What have I done in the past 5 months?

(numerical fun with the global weathering thermostat and other climate control knobs)

Andy Ridgwell

Talk outline: ~~PALEO~~

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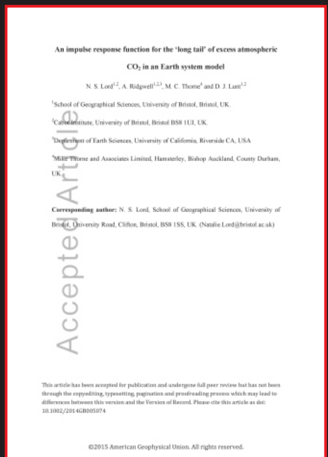
long-term feedbacks on atmospheric CO_2

Talk outline: ~~PALEO~~

GEO250.2015


An impulse response function for the 'long tail' of excess atmospheric CO_2 in an Earth system model

N. S. Lord[1,2], A. Ridgwell[1,2,3], M. C. Thorne[4] and D. J. Lunt[1,2]

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Accepted Article

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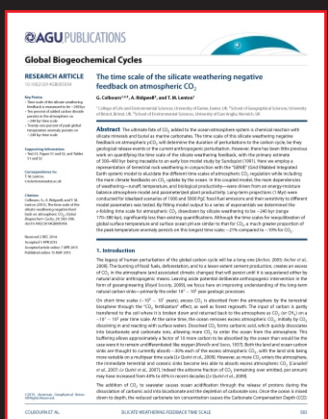
Lord et al. [in press]

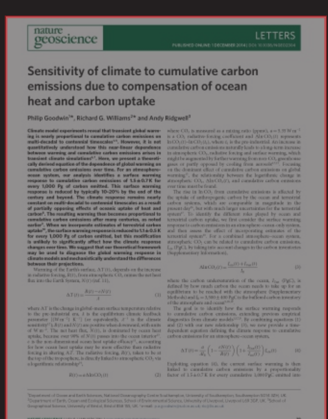

AGU PUBLICATIONS

Global Biogeochemical Cycles

RESEARCH ARTICLE

The time scale of the silicate weathering negative feedback on atmospheric CO_2

Colbourn et al. [2015]


nature geoscience

LETTERS

Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake

Philip Goodwin, Richard G. Williams and Andy Ridgwell

Goodwin et al. [2015]

long-term feedbacks on atmospheric CO_2

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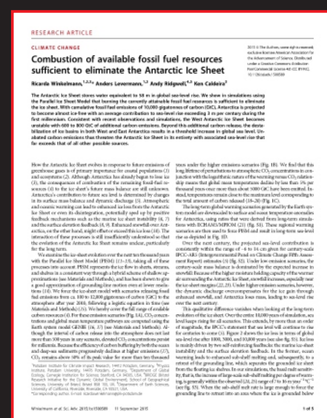
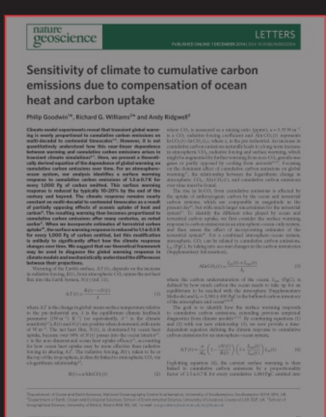


Winkelmann et al. [2015]



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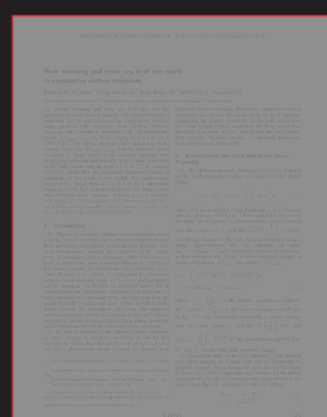

Williams et al. [2012]

Talk outline: ~~PALEO~~

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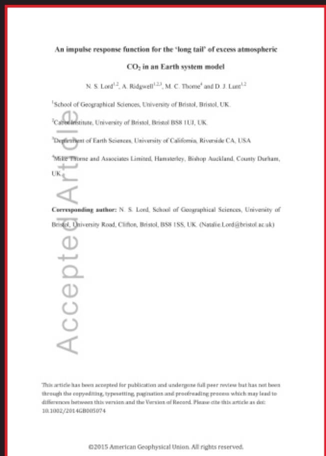
long-term feedbacks on atmospheric CO_2



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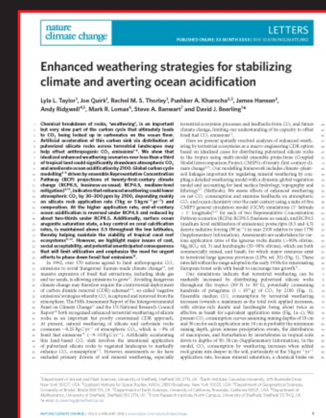
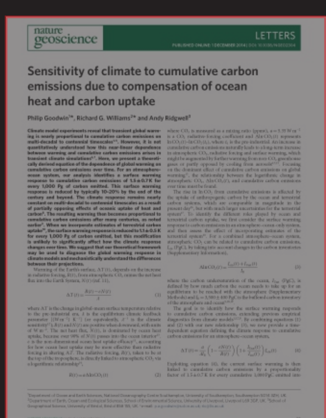
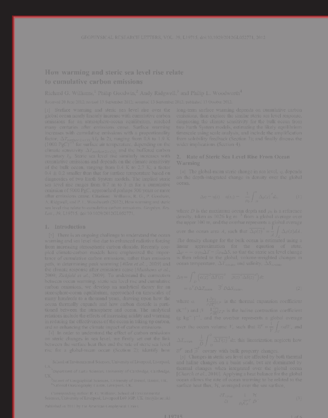


Taylor et al. [in press]



Goodwin et al. [2015]



Williams et al. [2012]

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long-term feedbacks on atmospheric CO_2

Lord et al. [in press]

Colbourn et al. [2015]

Winkelmann et al. [2015]

Taylor et al. [in press]

Jackson et al. [2015]

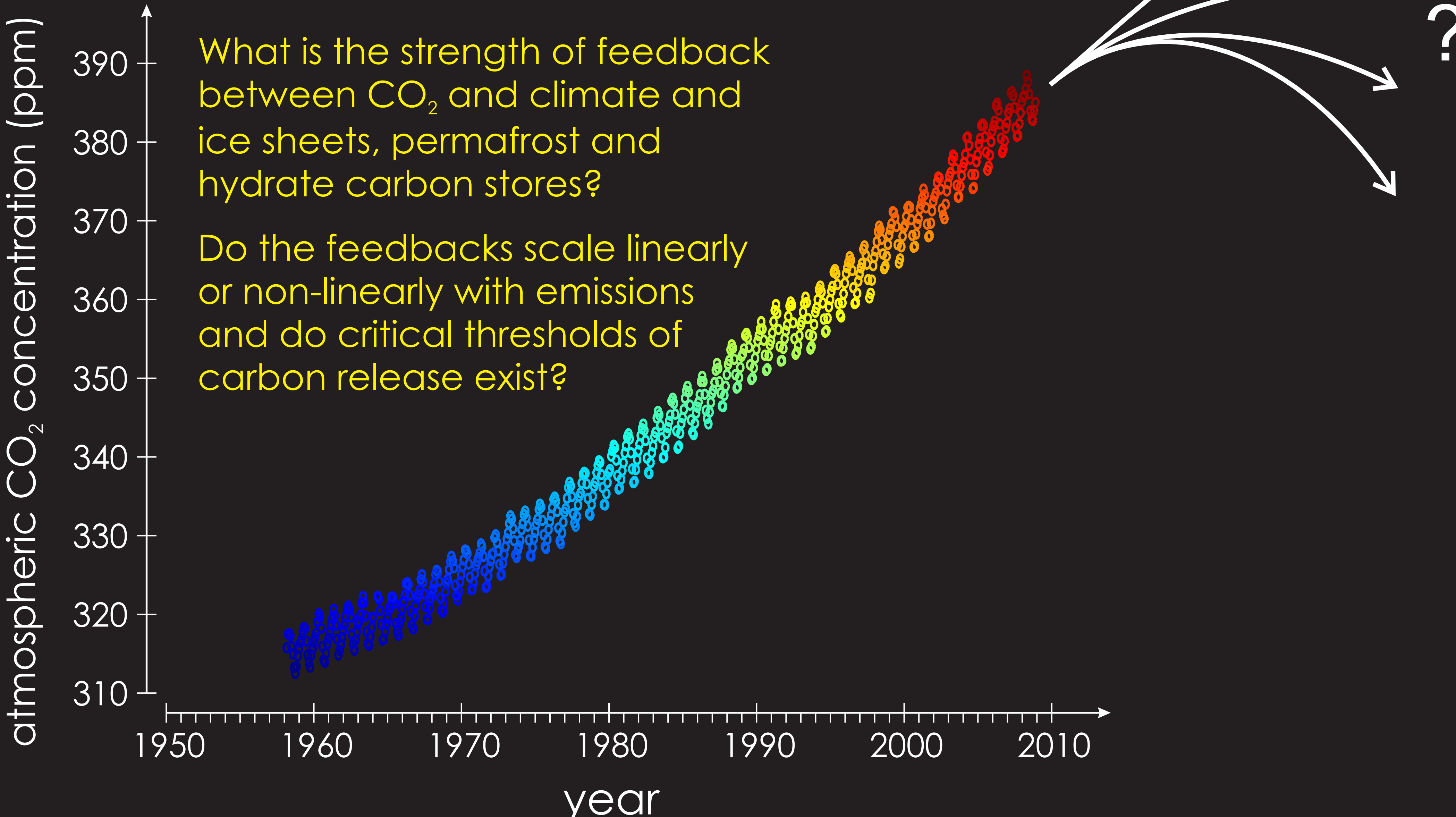
Goodwin et al. [2015]

Williams et al. [2012]

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

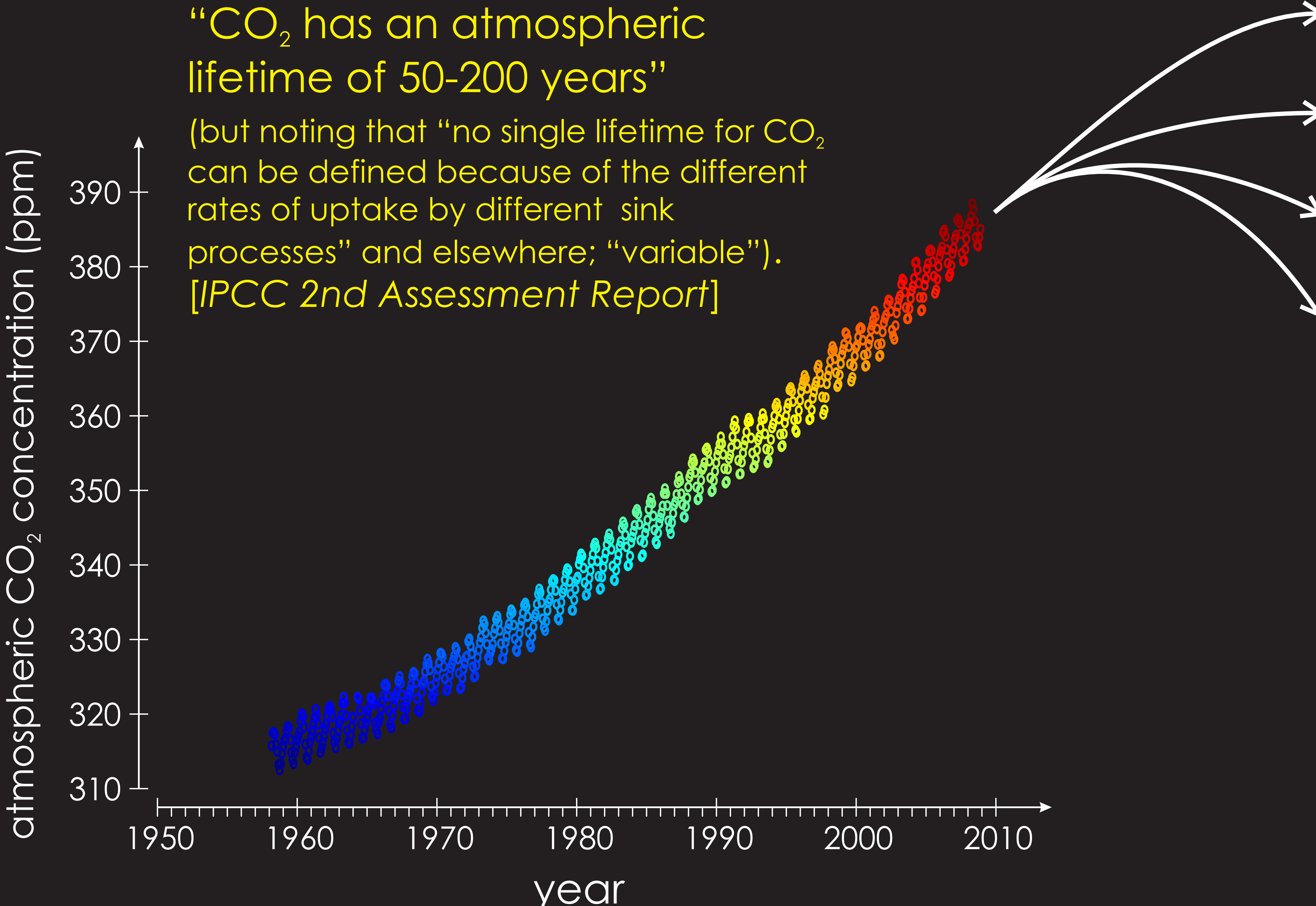
What is the strength of feedback between CO_2 and climate and ice sheets, permafrost and hydrate carbon stores?

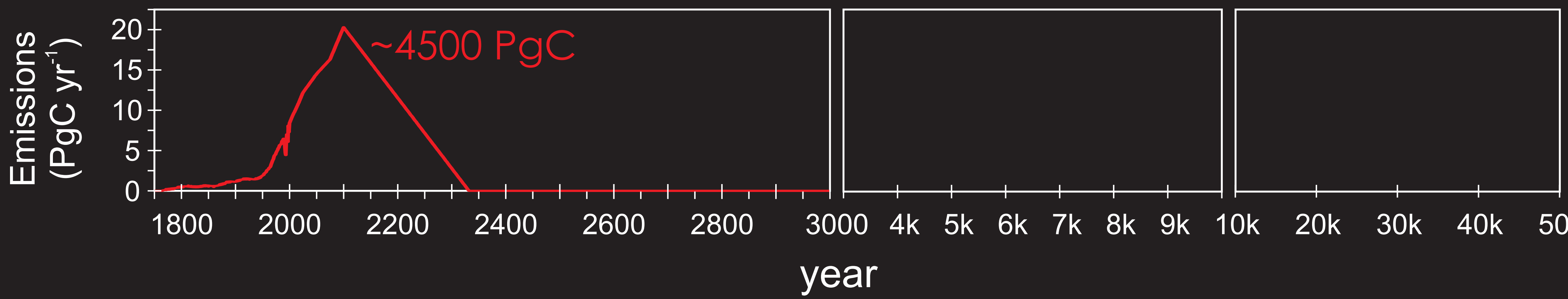
Do the feedbacks scale linearly or non-linearly with emissions and do critical thresholds of carbon release exist?



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

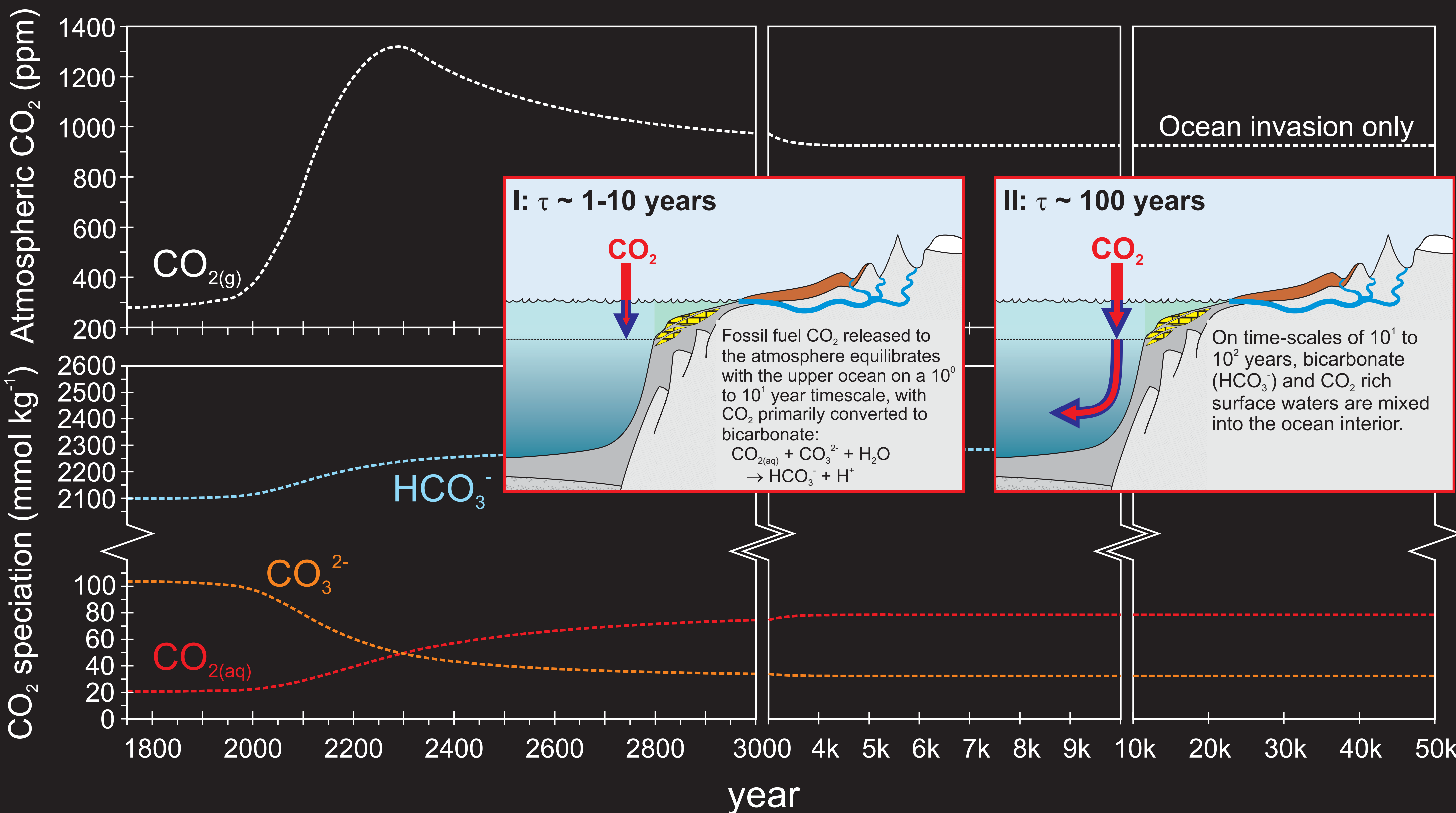
(but noting that "no single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes" and elsewhere; "variable").
[*IPCC 2nd Assessment Report*]



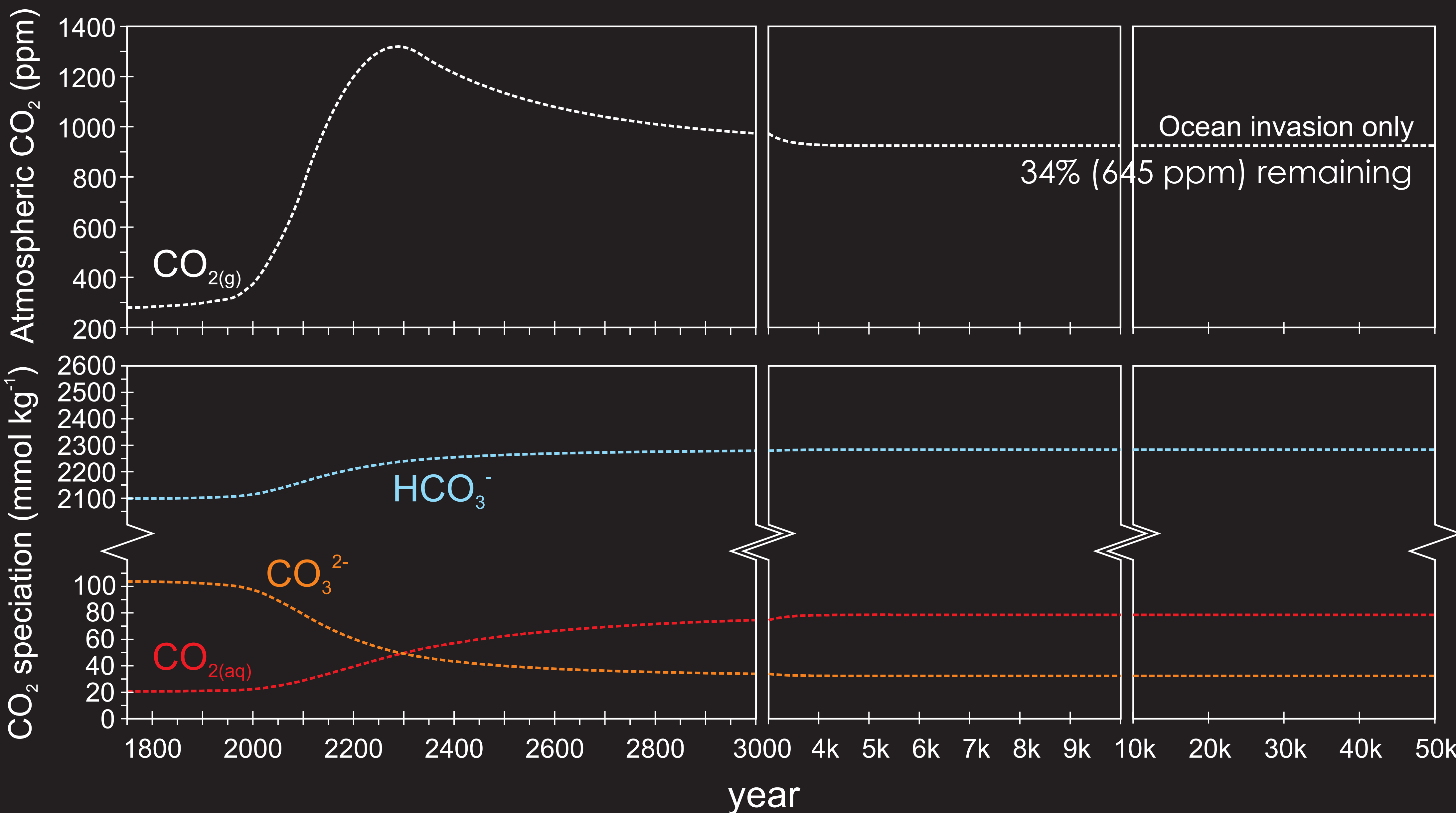


From: *Ridgwell and Hargreaves* [2007] (*GBC*)

Introduction: The fate of (fossil fuel) CO_2 emissions

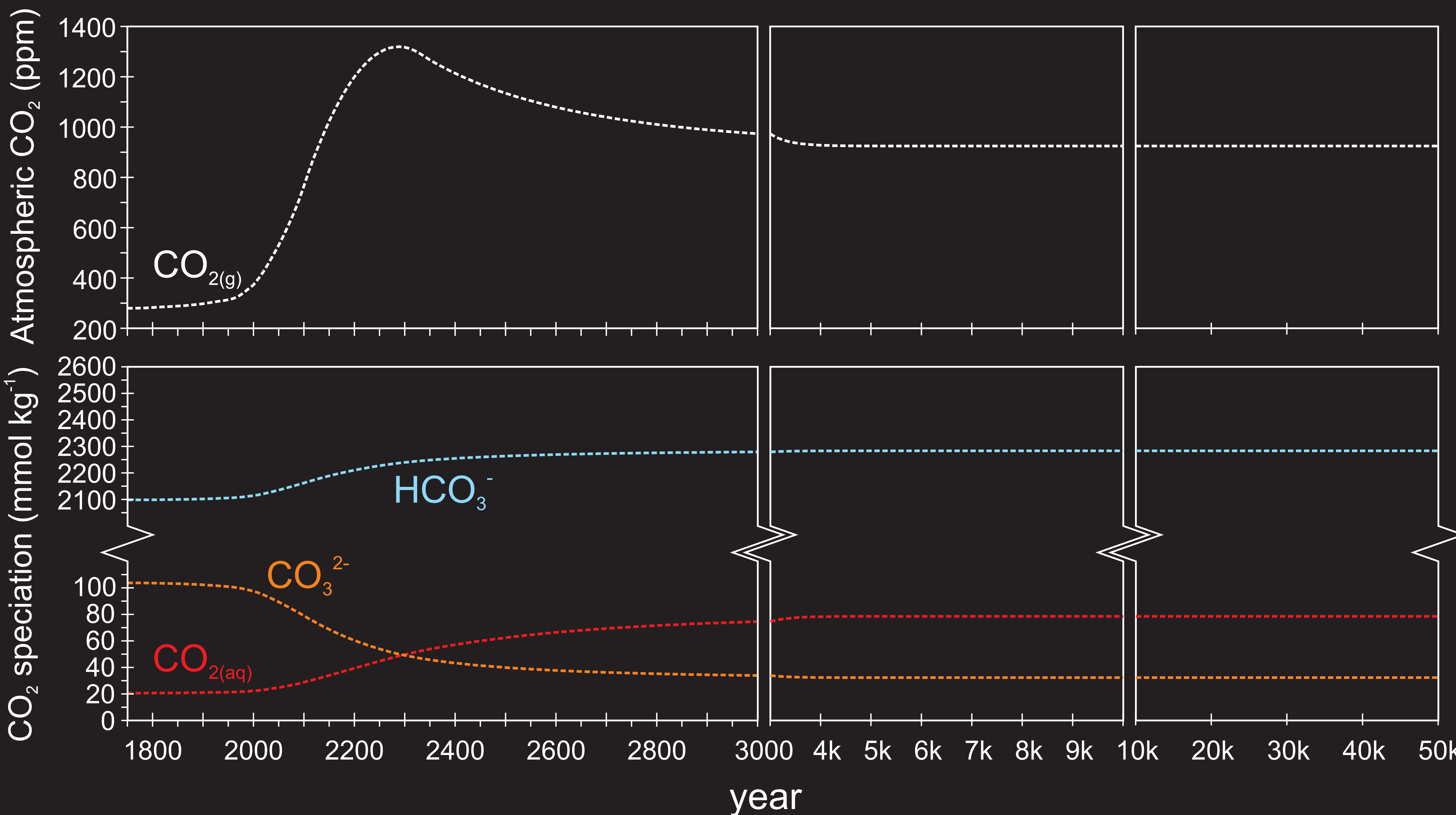


From: *Ridgwell and Hargreaves* [2007] (*GBC*)

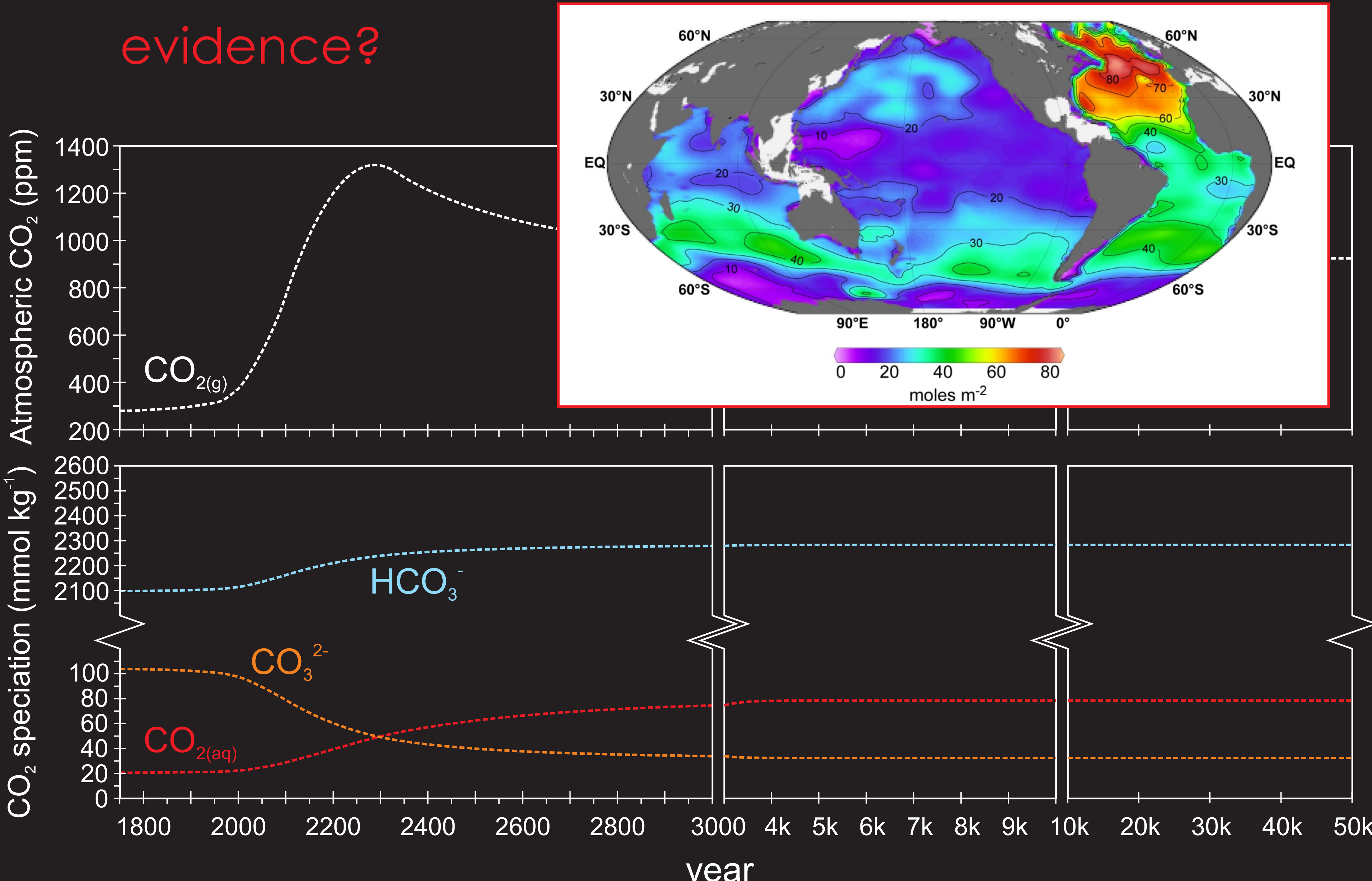


From: *Ridgwell and Hargreaves* [2007] (GBC)

evidence?

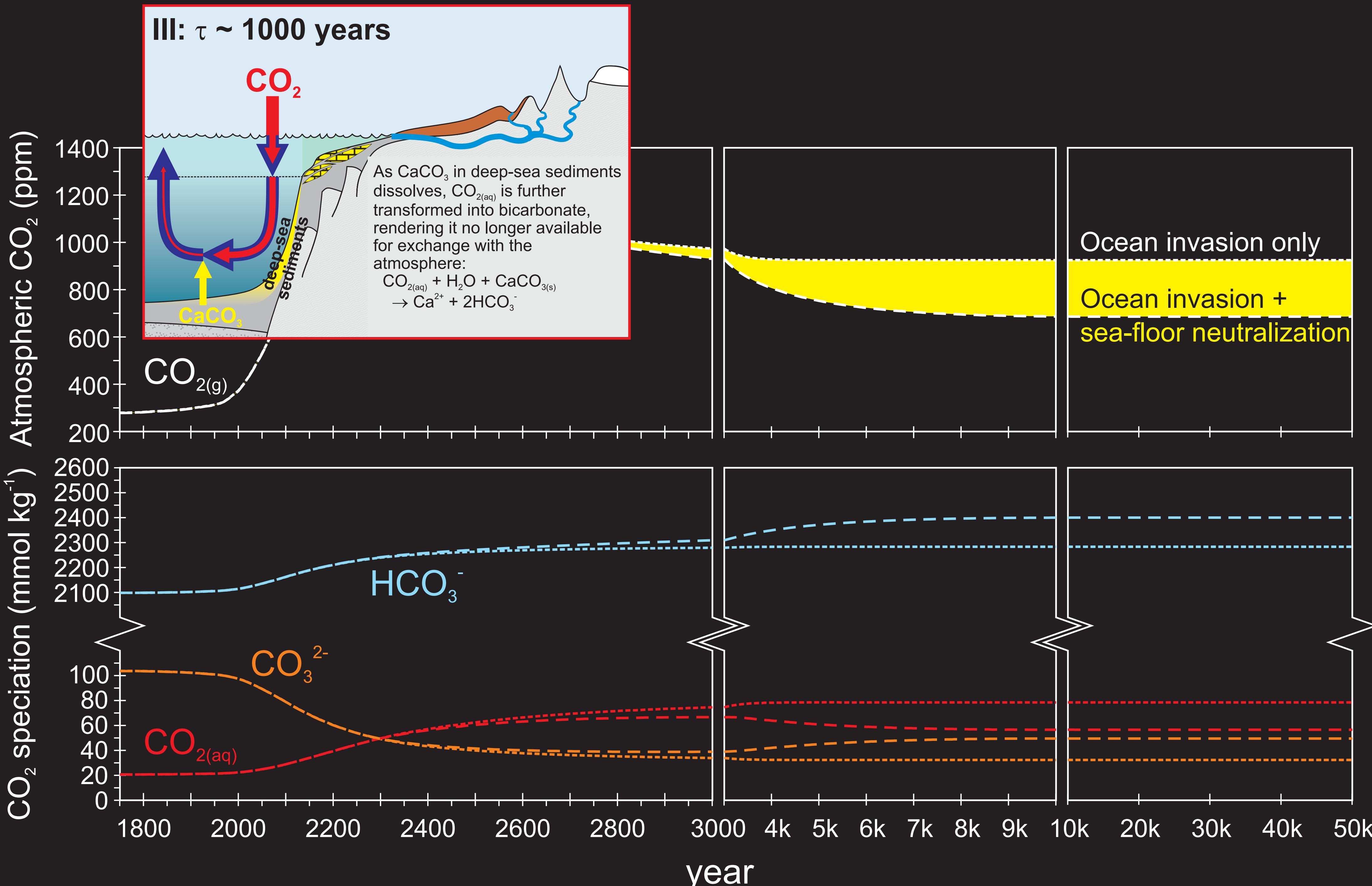

Atmospheric CO2 (ppm)
1400
1200
1000
800
600
400
200
CO2(g)
CO2 speciation (mmol kg-1)
2600
2500
2400
2300
2200
2100
HCO3-
CO32-
100
80
60
40
20
0
CO2(aq)
1800
2000
2200
2400
2600
2800
3000
4k
5k
6k
7k
8k
9k
10k
20k
30k
40k
50k
year

evidence?



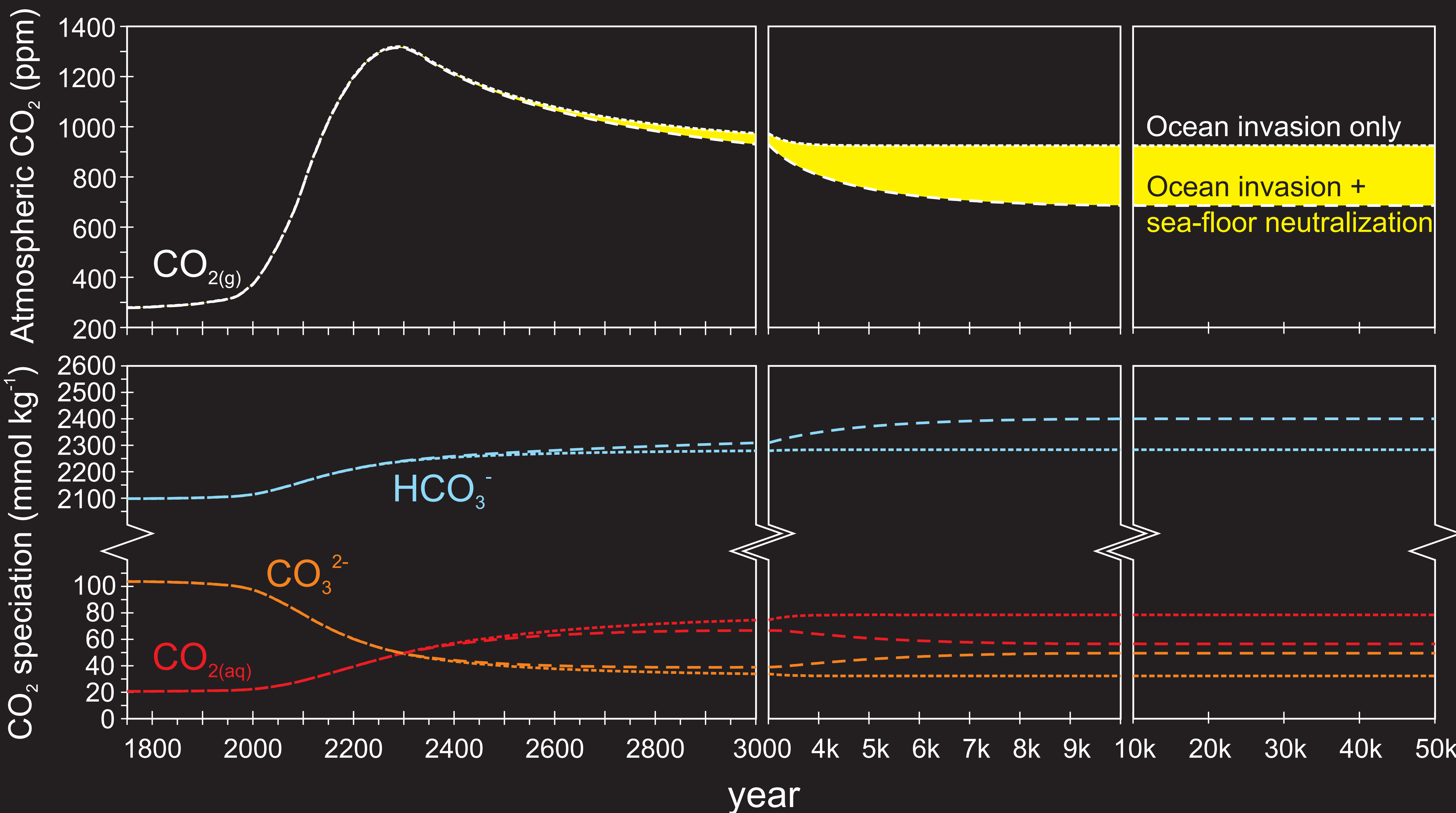
From: *Sabine et al.* [2004] (*Science*)

Introduction: The fate of (fossil fuel) CO_2 emissions



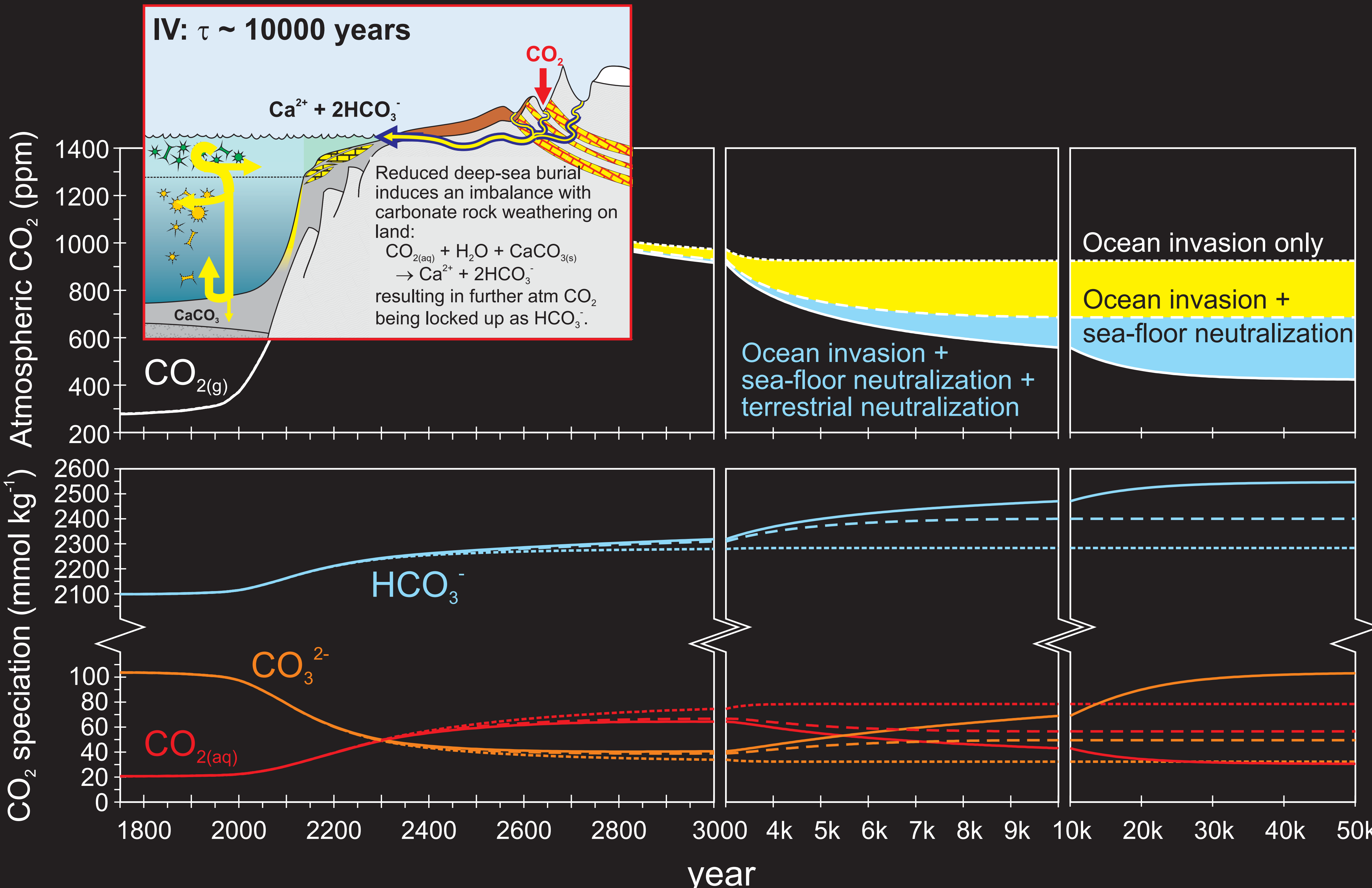
From: *Ridgwell and Hargreaves* [2007] (*GBC*)

evidence?



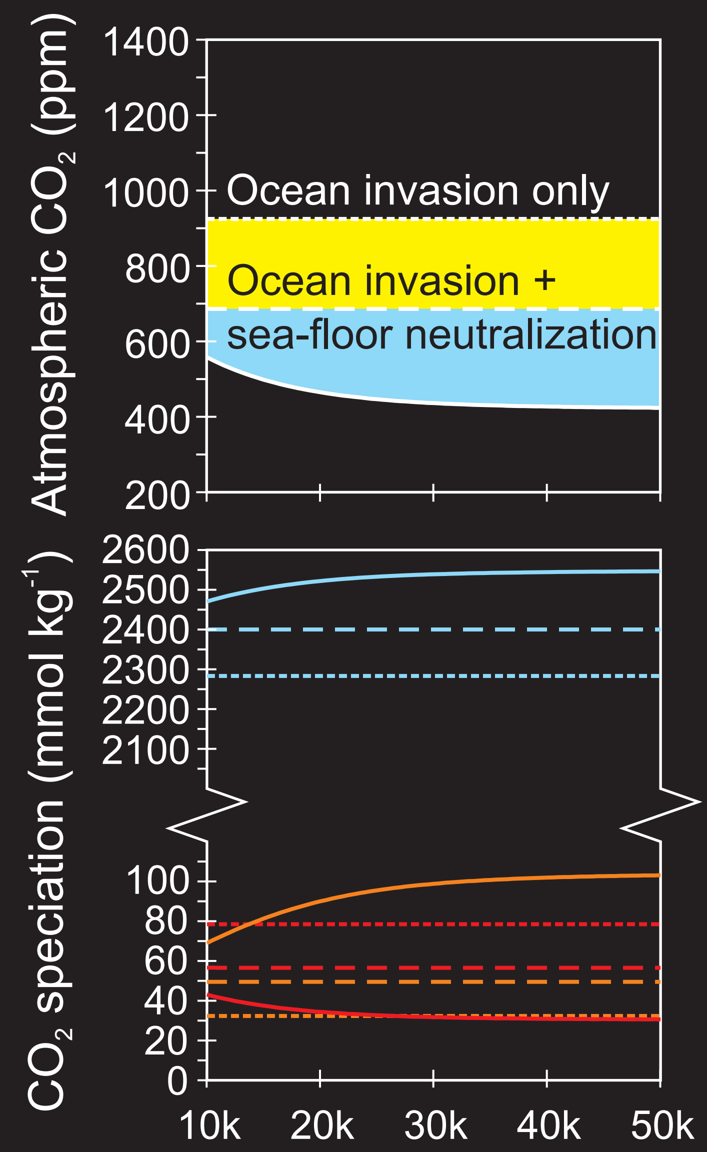
From: *Ridgwell and Hargreaves* [2007] (*GBC*)

Introduction: The fate of (fossil fuel) CO_2 emissions



From: *Ridgwell and Hargreaves* [2007] (GBC)

Q. Is a residual fraction of CO_2 persisting for ever ... 'OK'?



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.

Furthermore, the rate of silicate weathering should scale with climate. Hence a ca. 100 kyr time-scale **silicate weathering feedback** is formed:

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

(A regulating feedback system linking CO_2 and climate with ocean productivity and oxygenation, and organic carbon burial, can also be formulated but not discussed further here.)

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long-term feedbacks on atmospheric CO_2

An impulse response function for the 'long tail' of excess atmospheric CO_2 in an Earth system model

Lord et al. [in press]

The time scale of the silicate weathering negative feedback on atmospheric CO_2

Colbourn et al. [2015]

Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet

Winkelmann et al. [2015]

Enhanced weathering strategies for stabilizing climate and averting ocean acidification

Taylor et al. [in press]

Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering

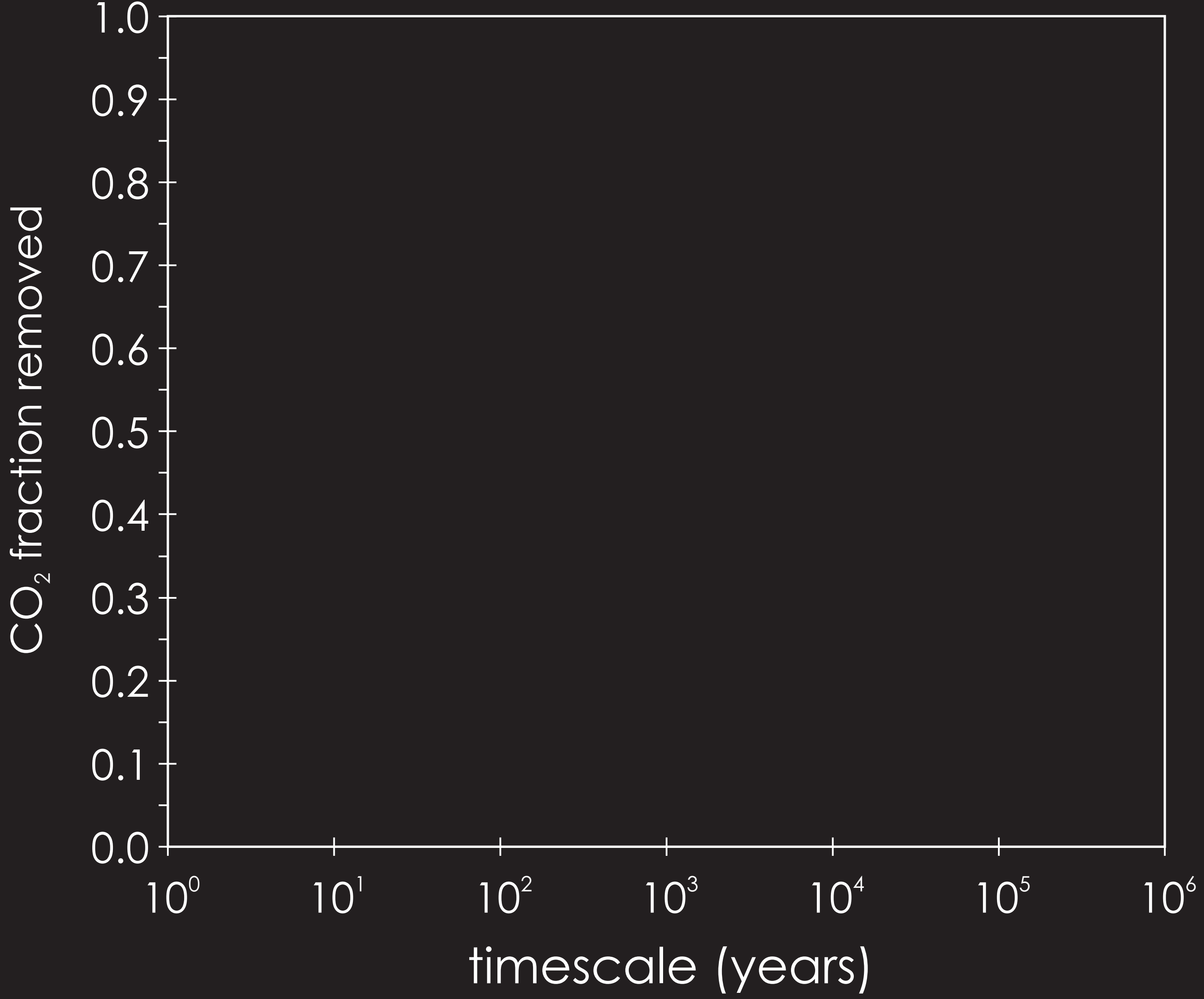
Jackson et al. [2015]

Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake

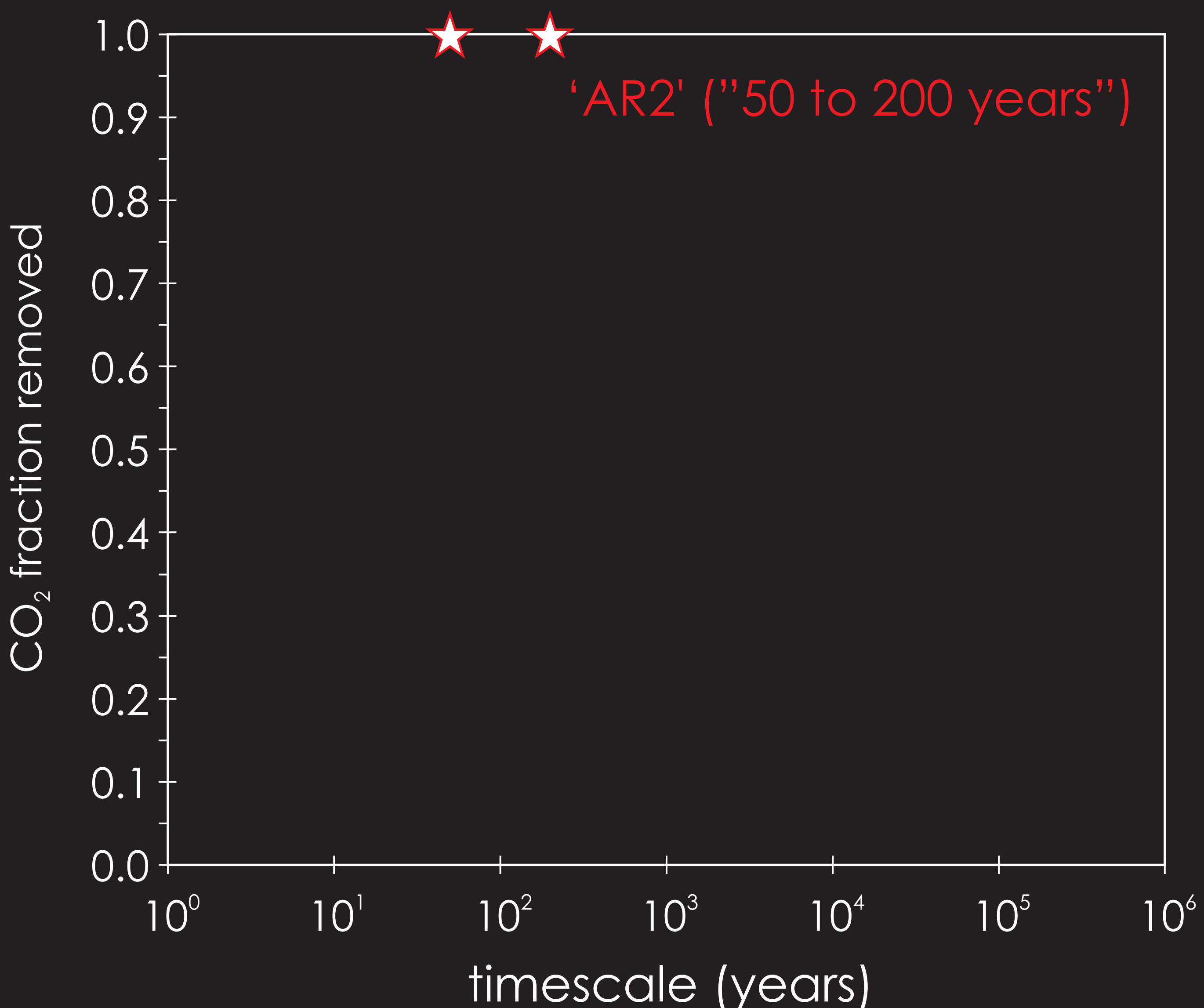
Goodwin et al. [2015]

Williams et al. [2012]

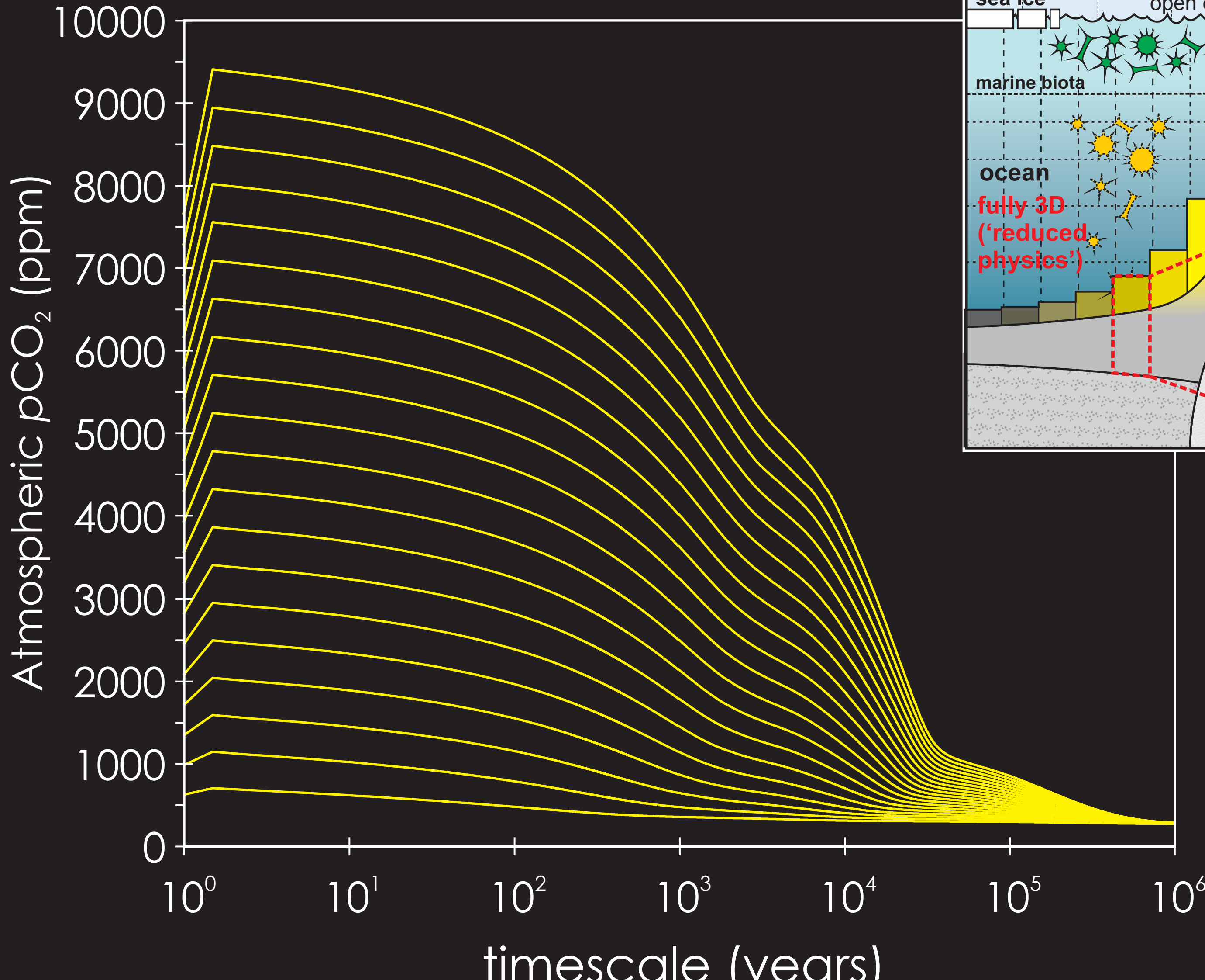
Cross-plot of the fraction of total CO_2 emissions to the atmosphere removed by a particular process (carbon sink), vs. the characteristic (e-folding) time-scale of that process (log_{10} scale).

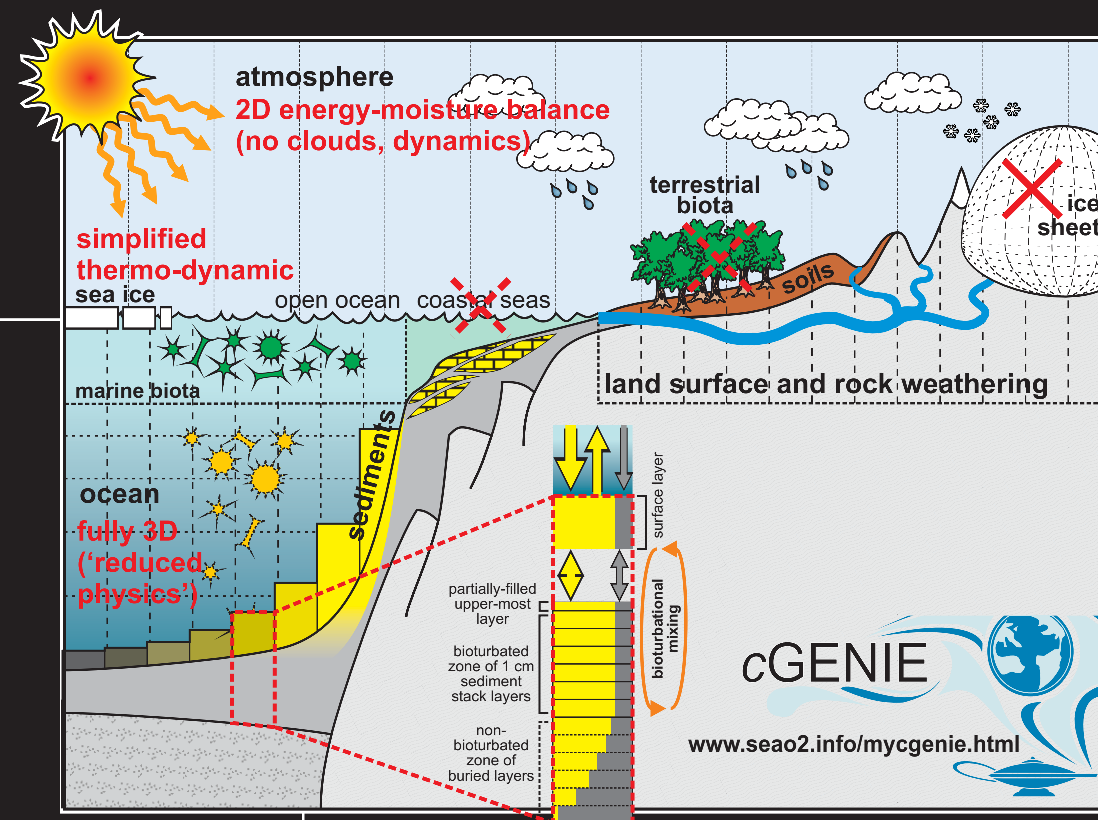


(I) *An impulse response function for the 'long tail' of $CO_{2(excess)}$*



(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. [in press]

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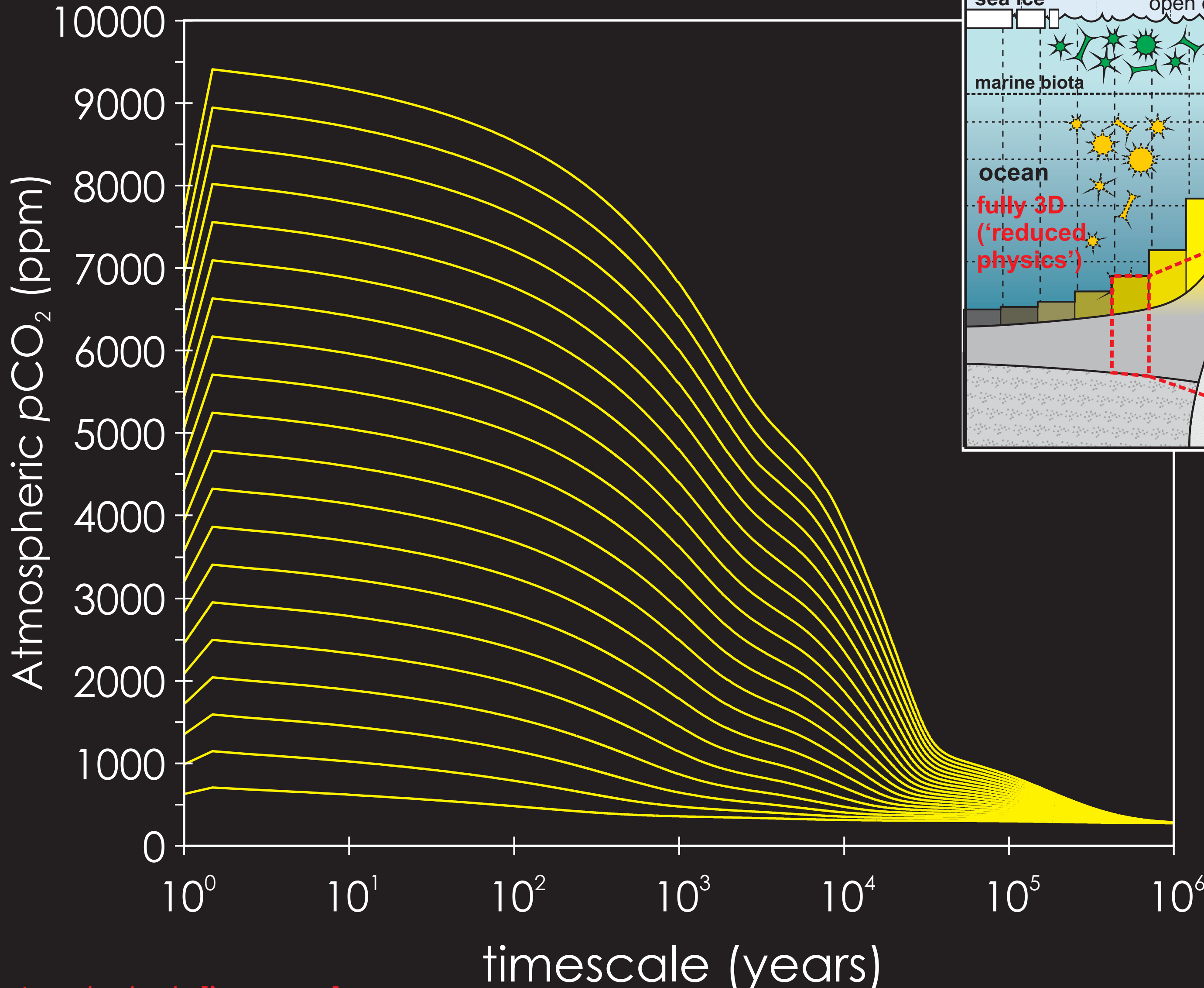
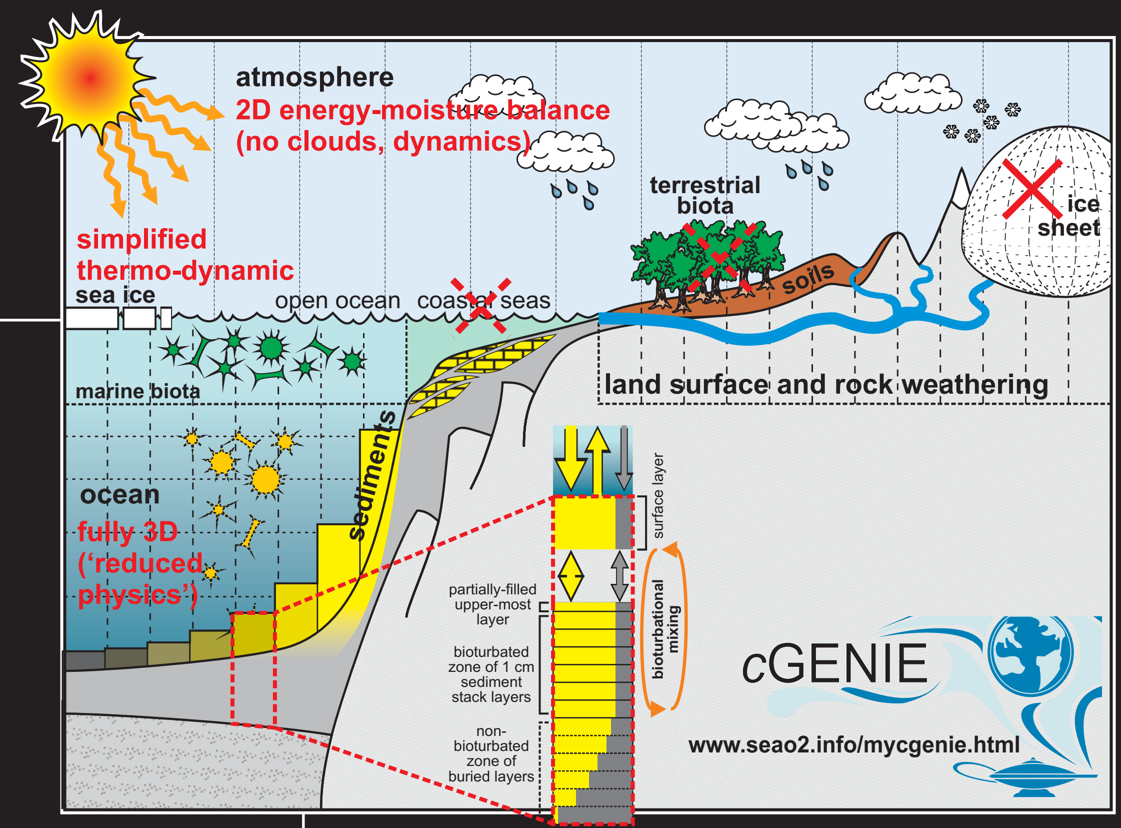


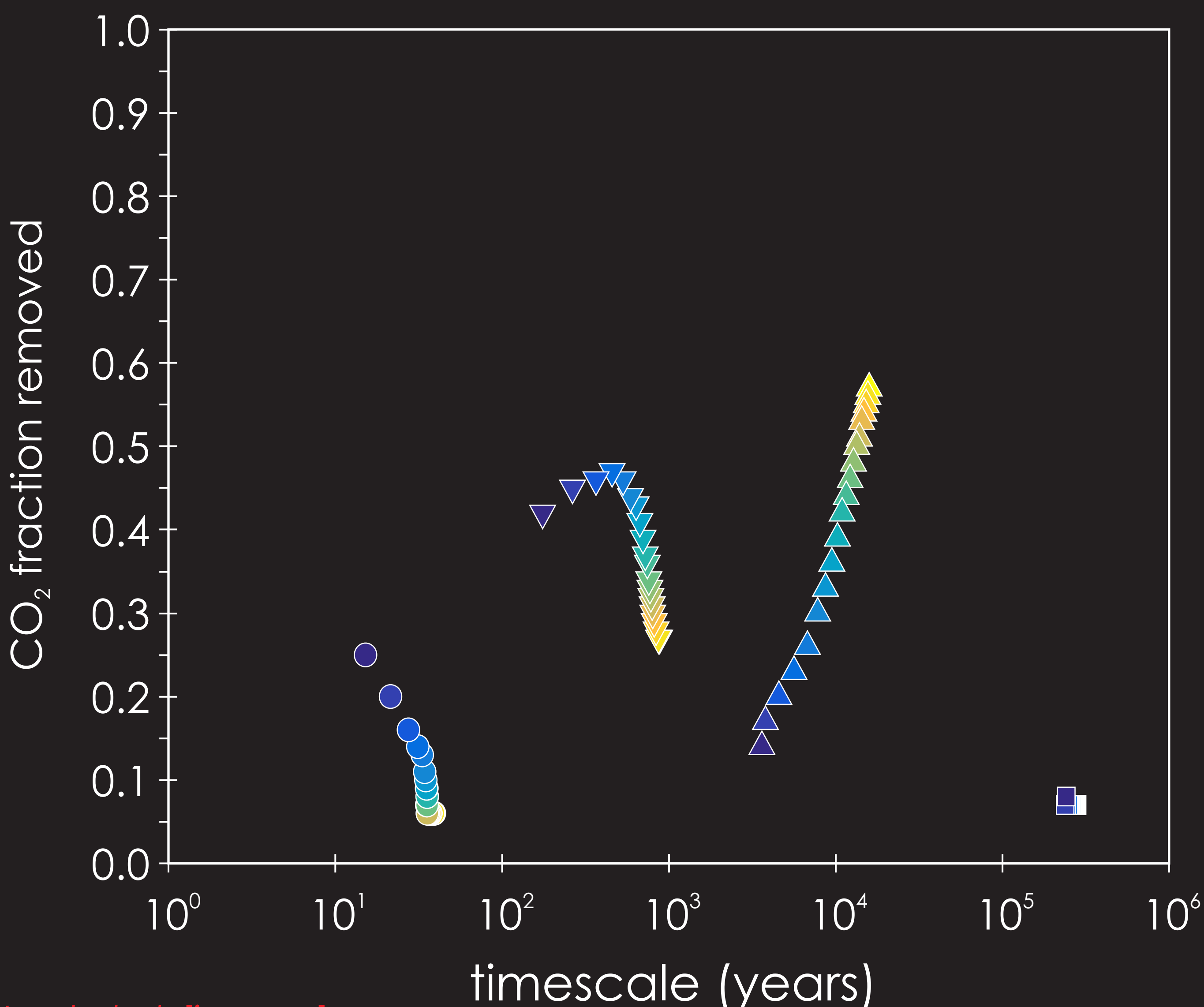


(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

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

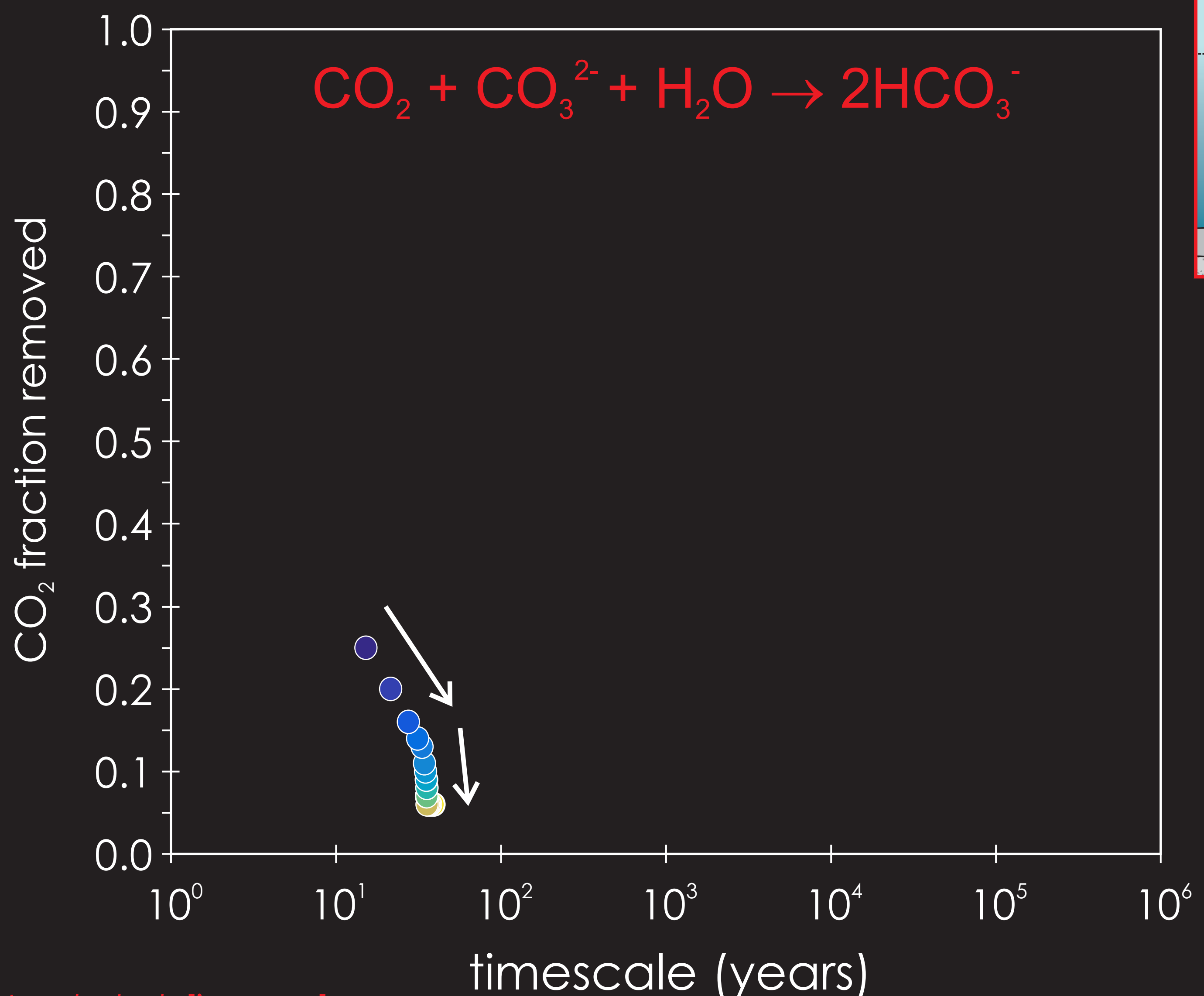
Lord et al. [in press]

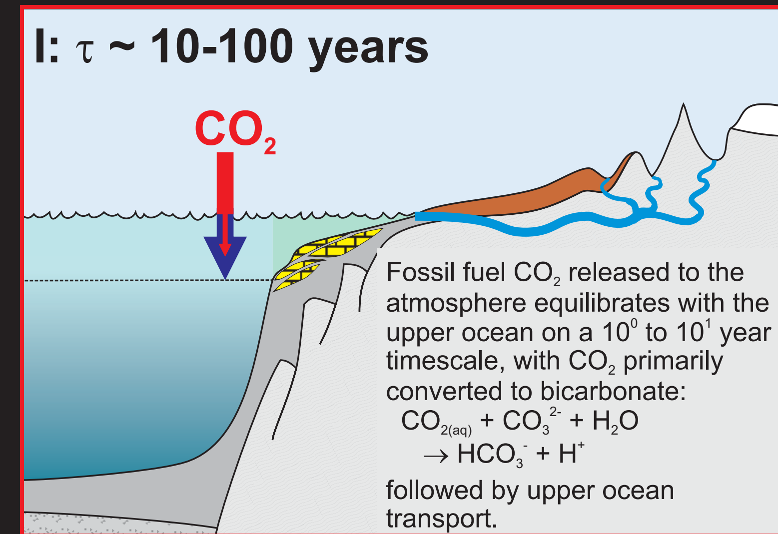
Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).



Lord et al. [in press]

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

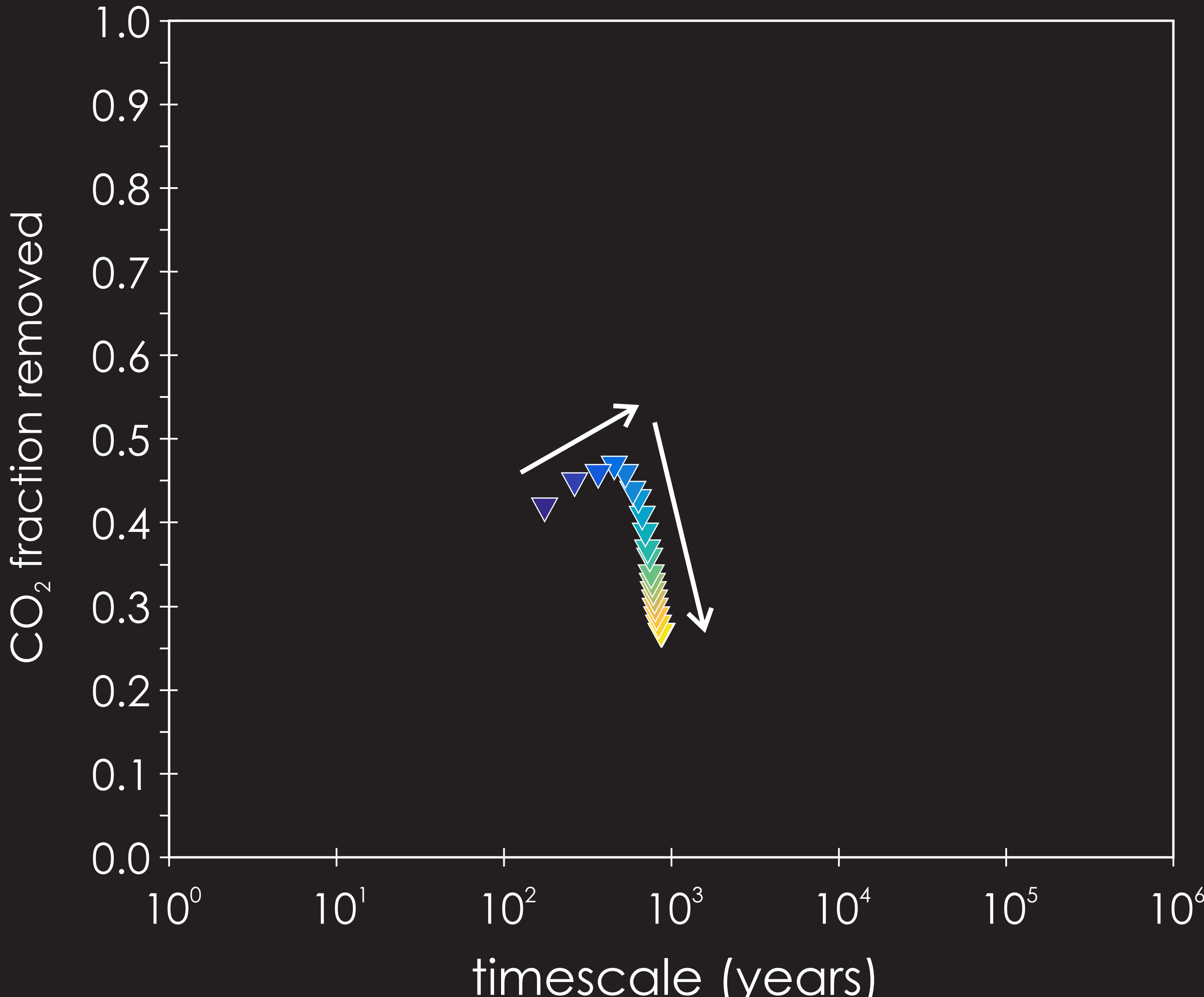


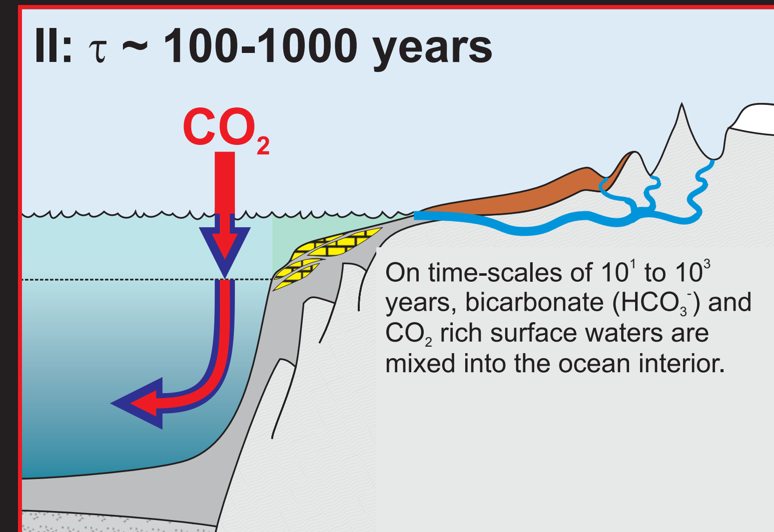


Lord et al. [in press]

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

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

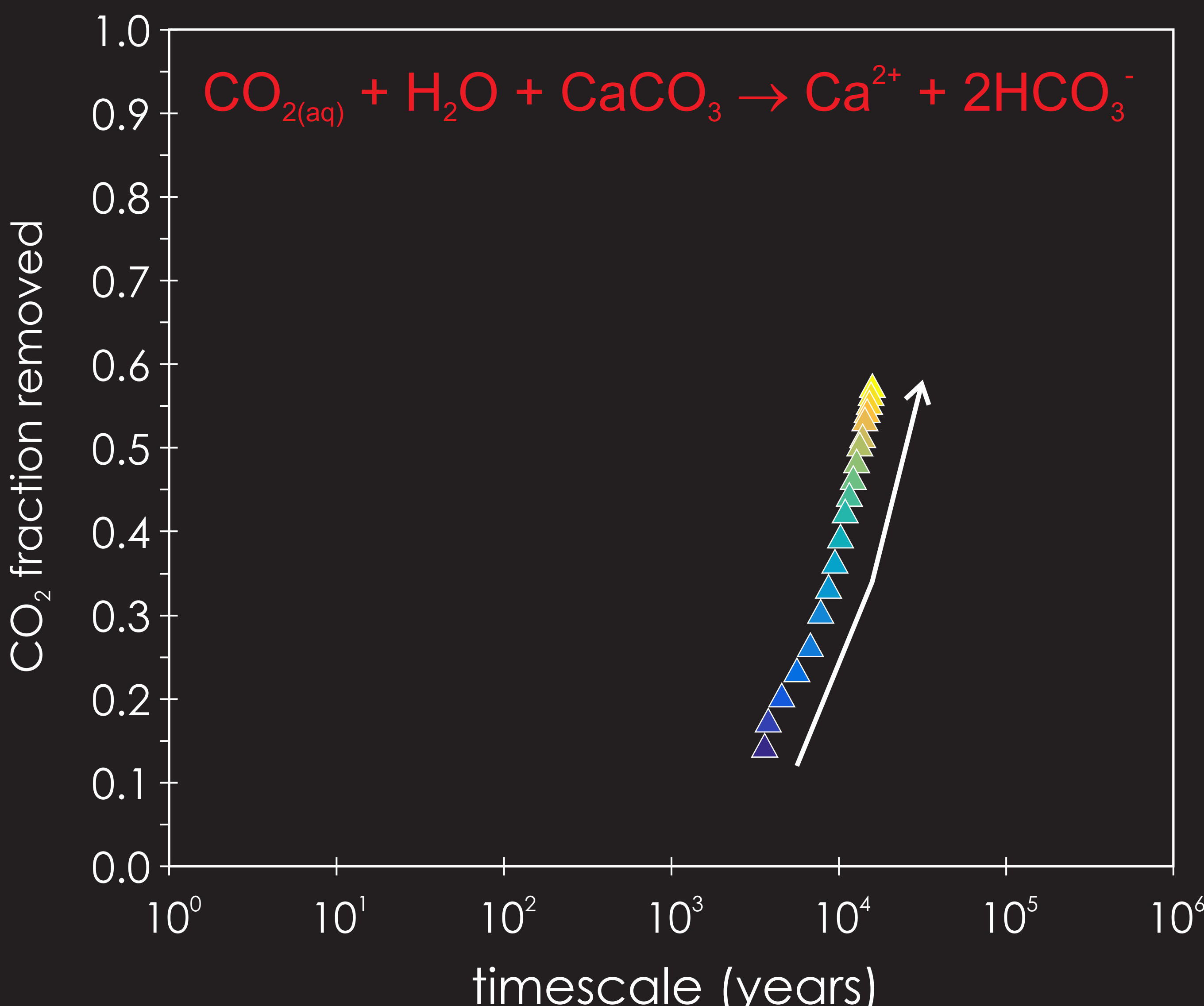




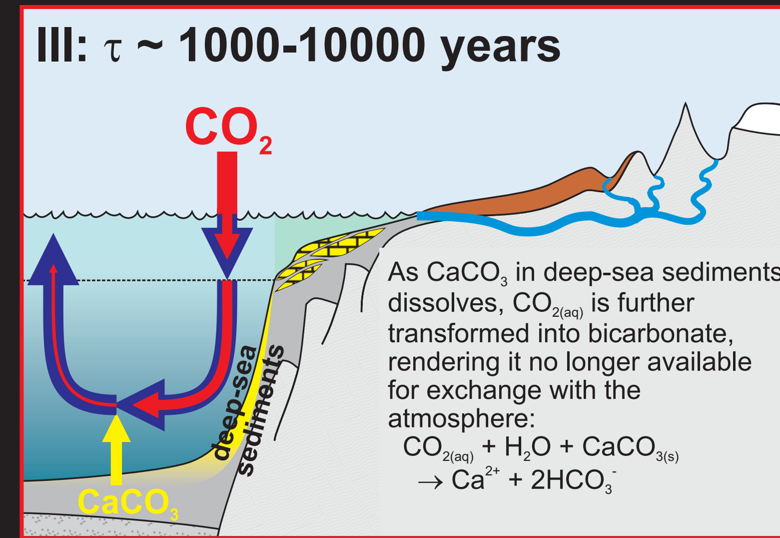
Lord et al. [in press]

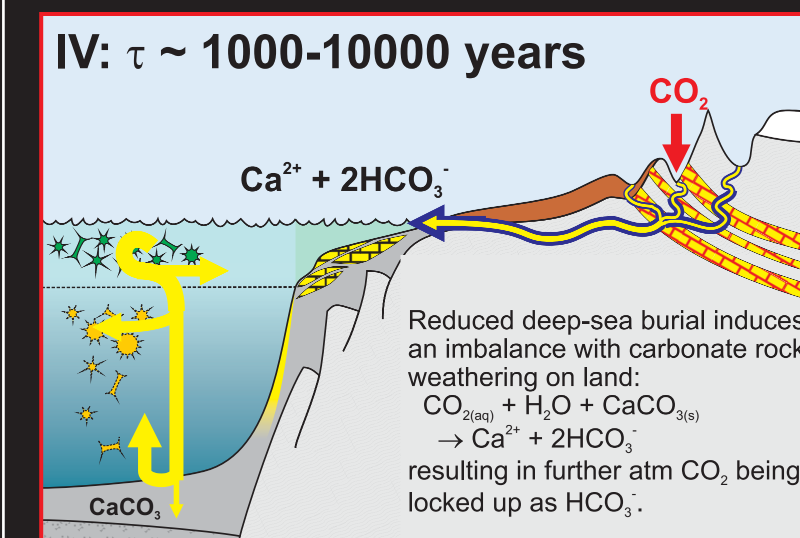
(I) An impulse response function for the 'long tail' of $CO_{2(excess)}$

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



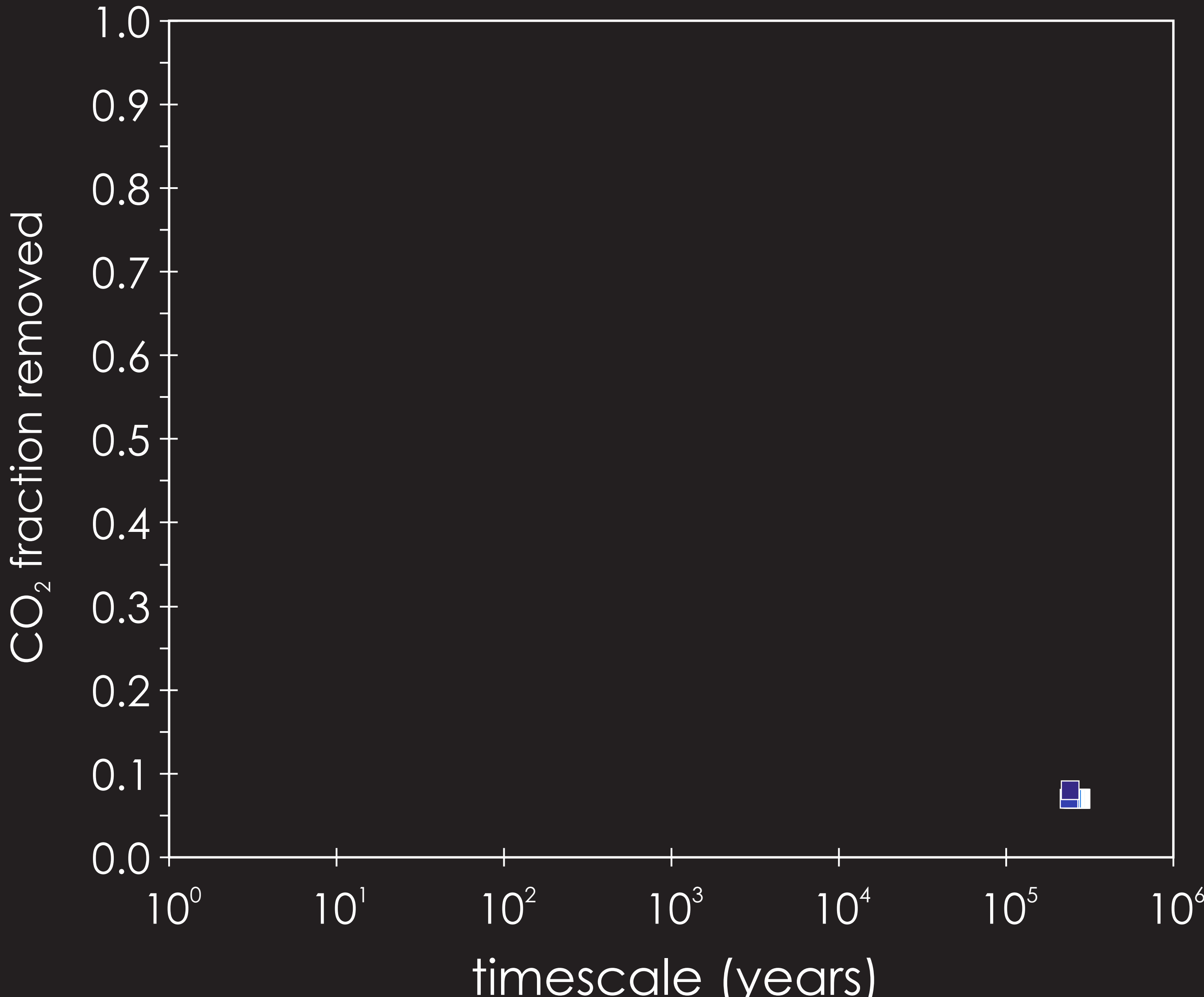
Lord et al. [in press]

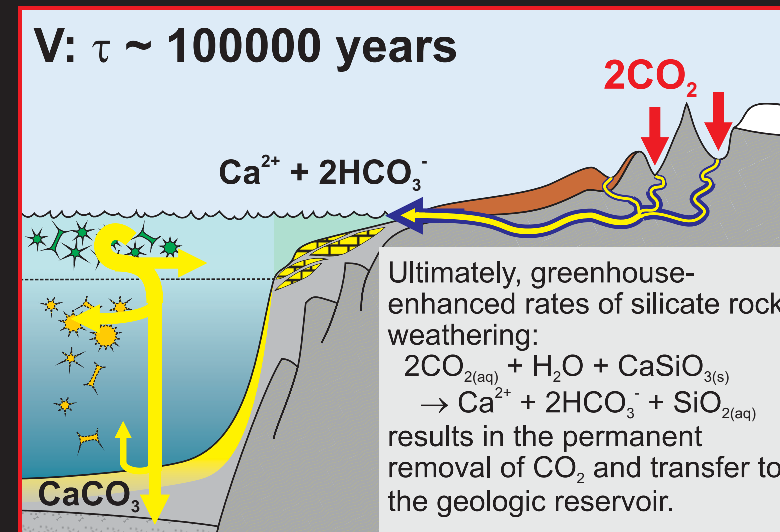




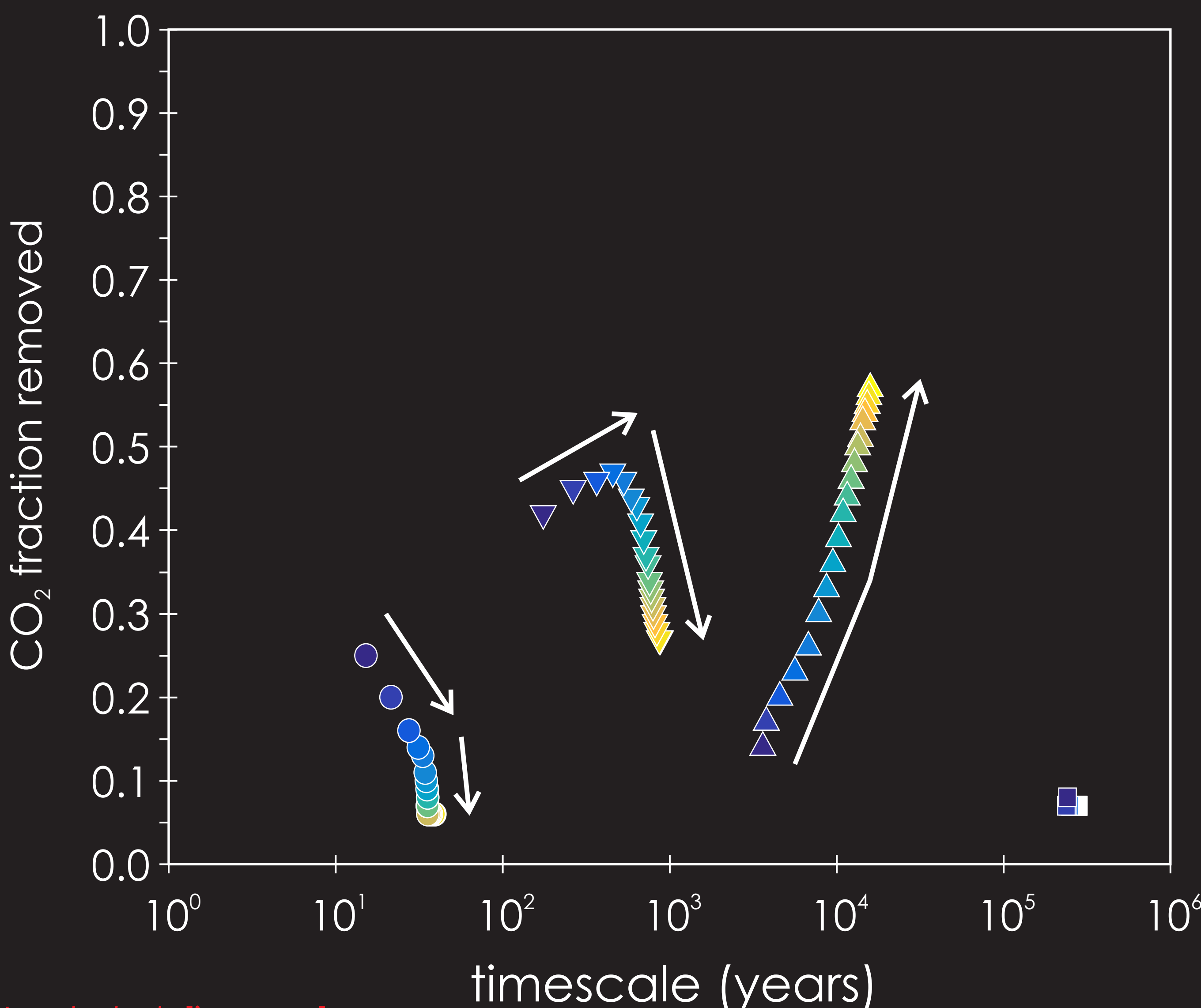
(I) *An impulse response function for the 'long tail' of $CO_{2(excess)}$*

Silicate weathering (no time-scale response!).





Lord et al. [in press]



Lord et al. [in press]

Summary:

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 (and hence warming) will hence become more persistent as the main short-term CO_2 feedbacks weaken.

Only a (almost invariant) small fraction(~7%) of CO_2 is extremely persistent.
BUT, the majority of carbon removal beyond ~10,000 PgC is removed only on time-scales exceeding 10,000 years.

long-term feedbacks on atmospheric CO_2

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Colbourn et al. [2015]

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Jackson et al. [2015]

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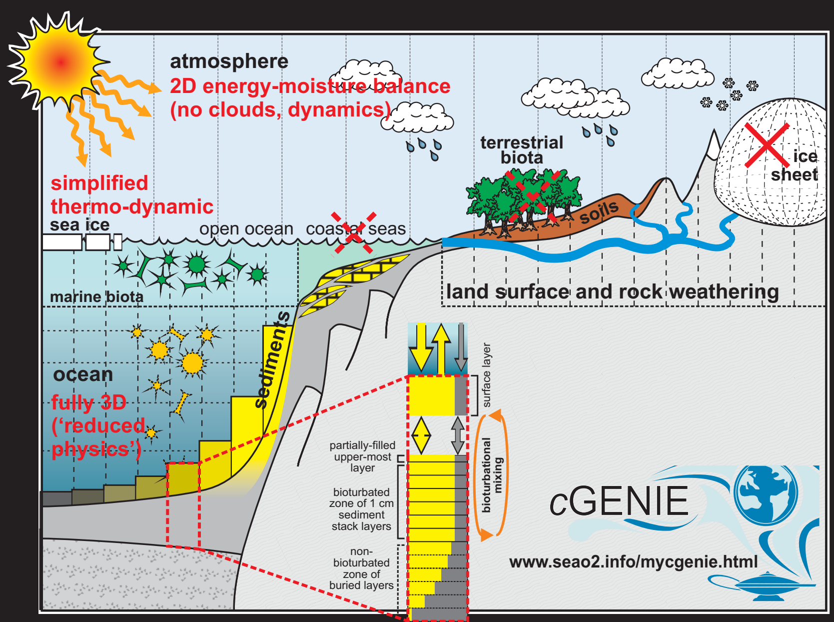
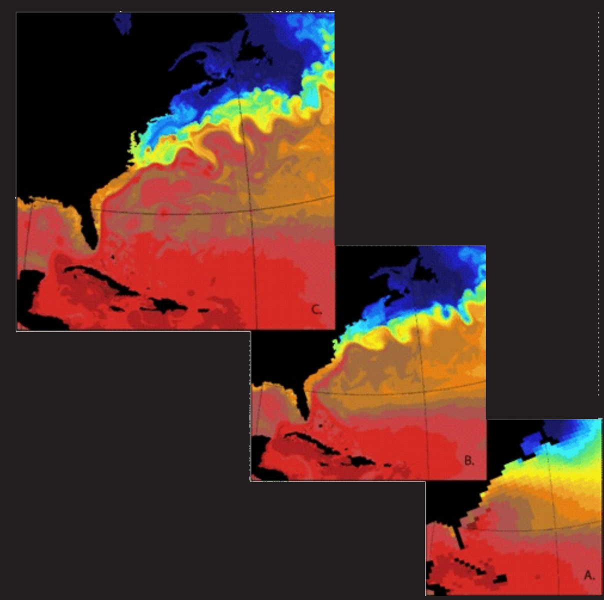
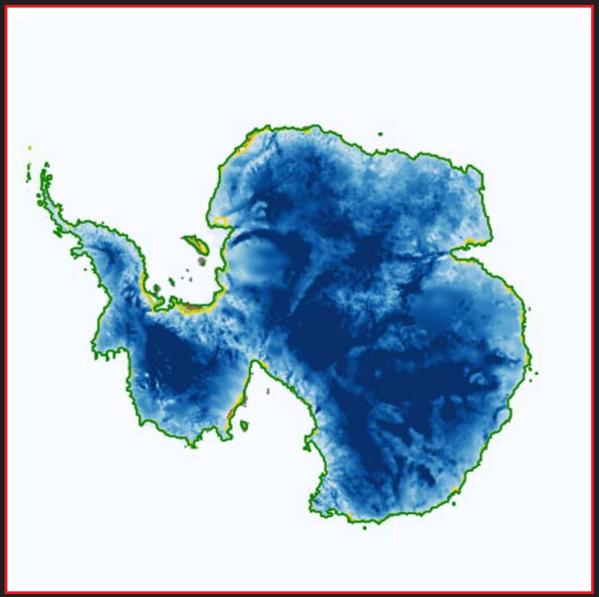


Earth system model
(CO_2 and mean SST trajectories)

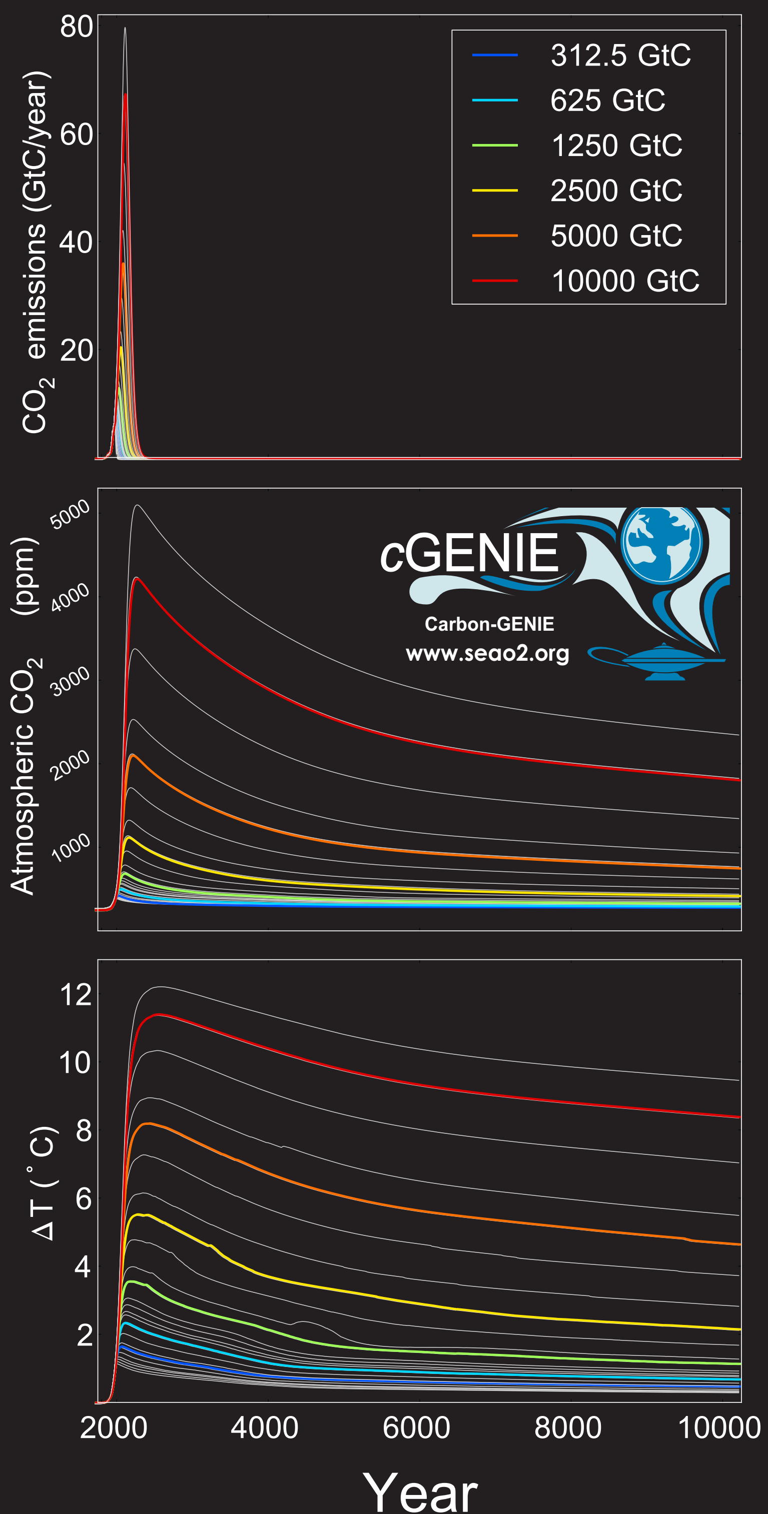


Downscaling
(SO SST and regional climate)



Ice sheet model

(II) *Melting Antarctica*



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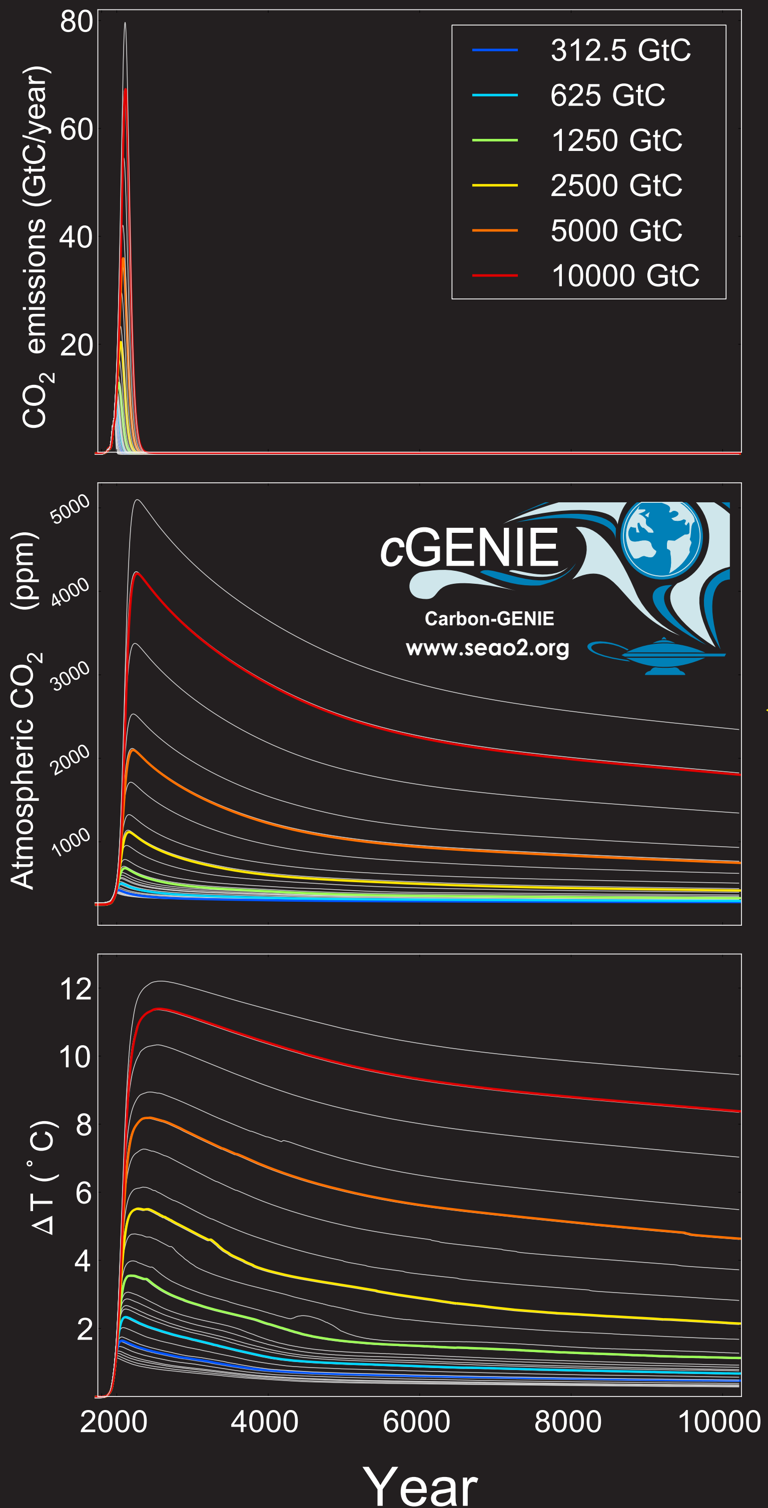
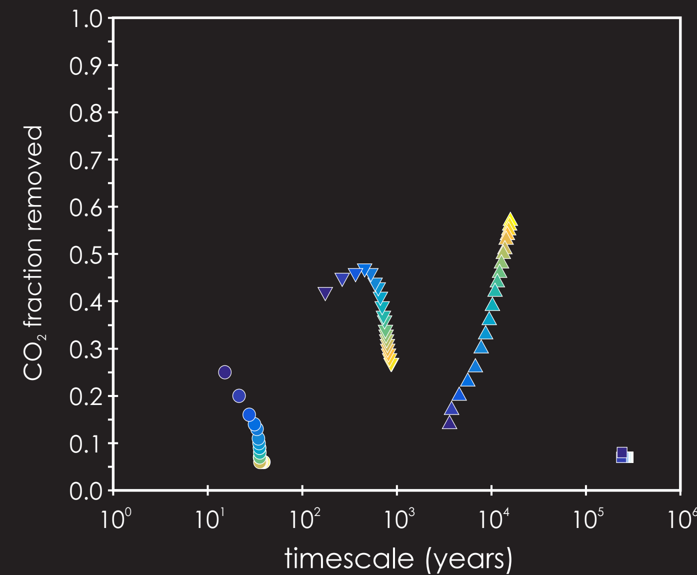
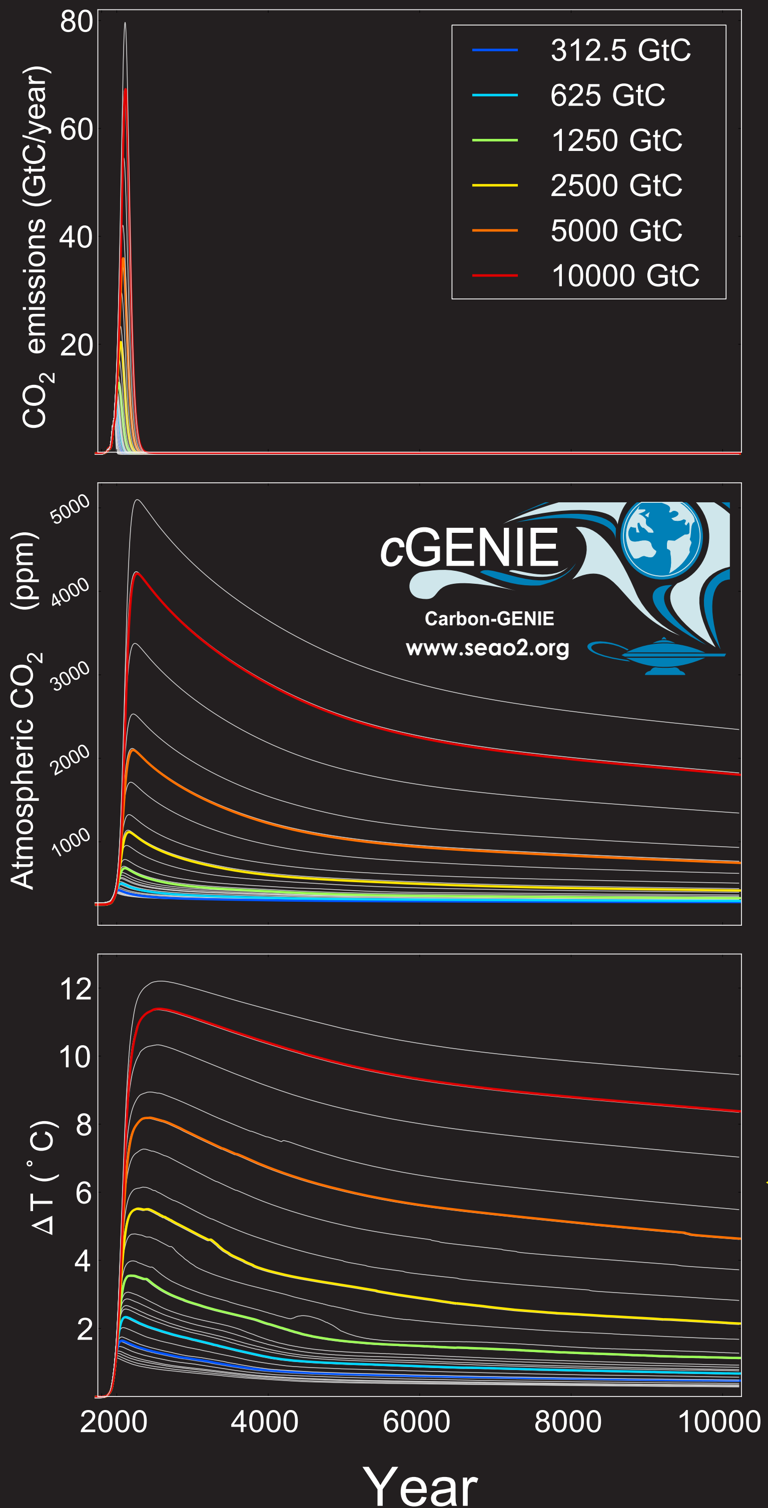
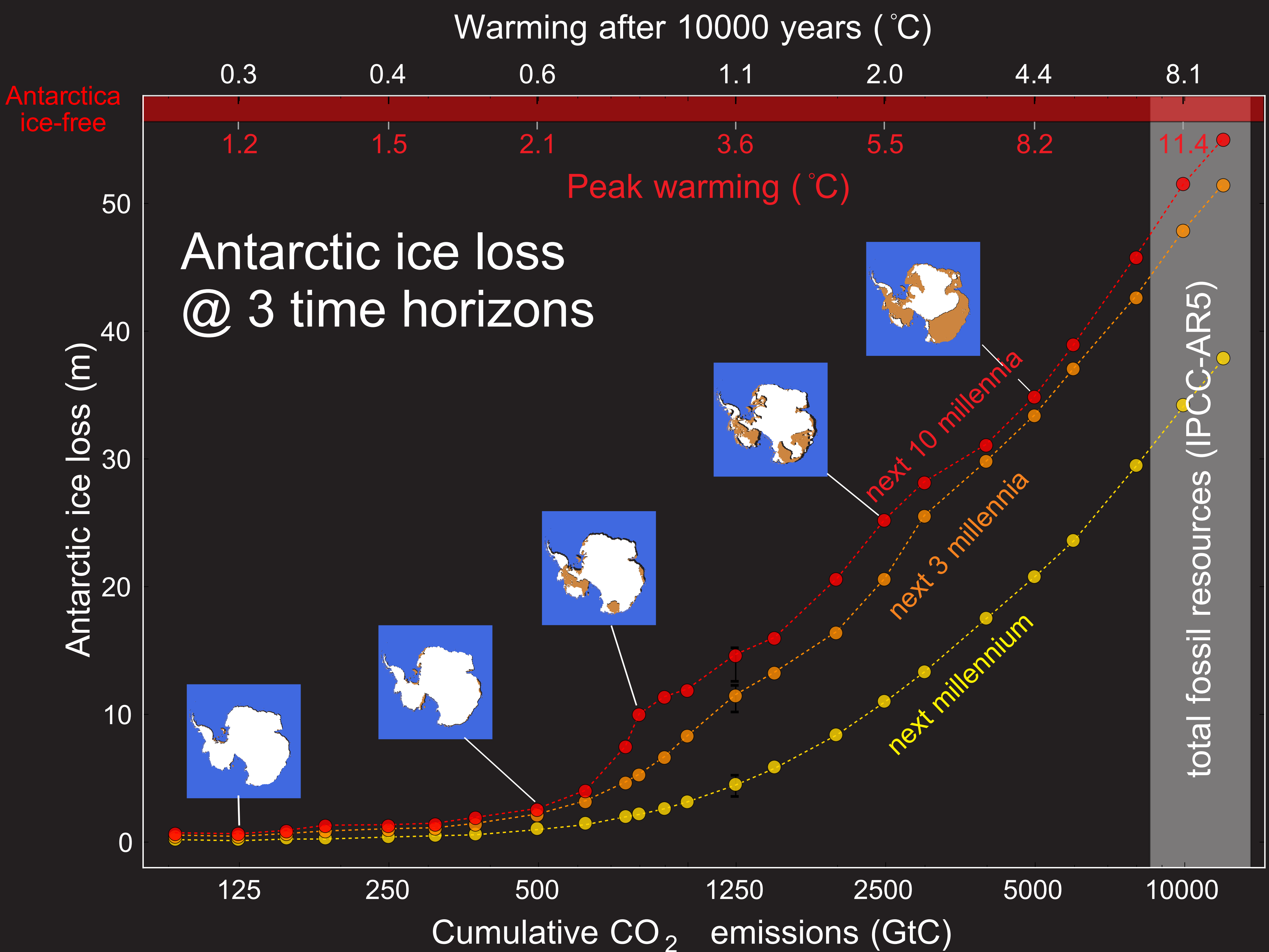


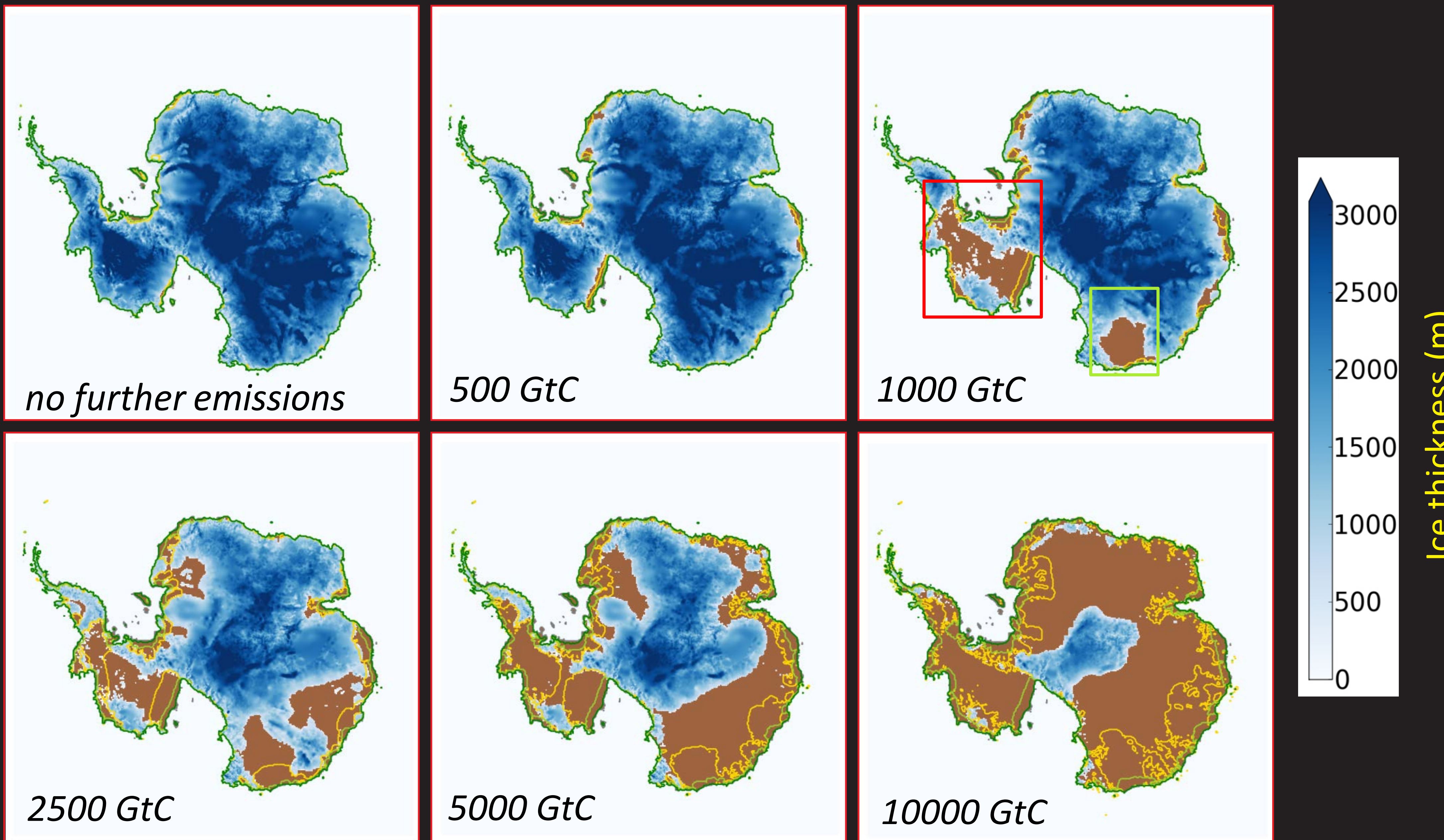




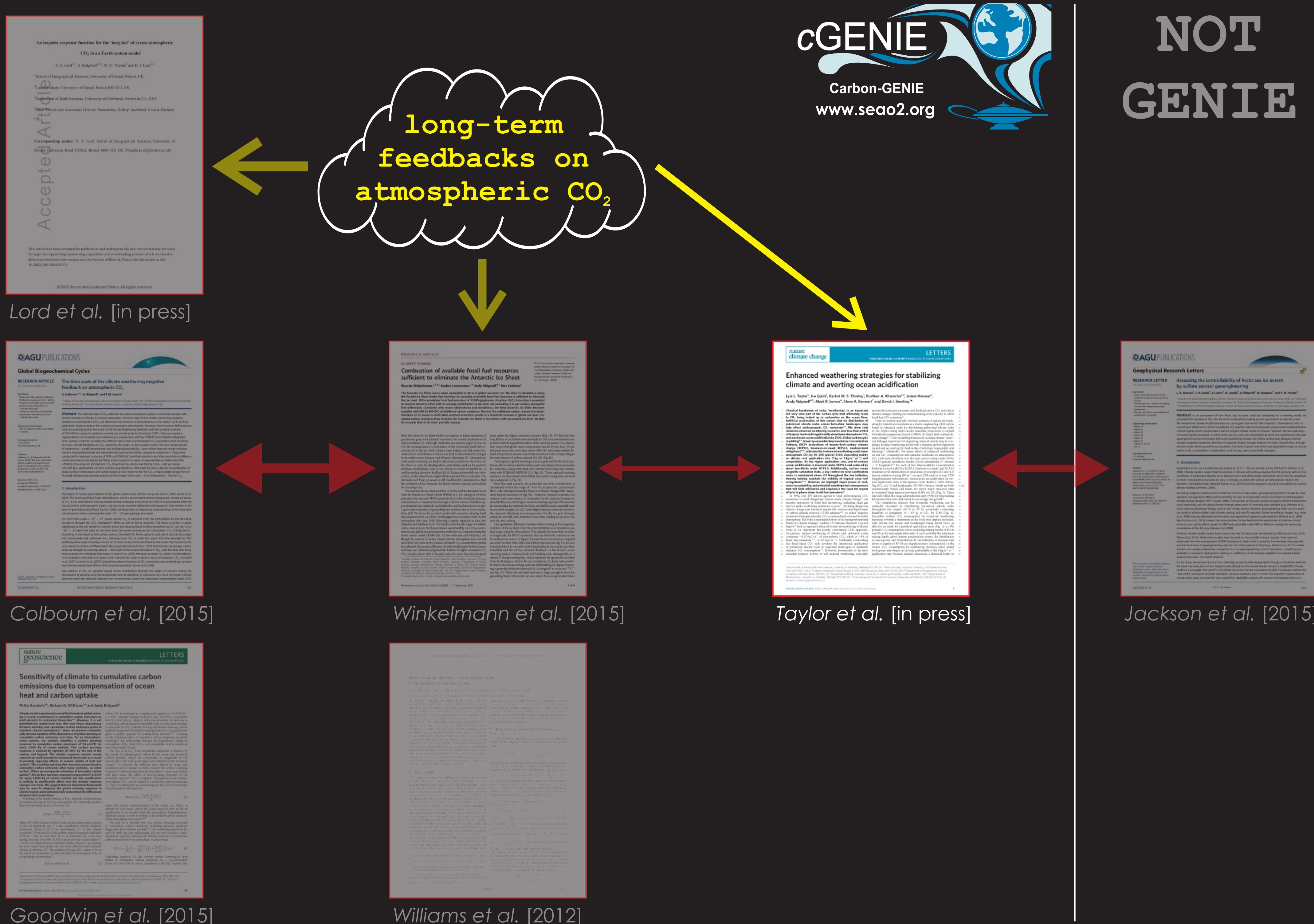
$\Delta F \propto \ln(C/C_o)$


Warming after 10000 years (°C)
0.3
0.4
0.6
1.1
2.0
4.4
8.1
Antarctica ice-free
1.2
1.5
2.1
3.6
5.5
8.2
11.4
Peak warming (°C)
Antarctic ice loss
@ 3 time horizons
Antarctic ice loss (m)
50
40
30
20
10
0
next 10 millennia
next 3 millennia
next millennium
total fossil resources (IPCC-AR5)
125
250
500
1250
2500
5000
10000
Cumulative CO_2 emissions (GtC)

Projected ice sheet extent after 10,000 years



(III) *Enhanced weathering (CO_2 removal geoengineering)*



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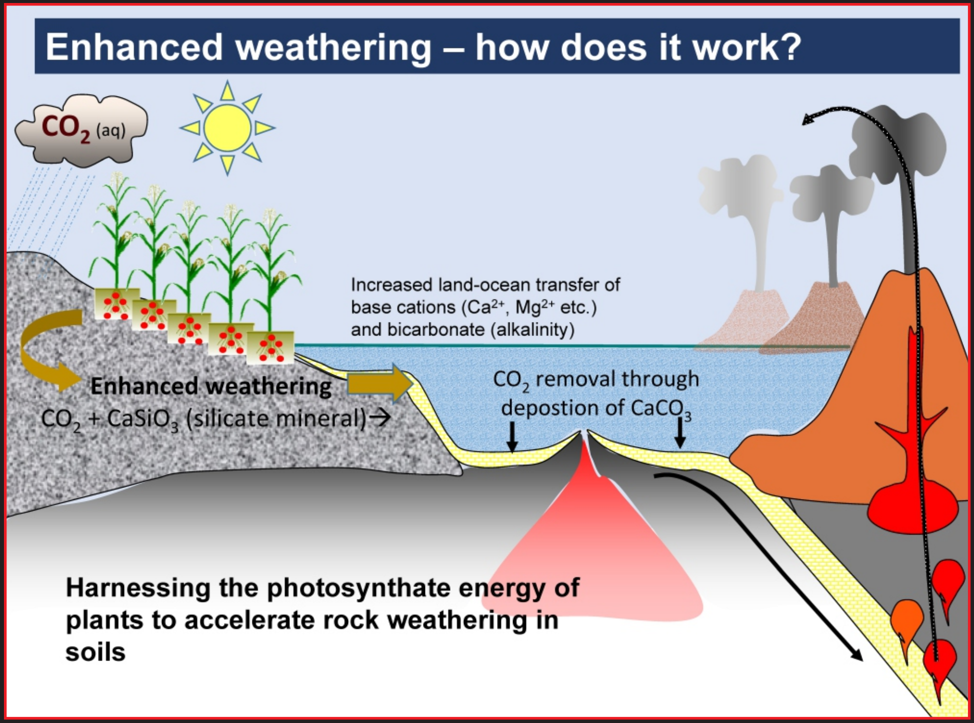


David Beerling

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.

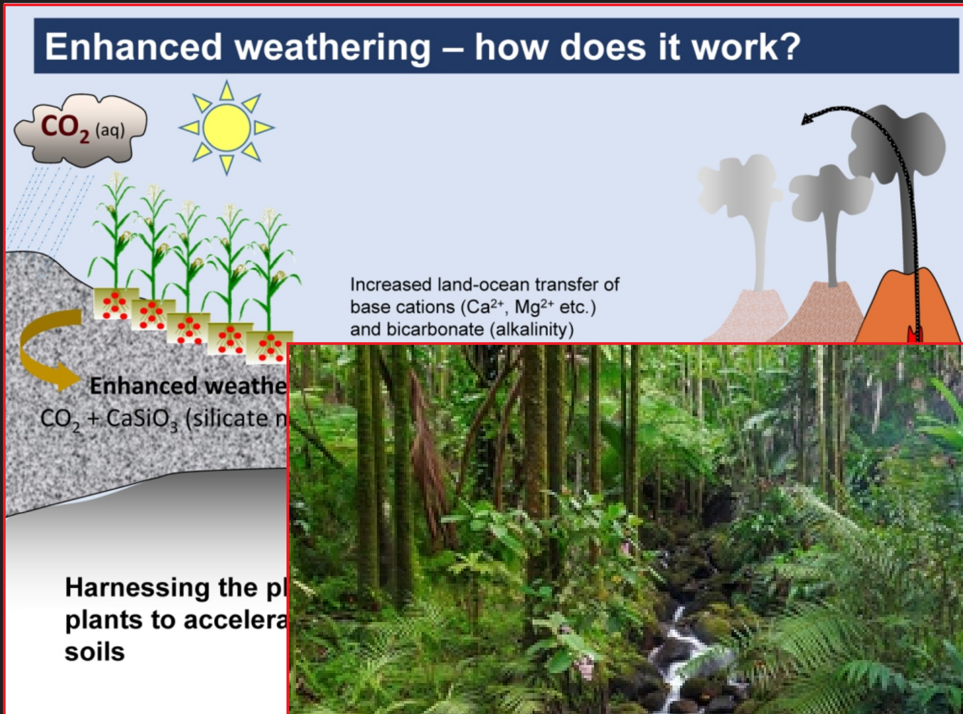
Furthermore, the rate of silicate weathering should scale with climate:

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

Equally:

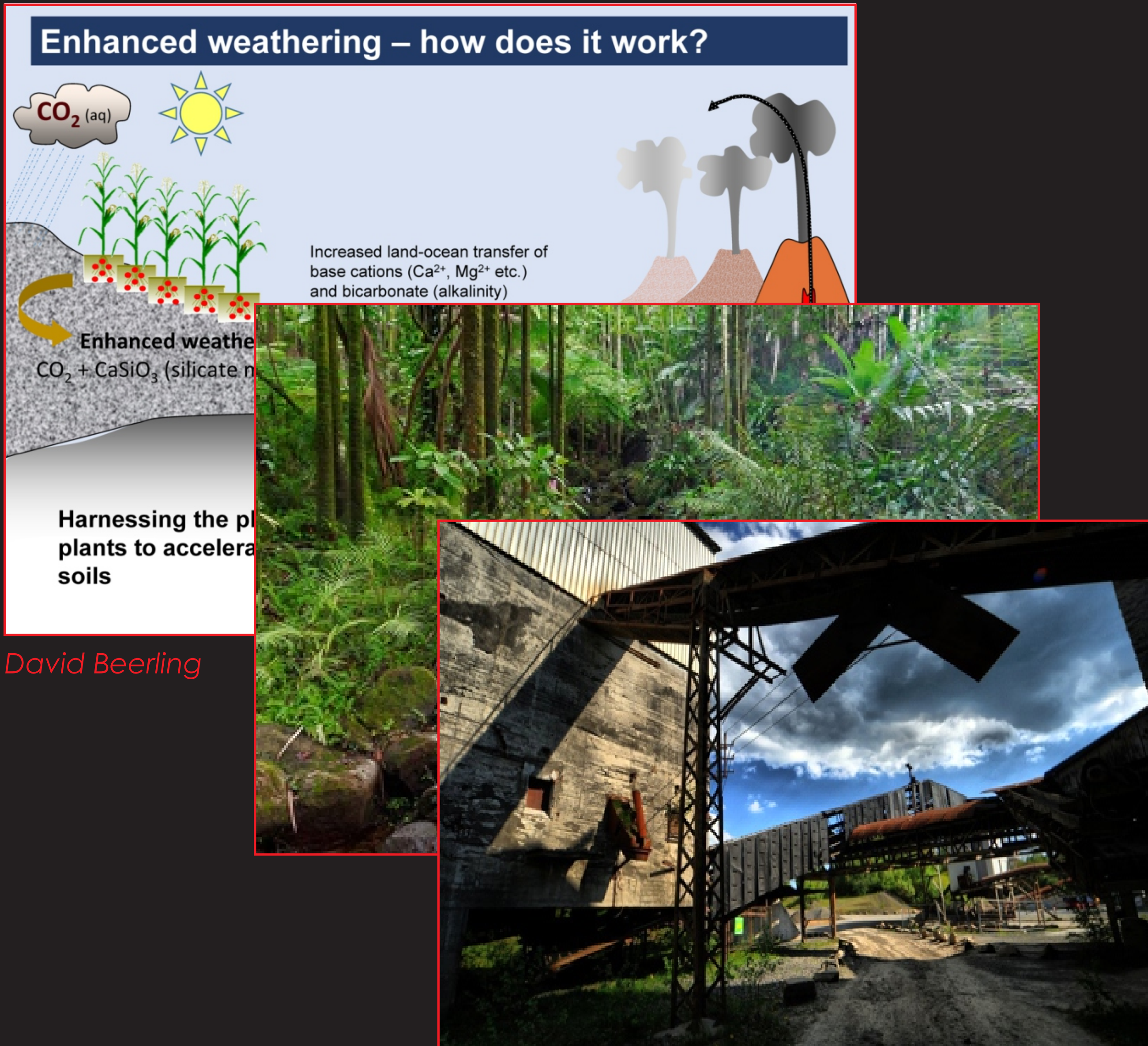
greater mineral surface availability → higher weathering rates → lower pCO_2

(III) *Enhanced weathering (CO_2 removal geoengineering)*

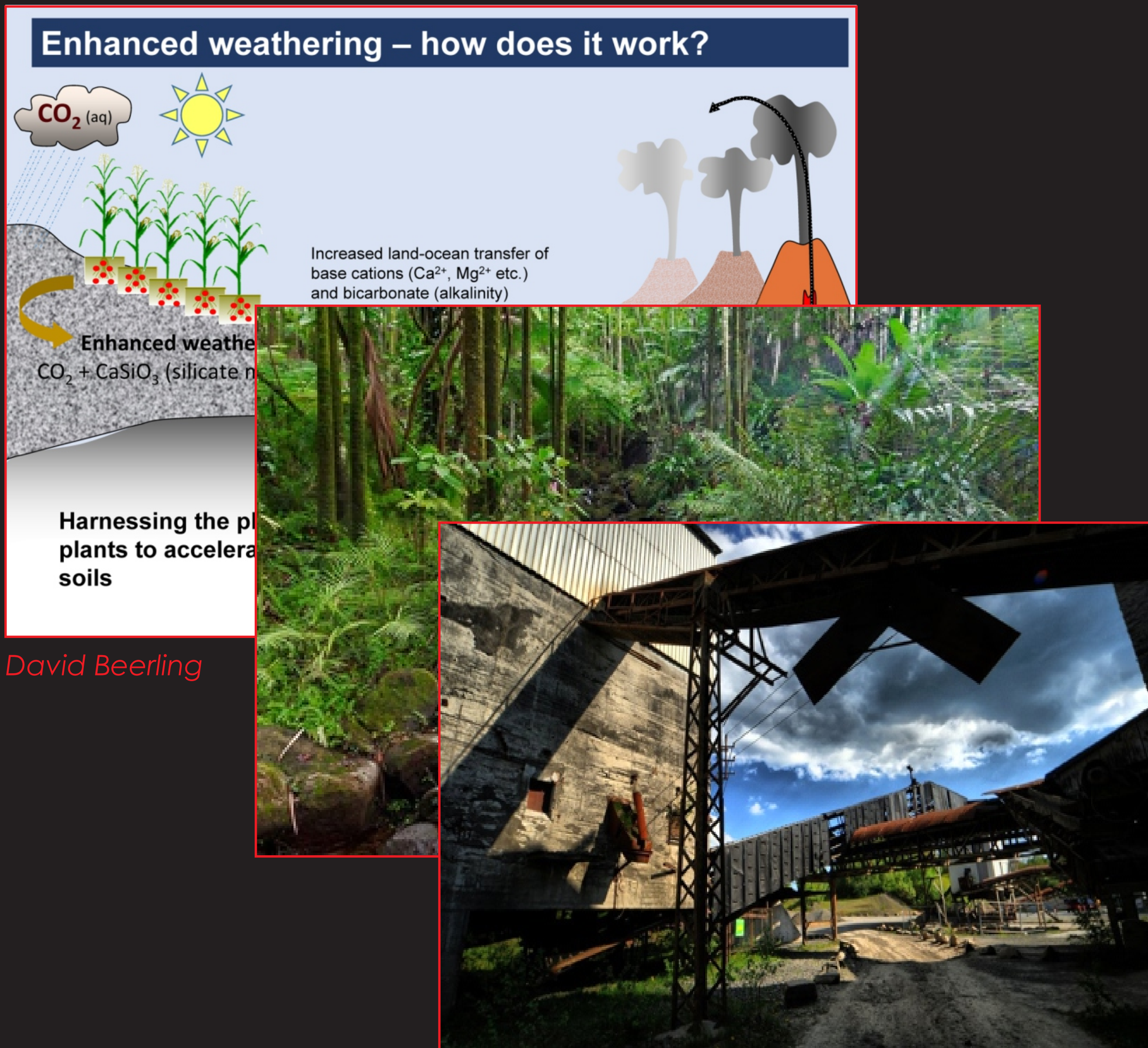


David Beerling

(III) *Enhanced weathering (CO_2 removal geoengineering)*



David Beerling



David Beerling

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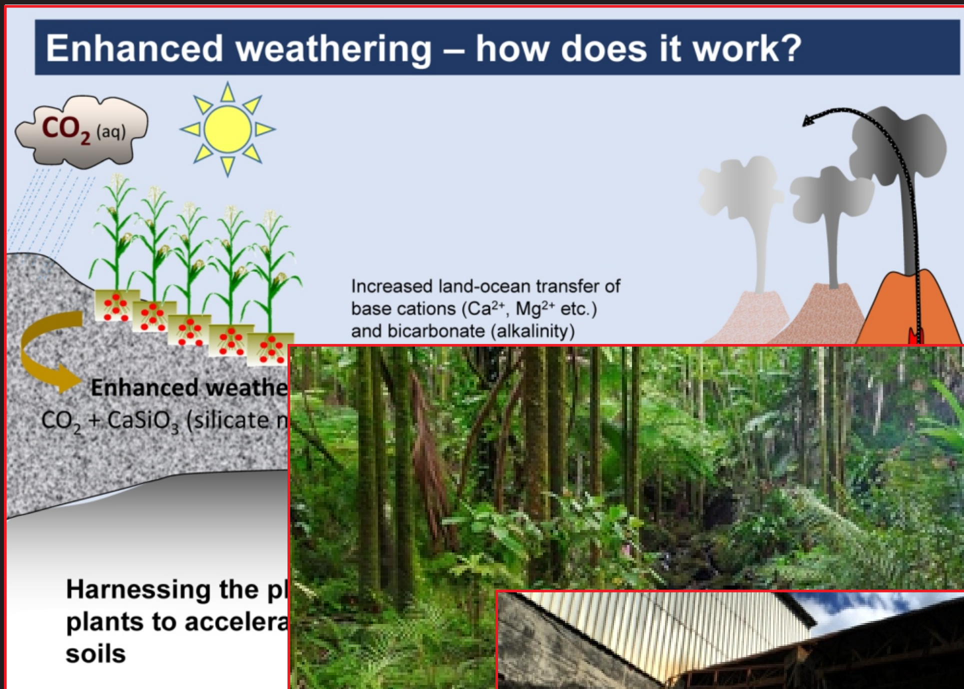

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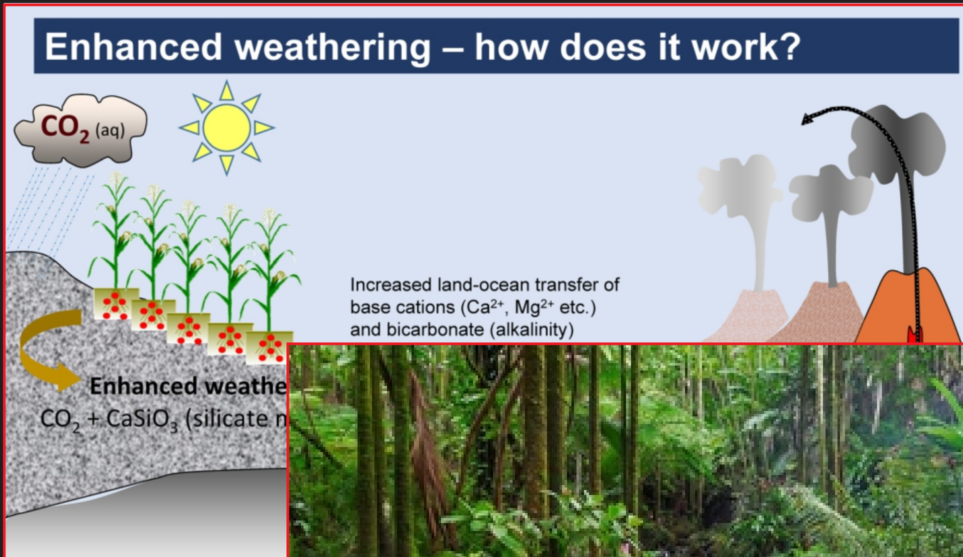


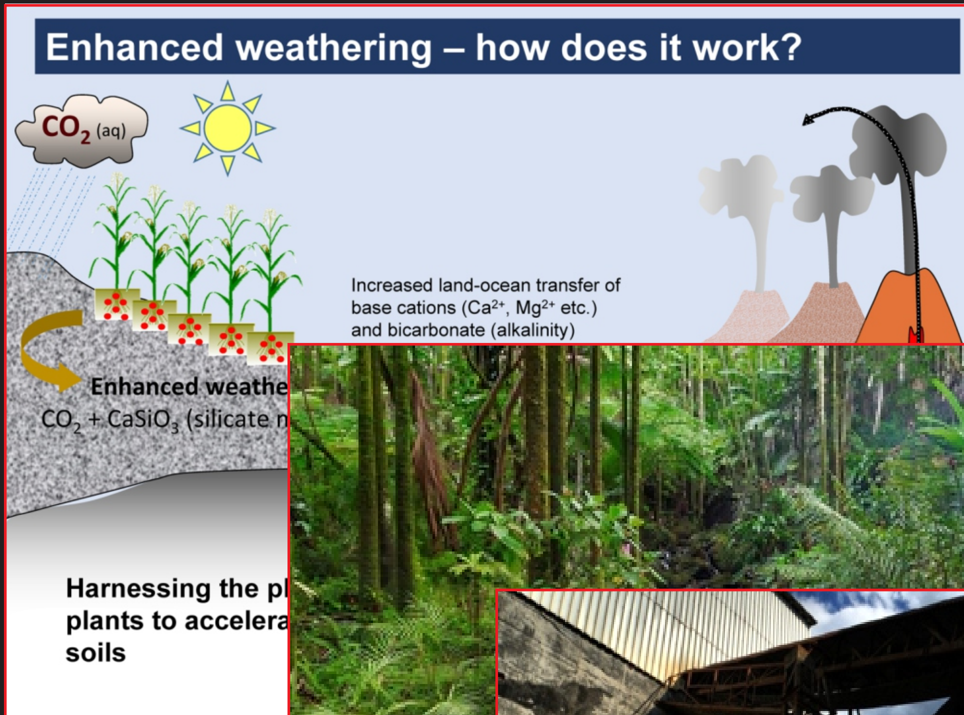
David Beerling

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

Dunite

(III) *Enhanced weathering (CO_2 removal geoengineering)*

GEO250.2015



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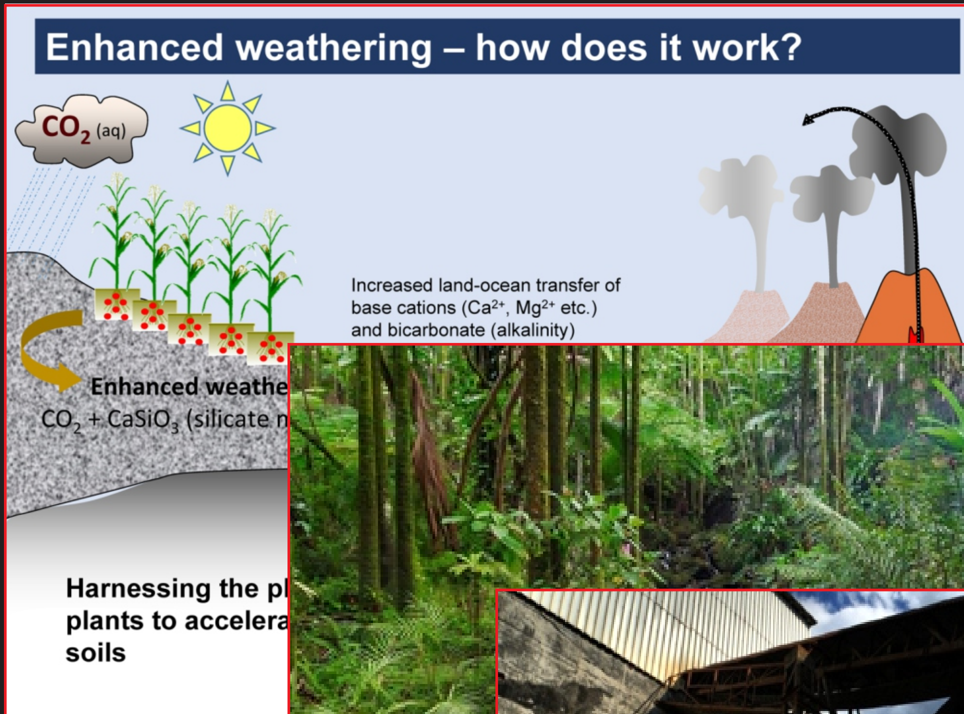

David Beerling

~ olivine + pyroxene

Harzburgite

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

Dunite

(III) *Enhanced weathering (CO_2 removal geoengineering)*

David Beerling

~ olivine + pyroxene

Harzburgite

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

Dunite

(III) *Enhanced weathering (CO_2 removal geoengineering)*

David Beerling

Harzburgite

~ olivine + pyroxene

~ plagioclase + pyroxene (+olivine)

Dunite

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

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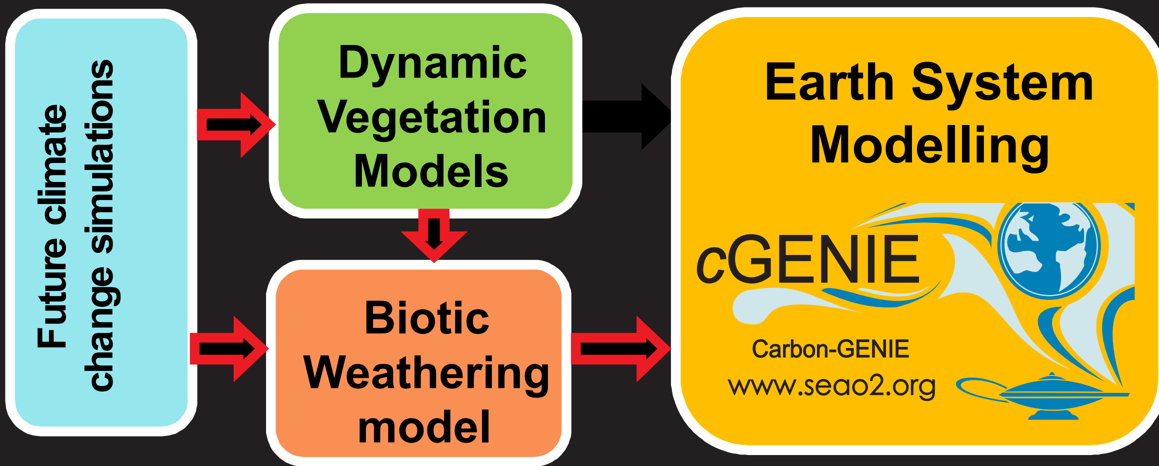

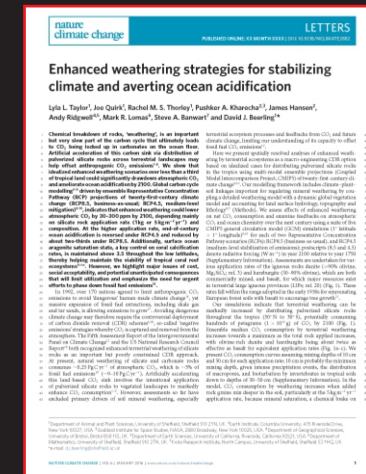

Taylor et al. [in press]

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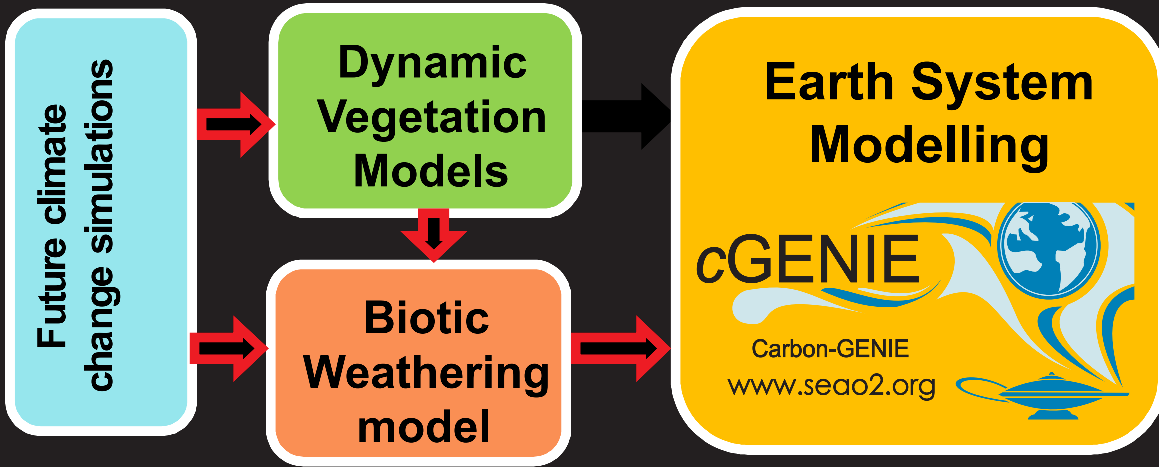

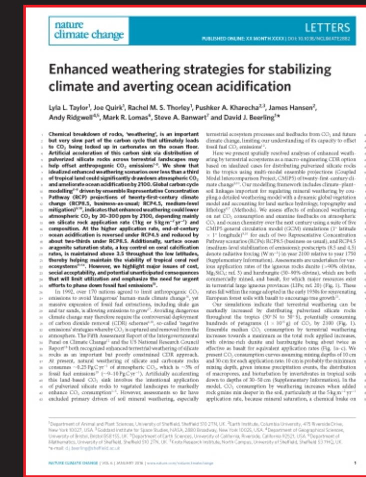
nature climate change
LETTERS

Enhanced weathering strategies for stabilizing climate and averting ocean acidification

Lyla L. Taylor, Joe Quirk, Rachel M. S. Thorley, Pushker A. Kharecha, James Hansen, Andy Ridgwell, Mark R. Lomas, Steve A. Banwart and David J. Beerling

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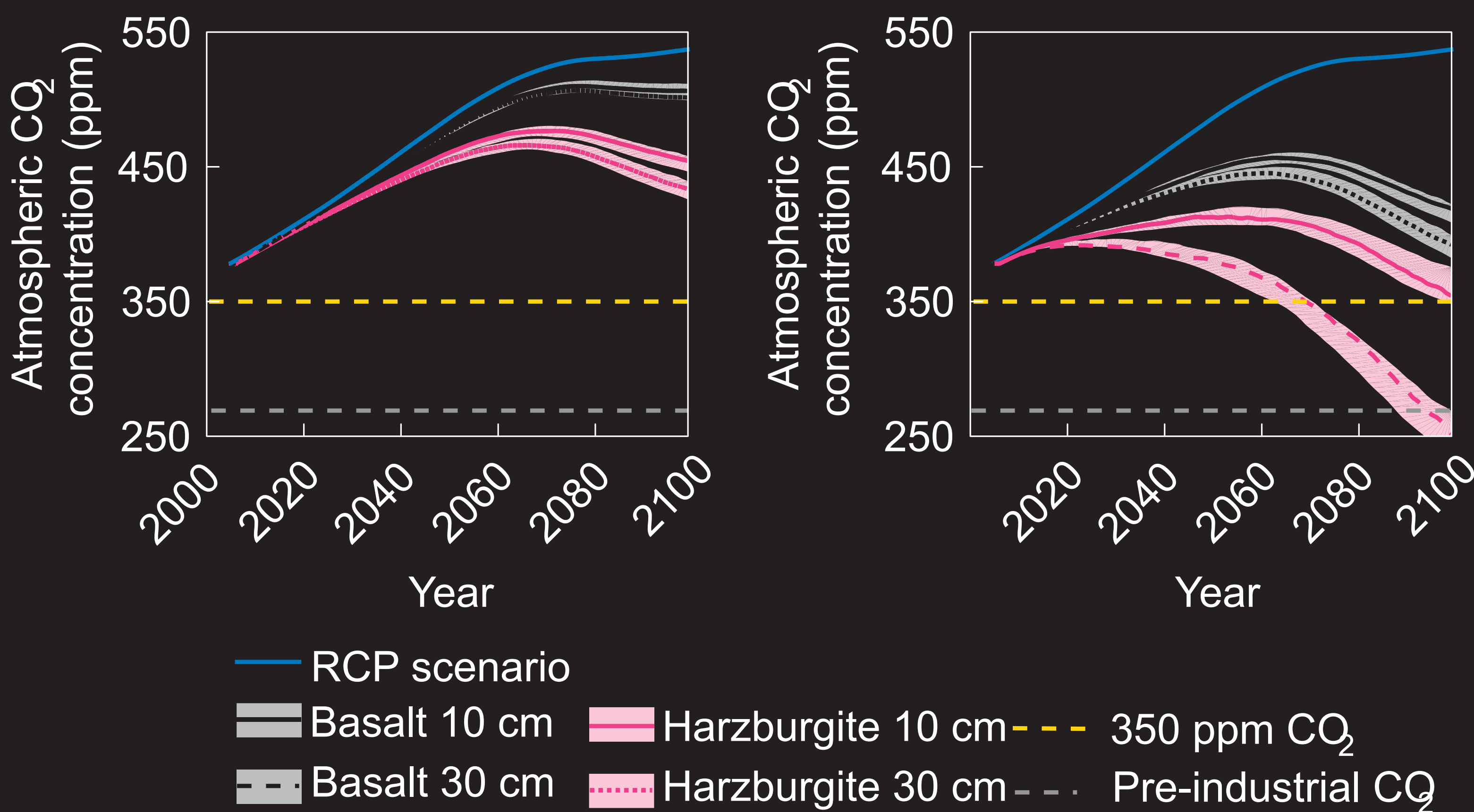
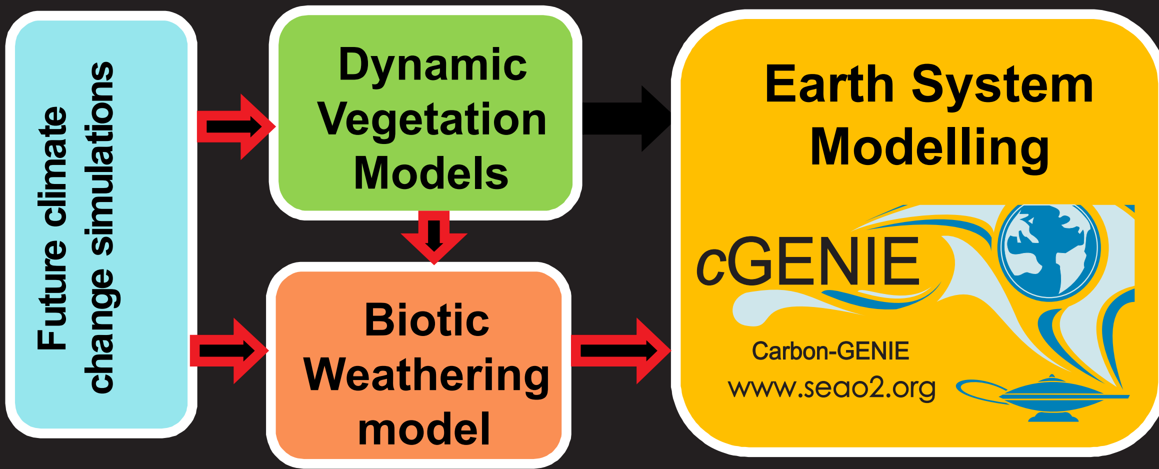
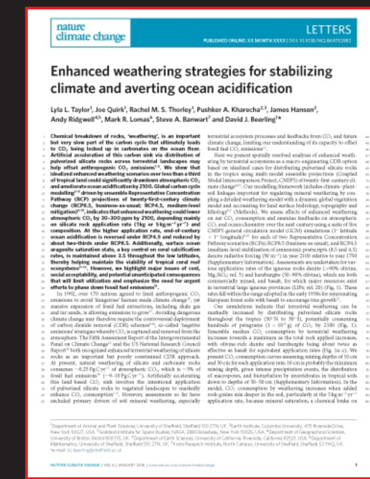


(III) *Enhanced weathering* (CO_2 *removal geoengineering*)

GEO250.2015





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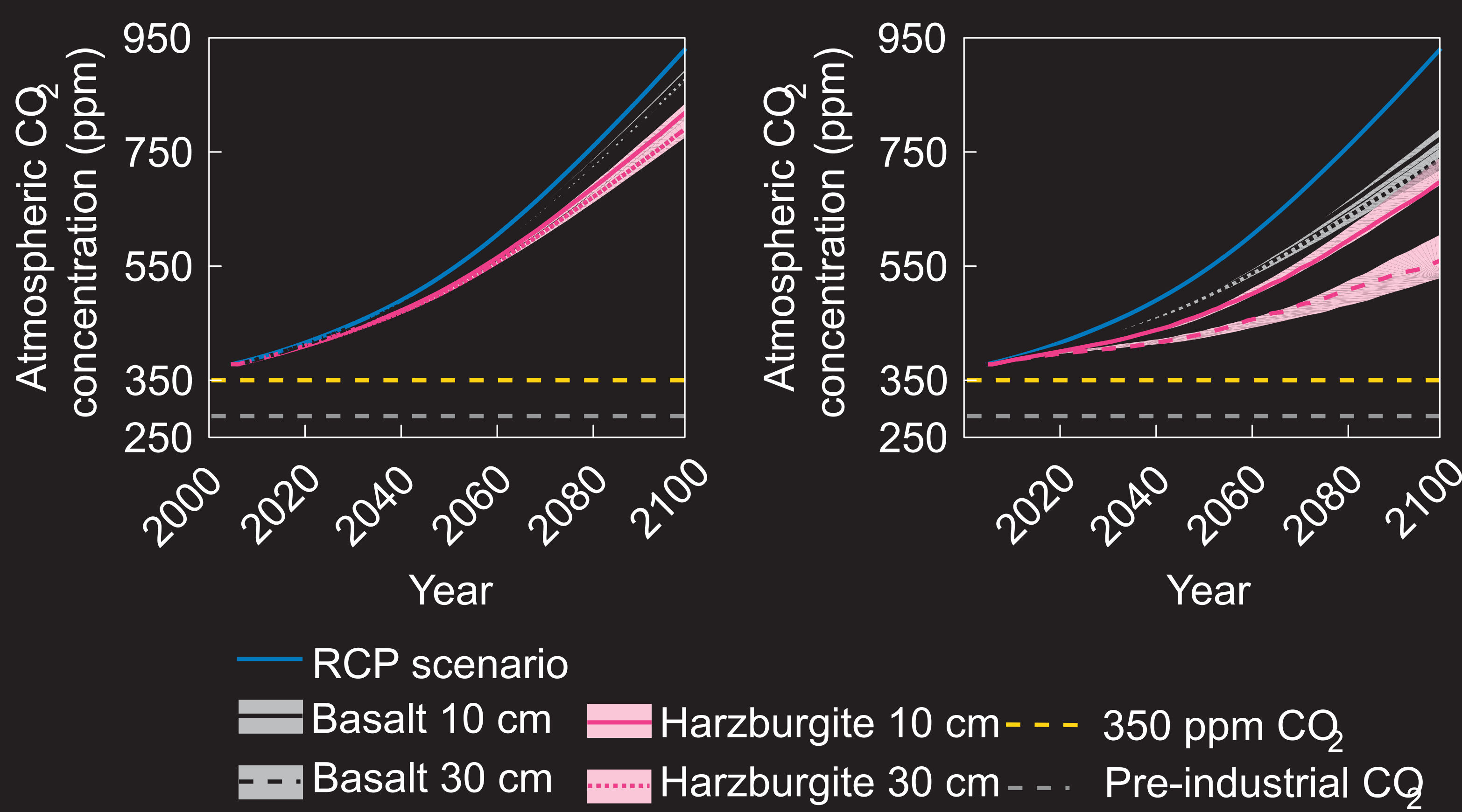

Current global oil consumption = $90{,}136 \times 10^3$ barrels per day

1.0 barrel = 159 l
= 159×10^3 cm^3

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

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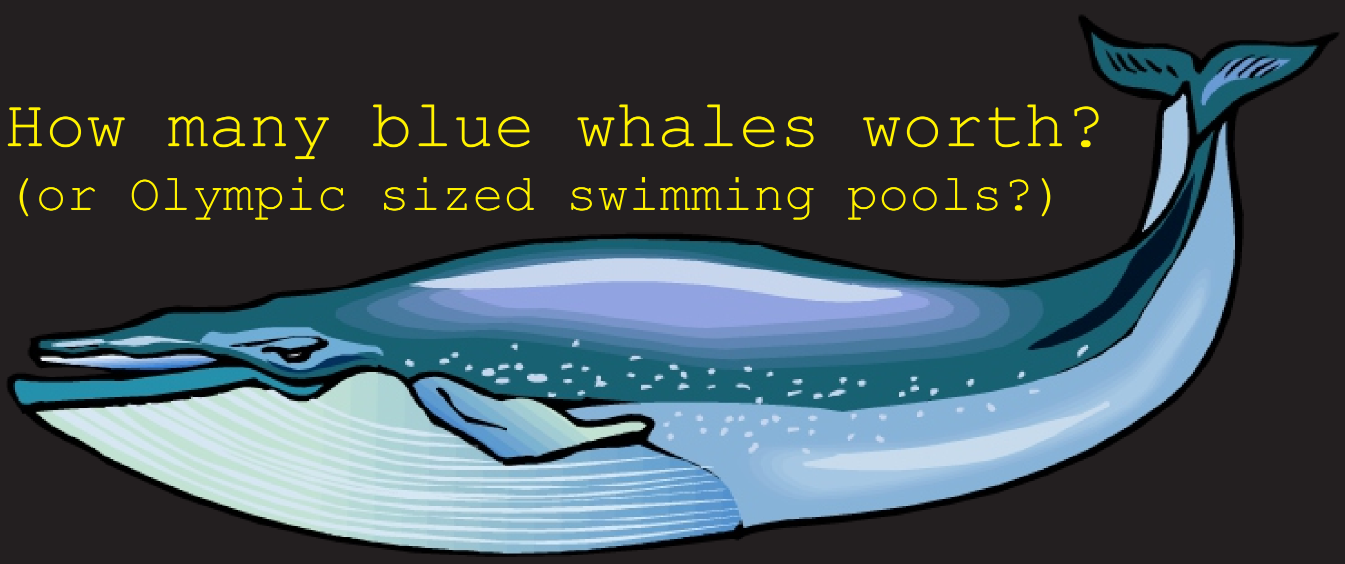
$\Rightarrow$ oil consumption
= 5.23×10^{15} cm^{3} $year^{-1}$
= 5.23 km^{3} $year^{-1}$

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



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How many Yosemite Valleys?
(equivalent volume)

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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)

NOT GENIE

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering

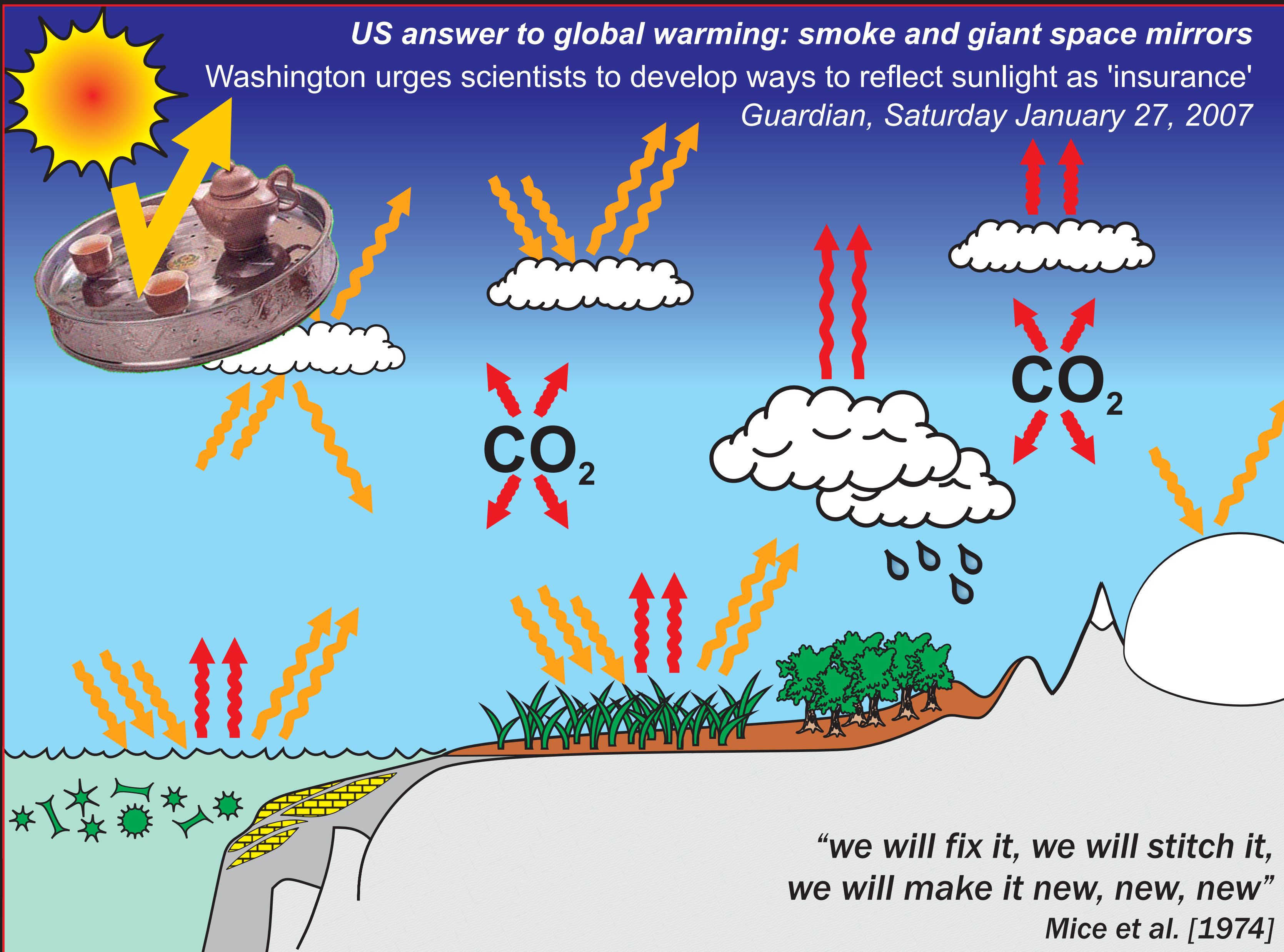
L. S. Jackson[1], J. A. Crook[1], A. Jarvis[2], D. Leedal[2], A. Ridgwell[3], N. Vaughan[4], and P. M. Forster[1]

Abstract In an assessment of how Arctic sea ice cover could be remediated in a warming world, we simulated the injection of SO_2 into the Arctic stratosphere making annual adjustments to injection rates. We treated one climate model realization as a surrogate "real world" with imperfect "observations" and no rerunning or reference to control simulations. SO_2 injection rates were proposed using a novel model predictive control regime which incorporated a second simpler climate model to forecast "optimal" decision pathways. Commencing the simulation in 2018, Arctic sea ice cover was remediated by 2043 and maintained until solar geoengineering was terminated. We found quantifying climate side effects problematic because internal climate variability hampered detection of regional climate changes beyond the Arctic. Nevertheless, through decision maker learning and the accumulation of at least 10 years time series data exploited through an annual review cycle, uncertainties in observations and forcings were successfully managed.

1. Introduction

Jackson et al. [2015]

(IV) *Not GENIE (stratospheric sulphate geoengineering)*



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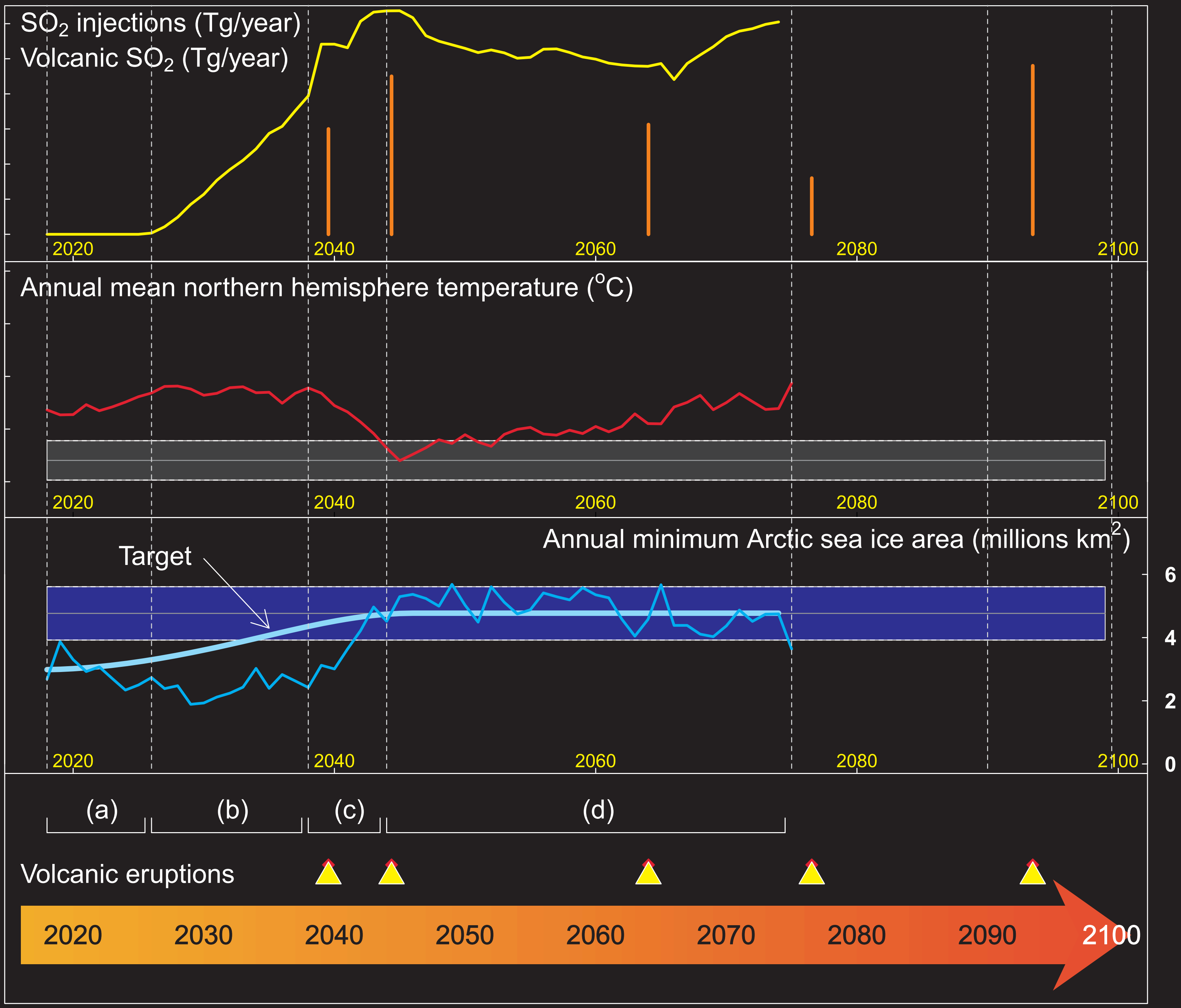

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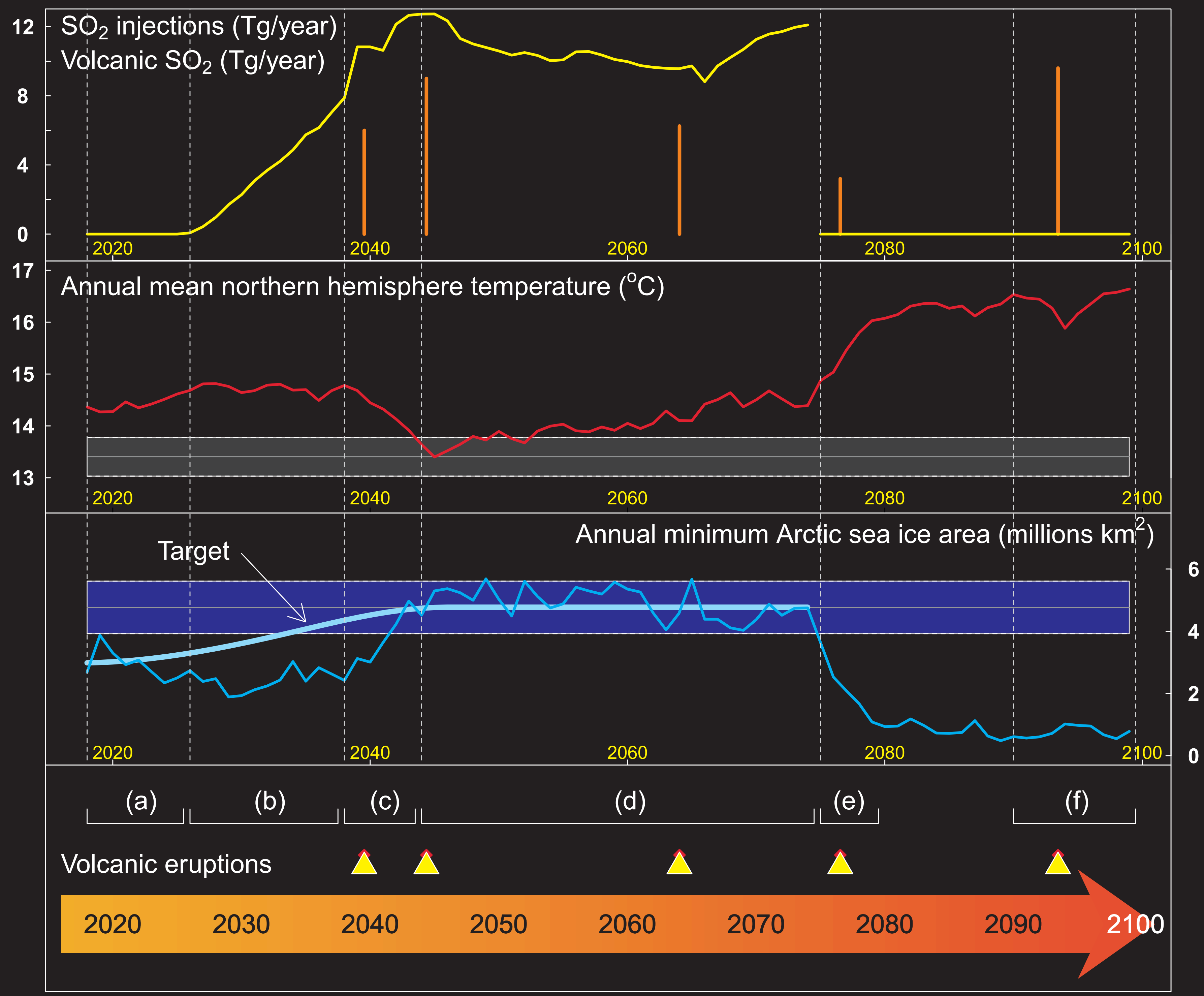

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