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An empirical response function for the long-term fate of excess atmospheric CO_2

Natalie S. Lord[1], Dan J. Lunt[1], Andy Ridgwell[1], Mike C. Thorne[2]

[1] School of Geographical Sciences, University of Bristol, [2] Mike Thorne and Associates Limited

Contact: Natalie.Lord@bristol.ac.uk

Introduction

The ultimate fate of fossil fuel CO_2 emitted to the atmosphere is governed by a range of sedimentological and geological processes operating on timescales of up to hundreds of thousands of years.

However, the response of these carbon cycle processes to increasing total emissions is uncertain, such as whether some sinks might saturate or feedbacks weaken.

The lifetime of an atmospheric CO_2 perturbation will have important implications for components of the Earth system that are temperature-sensitive and have slow response times, such as ice sheets.

Objectives

- Investigate the atmospheric lifetime of a range of future CO_2 emissions.
- Perform a multi-exponential analysis to identify some of the carbon cycle processes acting to remove excess CO_2 from the atmosphere.
- Derive an empirical response function that can project the response of atmospheric pCO_2 to any arbitrary CO_2 emission.

Methodology

- Used *c*GENIE (Fig. 1), a coupled climate-carbon cycle Earth system model[1].

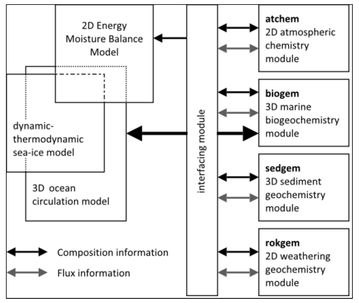

Fig. 1. *Schematic of the relationship between the different components of the cGENIE model. Arrows represent coupling.*

- Series of 1 Myr experiments (20) with pulse CO_2 emissions ranging from 1,000-20,000 PgC ("Pulse series"; Table 1).
- Series of 1 Myr experiments with time-dependent CO_2 emissions ranging from 1,500-6,300 PgC ("Time-dependent series"; Table 1).
  - Initiated from year 2010 following historical CO_2 emissions[2] (1750-2009).

Experiment ensemble	Total emissions (PgC)	Release period (yr)	Release year(s)
Pulse series	1,000 - 20,000	1	1
Time-dependent series	1,500 - 6,300	290	2010-2300

Table 1. *Summary of model experiments.*

The Long-Term Carbon Cycle

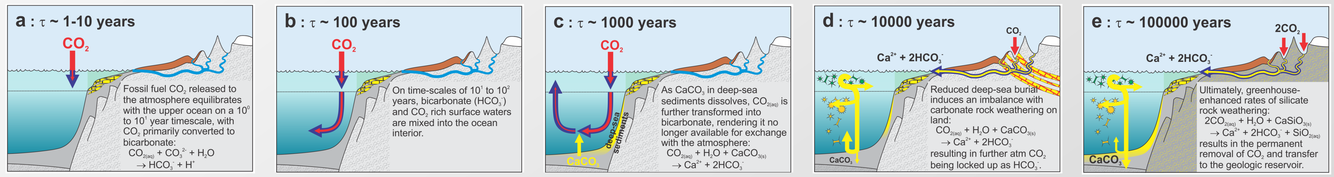

Fig. 2. *Illustration of the primary mechanisms of CO_2 sequestration from the atmosphere and their timescales of operation: (**a**) air-sea gas exchange, (**b**) ocean invasion, (**c**) seafloor $CaCO_3$ neutralization, (**d**) terrestrial $CaCO_3$ neutralization, and (**e**) the silicate weathering carbon sink.*

Analysis + Results

Multi-exponential analysis

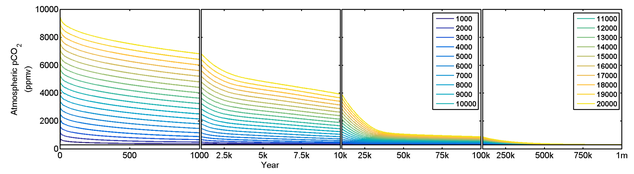

Fig. 3. *Atmospheric pCO_2 for the pulse release scenarios predicted by cGENIE. Pre-industrial concentrations are shown in black.*

- Pulse series (Fig. 3):
  - Each CO_2 decay curve was fitted with a series of exponentials (4 optimal): $CO_2(t) = B + E\sum_{i=1}^{n} A_i exp^{-(t-t_0)/\tau_i}$
  - Each exponential represents one or more of the carbon cycle processes described in Fig. 2.
  - For each exponential, the fraction of CO_2 (A_i) and the timescale of decay (τ_i) was extracted, as shown in Fig. 4.

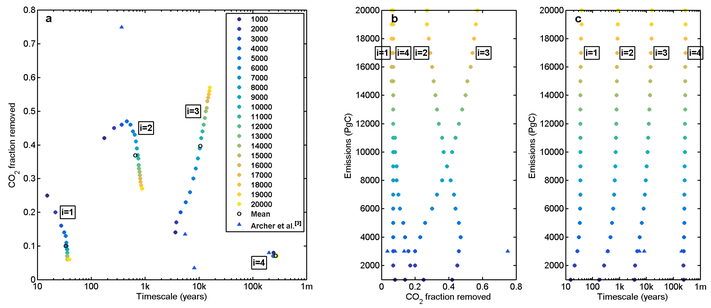

Fig. 4. *Change in fitting coefficient values (A_i and τ_i) with total CO_2 emissions in PgC (shown as different coloured dots; see legend in panel (a)). (**a**) CO_2 fraction removed vs timescale, (**b**) CO_2 fraction vs total emissions, and (**c**) timescale vs total emissions.*

Empirical response function

- The fitting coefficients (A_i and τ_i) were made quadratic functions of the total emissions.
- The predictive capability of the response function can be evaluated against the atmospheric pCO_2 predicted by *c*GENIE for the time-dependent series (Fig. 5a).

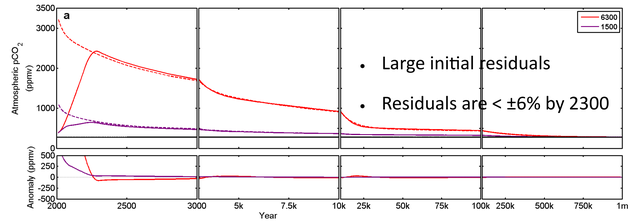

Fig. 5a. *Top panel: atmospheric pCO_2 for the time-dependent release scenarios predicted by cGENIE (solid line) and the response function (dashed line). Pre-industrial concentrations are shown in black. Bottom panel: pCO_2 anomaly.*

- A convolution analysis approach was then developed to improve the predictive performance of the response function for time-dependent emissions (Fig. 5b).

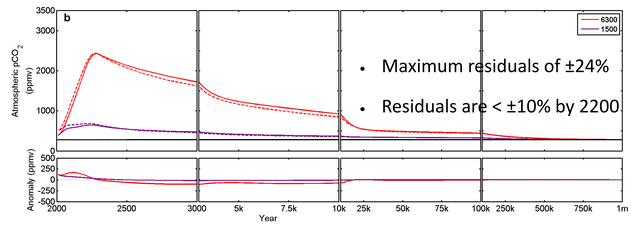

Fig. 5b. *Top panel: atmospheric pCO_2 for the time-dependent release scenarios predicted by cGENIE (solid line) and the convoluted response function (dashed line). Pre-industrial concentrations are shown in black. Bottom panel: pCO_2 anomaly.*

Conclusions

- Atmospheric CO_2 perturbations, and hence the resultant climate changes, can last for tens to hundreds of thousands of years.
- As total emissions increase, the response times of all carbon sinks (apart from silicate weathering) lengthen.
- The two processes with the shortest timescales weaken, while the ~10,000 year process of seafloor and terrestrial $CaCO_3$ neutralization strengthens.
- A number of thresholds may exist, resulting from feedbacks associated with elevated atmospheric pCO_2 levels.
- The empirical model provides a simple and practical tool for rapidly projecting the long-term fate of CO_2 emissions, and can be used in place of a mechanistic model.

References

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For further information please see: Lord et al. (in review) *Global Biogeochemical Cycles.*