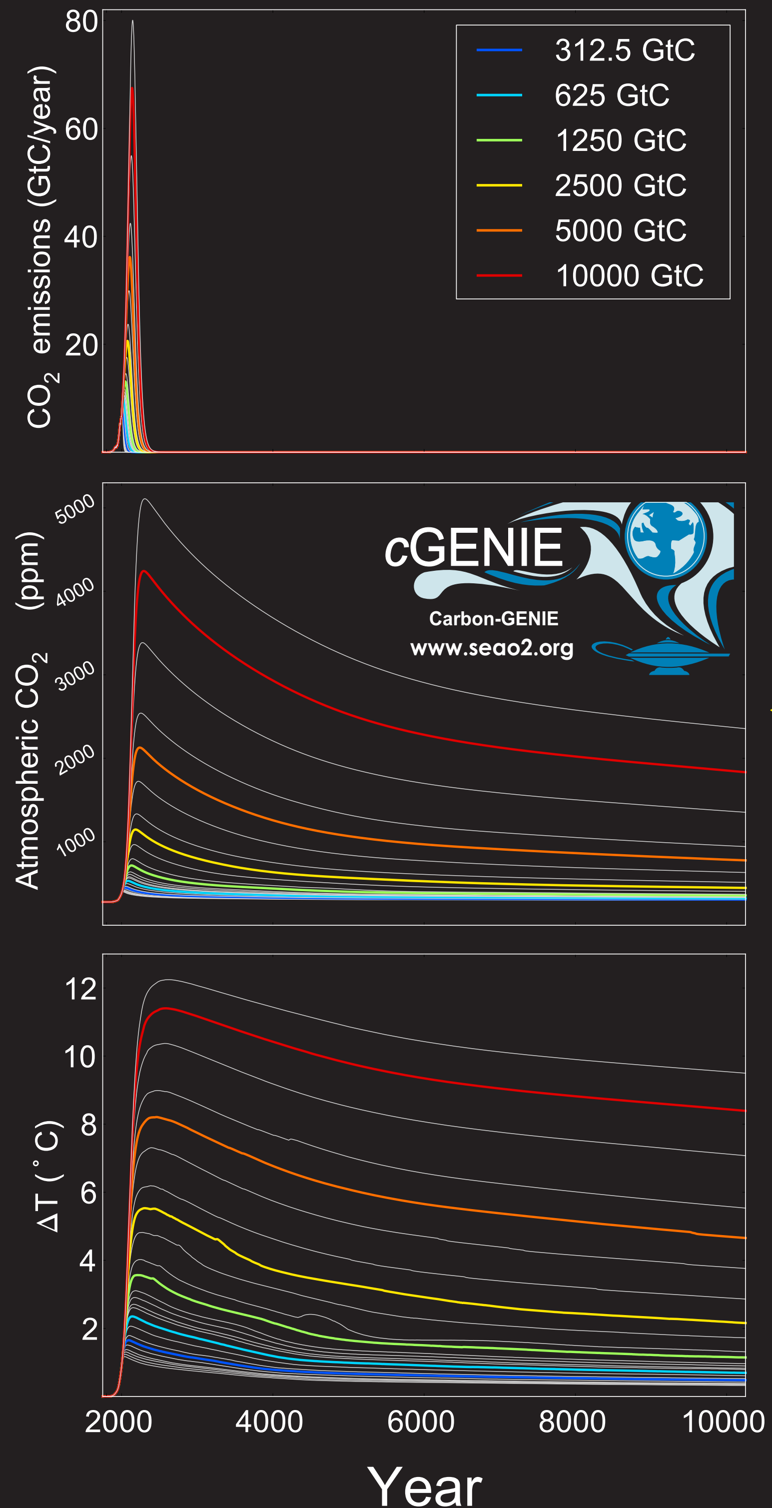
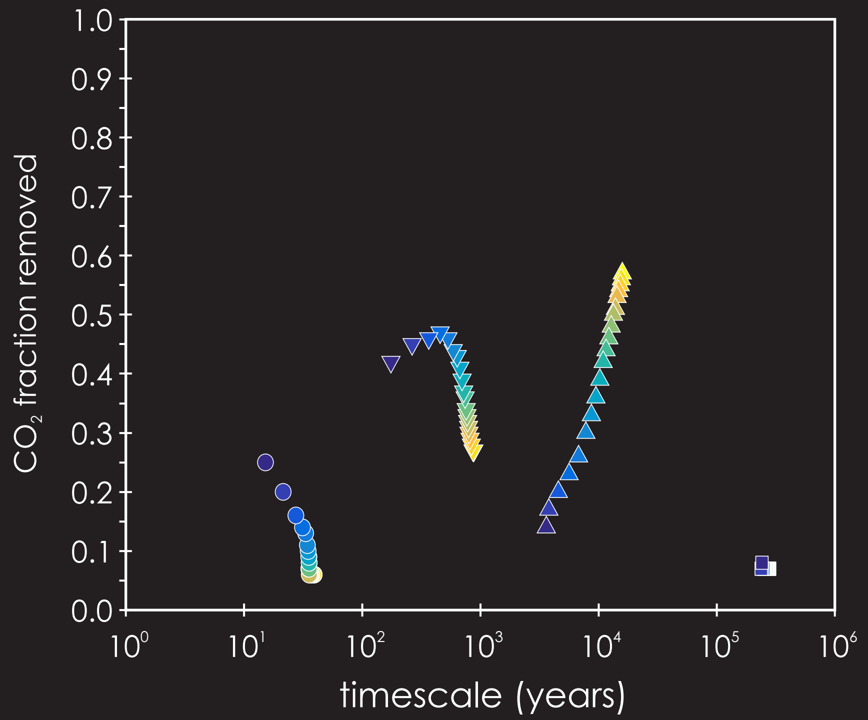
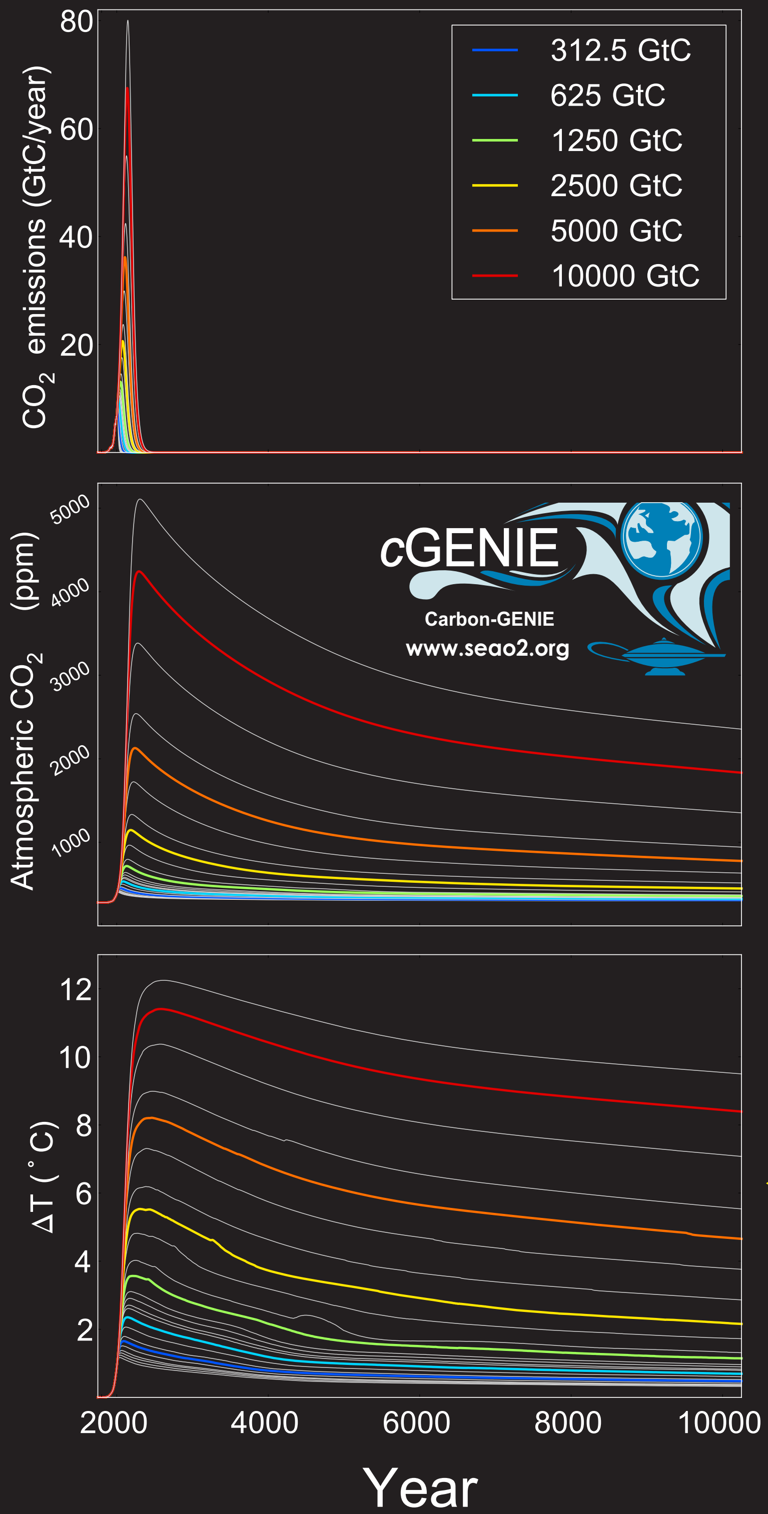




Winkelmann et al. [2015] (*Science Advances*)

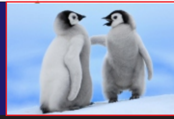
Melting Antarctica

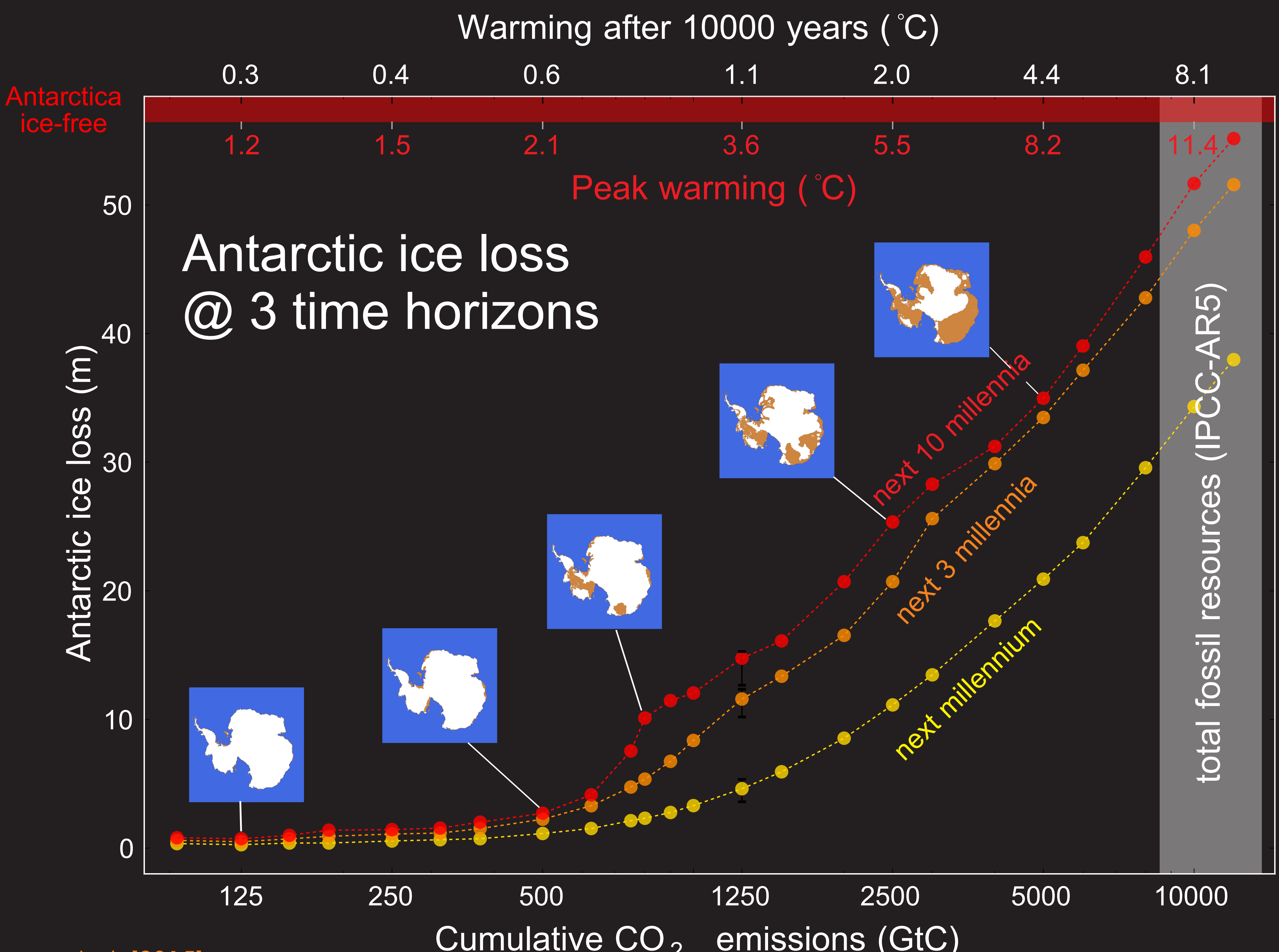


$$\Delta F \propto \ln(C/C_o)$$

Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica





Winkelmann et al. [2015]

Enhanced weathering (CO_2 removal geoengineering)

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Enhanced weathering (CO_2 removal geoengineering)

granite »

SiO_2 = 72%

...

CaO = 1.8%

...

MgO = 0.7%

...

basalt »

SiO_2 = 50%

...

CaO = 10%

...

MgO = 10%

...

Enhanced weathering (CO_2 removal geoengineering)

~ olivine + pyroxene

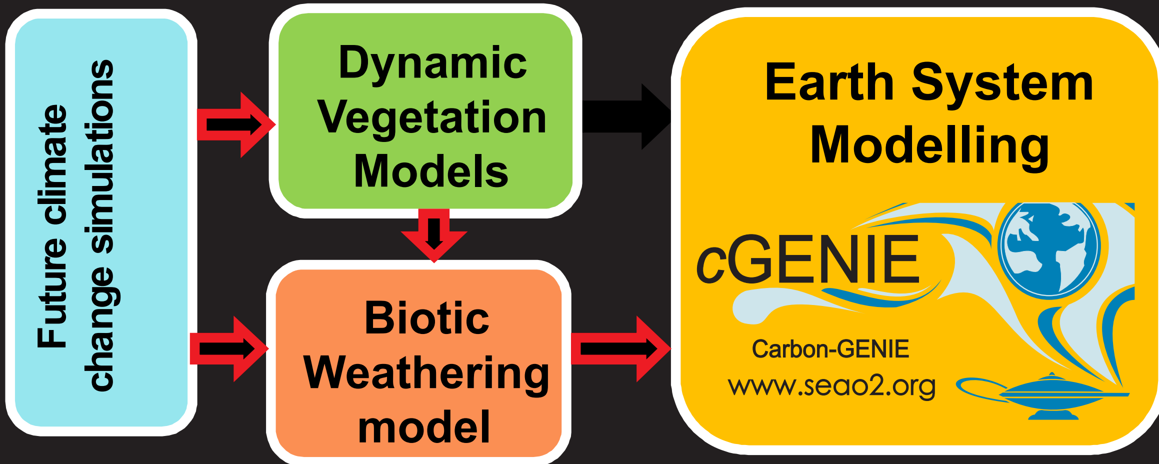
Harzburgite

~ plagioclase + pyroxene (+olivine)

>90% olivine: $(Mg^{+2}, Fe^{+2})2SiO_4$

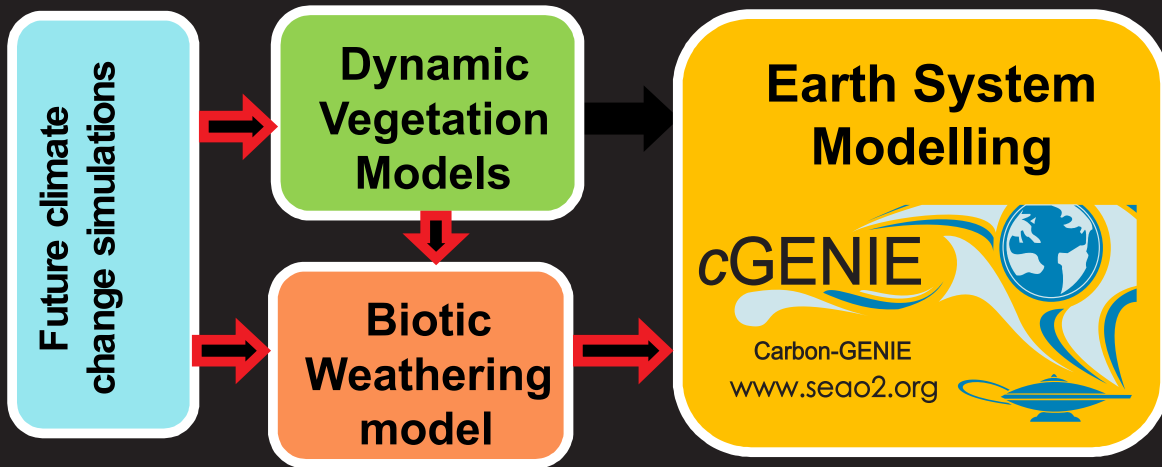
Dunite

Enhanced weathering (CO_2 removal geoengineering)



Taylor et al. [2015]
(Nature Climate Change)

Enhanced weathering (CO_2 removal geoengineering)



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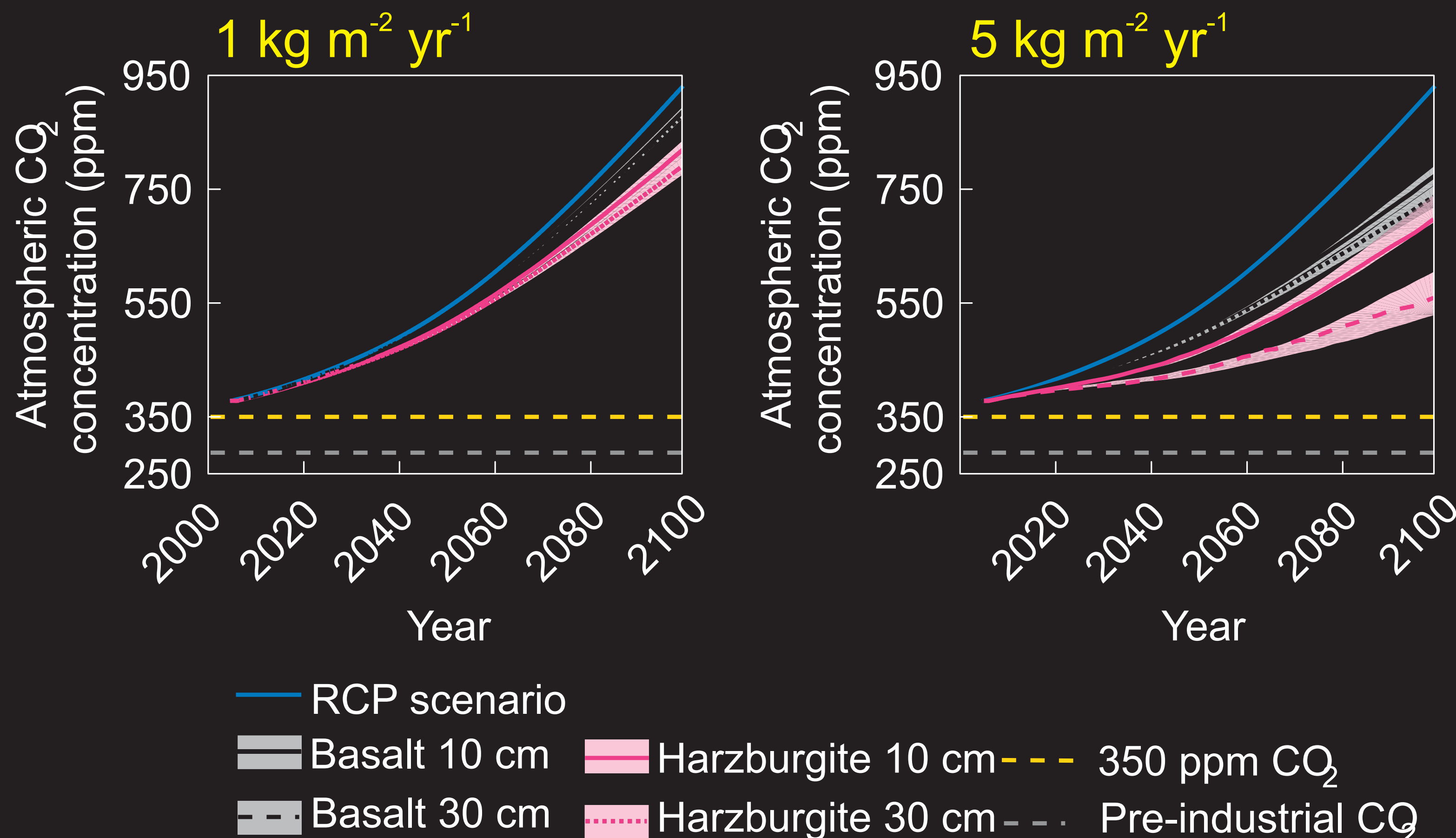
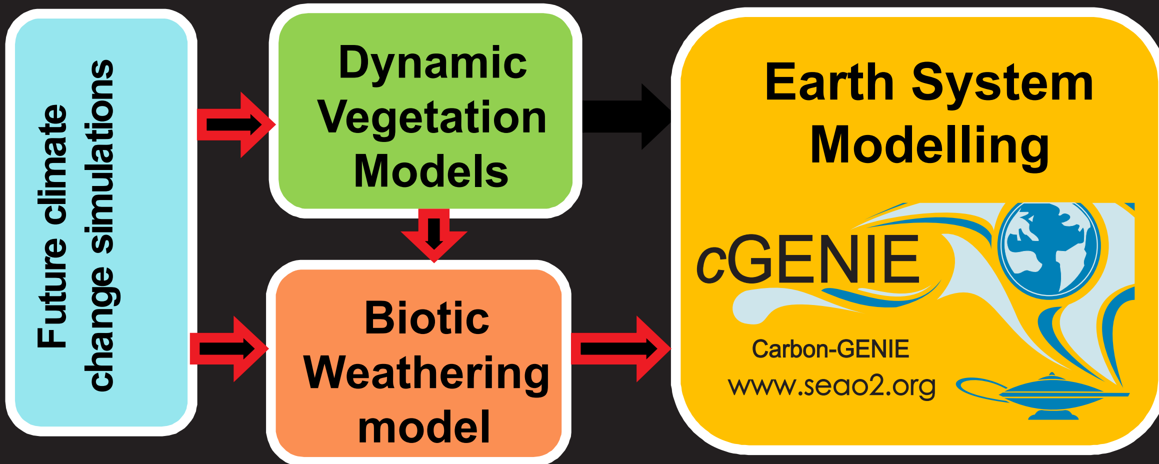


Ground rock application over 20×10^3 km^2 of tropical climatic 'hotspots'

Enhanced weathering (CO_2 removal geoengineering)



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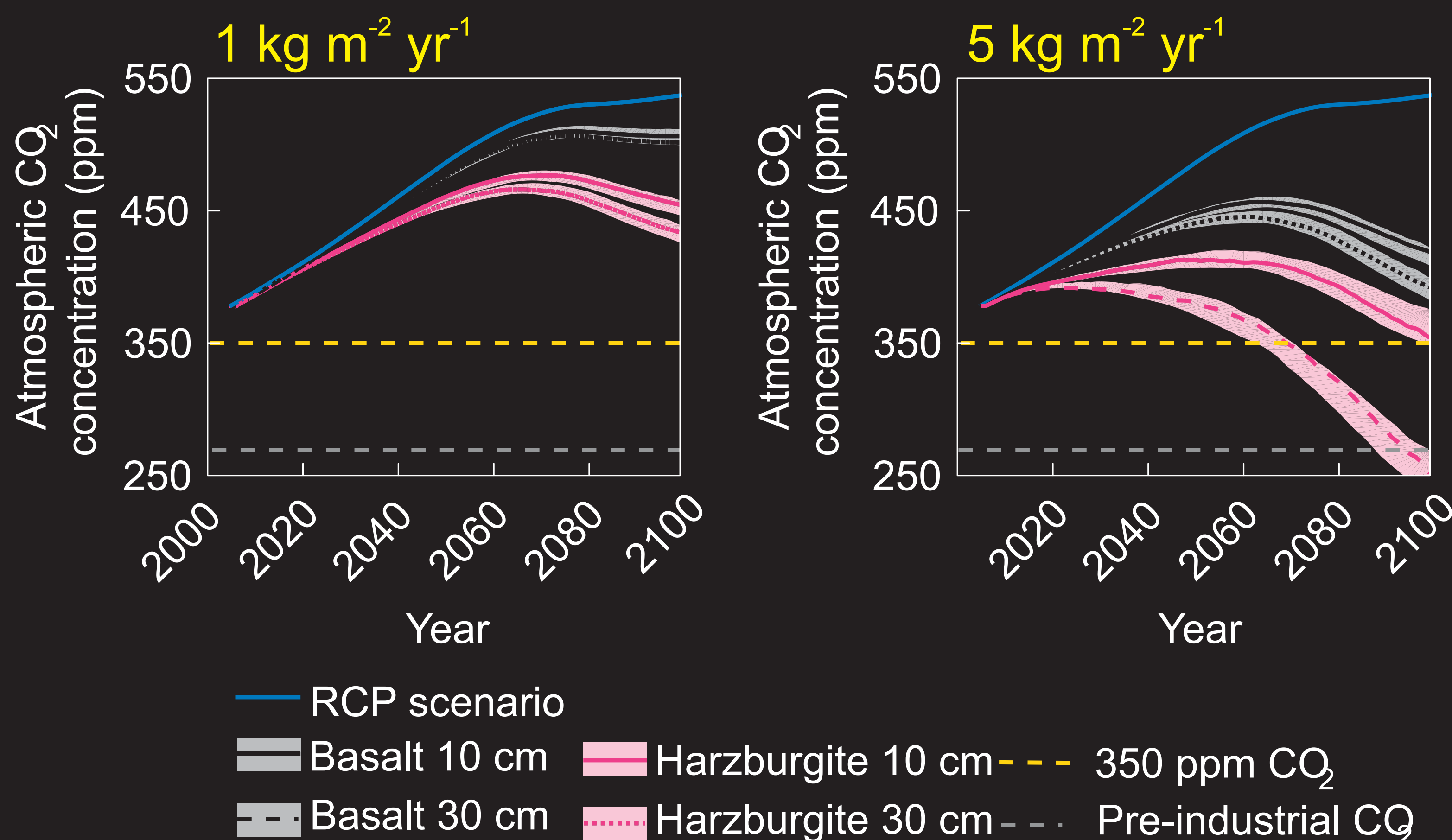

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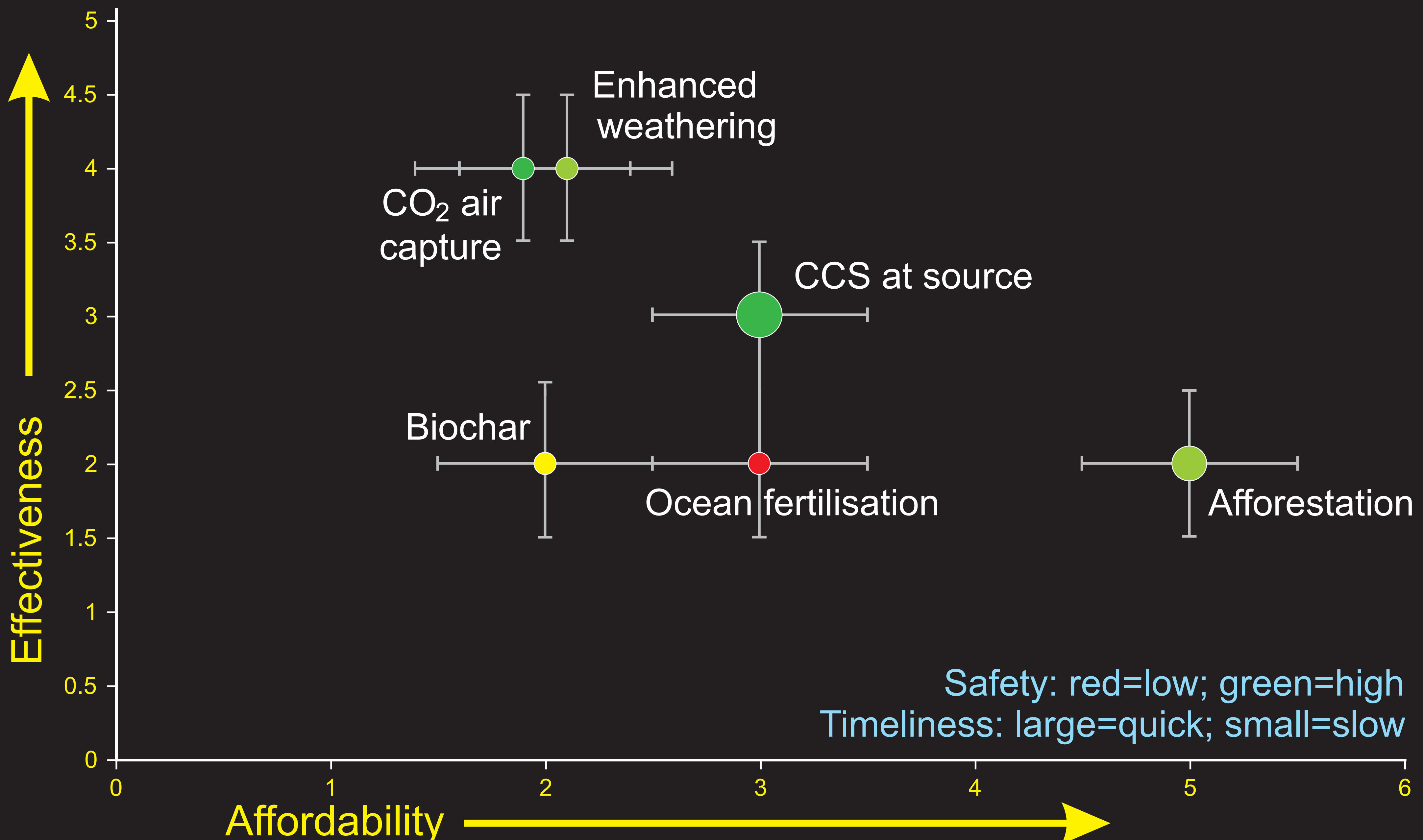
Enhanced weathering (CO_2 removal geoengineering)

Carbon dioxide removal geoengineering summary



Royal Society [2009]

Current global oil consumption = $90{,}136\times10^{3}$ barrels per day

1.0 barrel = 159 l
= 159×10^{3} cm^{3}

$\Rightarrow$ oil consumption
= 5.23×10^{15} cm^{3} $year^{-1}$
= 5.23 km^{3} $year^{-1}$

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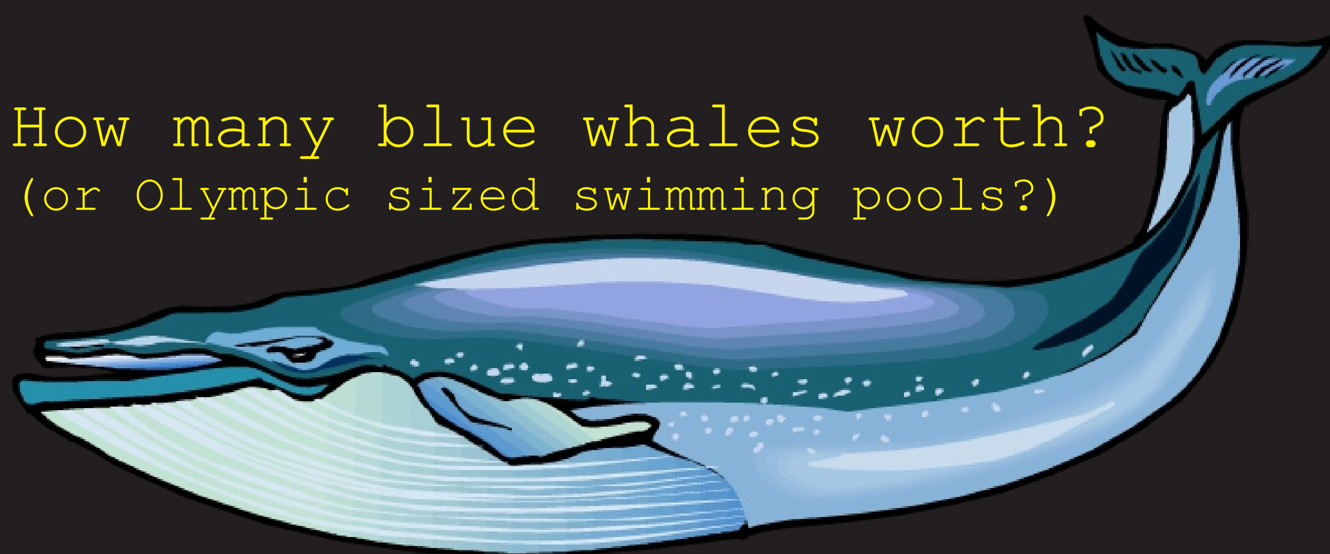

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How many Yosemite Valleys?
(equivalent volume)

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⇒ oil consumption
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= 5.23 km^3 $year^{-1}$

Yosemite Valley (Wikipedia):
1,200m deep × 1,600m across, 12.0 km long
⇒
volume = 1.2×1.6×12.0
= 23.0 km^3

How many Yosemite Valleys?
(equivalent volume)

Carbon and climate modellers, collaborators, and cold hard CA$H

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ERC