Shihan Li\textsuperscript{1}, Richard E Zeebe\textsuperscript{2}, and Shuang Zhang\textsuperscript{1}

\textsuperscript{1}Department of Oceanography, Texas A\&M University
\textsuperscript{2}School of Ocean and Earth Science and Technology, University of Hawaii at Manoa

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Tracking carbon cycling with iLOSAR: an extension of the LOSCAR model with double-inversion algorithm

Shihan Li¹, Richard E. Zeebe², Shuang Zhang¹
¹Department of Oceanography, Texas A&M University, College Station, Texas 77840 | School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI, 96822, USA

1. Introduction

1.1 Perturbed carbon cycle
• 2022 C Emission: ~10 Gt
• Since 1850
  - pCO₂: 280 – 420 ppmv
  - 1.1°C increase

1.2 Geologic hyperthermal events
• Anomalous δ¹³C excursion ➔ Carbon cycle perturbation
• Rapid global warming
• Trigger: large carbon injection ➔ Modern analog

1.3 Carbon emission trajectory
• Left: emission mass ➔ How much carbon released?
• Right: isotopic signature ➔ What is the carbon source?

1.4 Current method
• Combination of proxy records and the carbon cycle model
  \[ x_{\text{model}}(t) = f(f_{\text{cinp}}(t)) \]
  - Emission trajectory
  - Carbon cycle model \( f \)
  - Modeling proxy \( x_{\text{model}}(t) \)

1.5 Aim: Inversion model development
• Proxy records \( f_{\text{cinp}}(t) \)
  - \( f_{\text{cinp}}(t) = \arg\min_{k=1} \sum_{t=1}^{n} \frac{x_{\text{model}}(t_k) - x_{\text{obs}}(t_k)}{x_{\text{obs}}(t_k)} \)

2. Model development

2.1 Base model: LOSCAR
• Atmosphere, Ocean, Sediments
• Efficient: several seconds for a 200-kyr experiment

2.2 Inversion algorithm
i. Divide the proxy data to \( n \) intervals and assume a constant emission rate within each interval, i.e.,
  \[ F_{\text{cinp}}(t_k) = k_1 (t_1 < t < t_2) \]
  \[ k_1 = \frac{k_2}{k_3} = \frac{k_4}{k_5} (t_4 < t < t_5) \]

ii. Start from the \( (t_0, t_1) \) interval and \( k_1 \) is the only free parameter that can control the modeled \( \text{pCO}_2 \).
iii. Employ numerical methods to determine \( k_1 \)
iv. Save the corresponding \( \delta^{13}C(t_1) \) as the initial \( \delta^{13}C \) for the next interval \( t_1 < t_2 \)

v. Iterate the same process until \( k_n \) is solved

3. Model validation

Event: End Permian Mass Extinction (∼252 Ma)
• 5-6‰ δ¹³C decrease
• Low-latitude 8-10°C warming

Largest mass extinction in the Phanerozoic (∼90% or marine species)
• Recent emission trajectory estimate by Wu et al., 2023
  - c-GENIE (intermediate complexity) based inversion
  - Constraints: \( \text{pCO}_2 \) and \( \delta^{13}C \)
  - Ideal for model intercomparison

4. Case study

Event: Kasimovian–Gzhelian boundary (∼304 Ma)
• δ¹³C decrease, \( \text{pCO}_2 \) increase, and global warming (Chen et al., 2022)
• Paleo-glacial state

Inversion experiment
• Input: \( \text{pCO}_2 \), Sea surface δ¹³C
• Modeling results align with proxy records
  ~9,000 Gt C emission
• Two new features
  - Negative C emission ➔ Organic C burial
  - A gradual decrease in δ¹³C

5. Summary and outlook

iLOSAR development
• A reliable, efficient and user-friendly model tool
• Open-source, https://github.com/Shihan150/iloscar, tutorial available
• Better constrain the carbon emission trajectories in geologic hyperthermal events

Outlook
• Multiple proxies inversion
• Sensitivity test of inversion results on the model settings