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

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1. Introduction

1.1 Perturbed carbon cycle

- 2022 C Emission: ~10 Gt
- Since 1850
  - pCO_2: 280 – 420 ppmv
  - 1.1℃ increase

→

- Need to decipher the carbon cycle dynamics
- Observational data NOT enough

1.2 Geologic hyperthermal events

- Anomalous $\delta^{13}C$ excursion → Carbon cycle perturbation
- Rapid global warming
- Trigger: large carbon injection → Modern analog

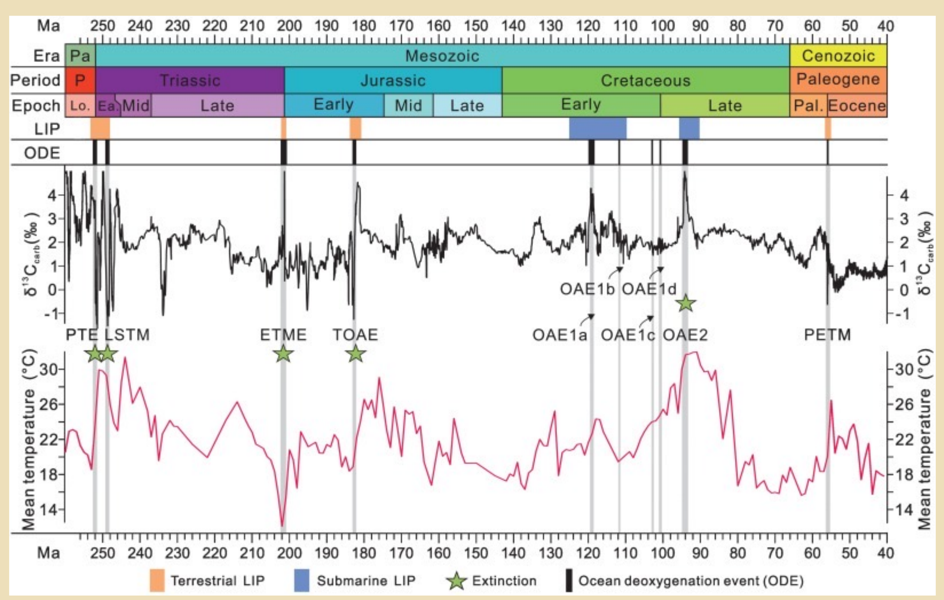

Figure 1. Integrated records of climate conditions, carbon cycle perturbations and geological hyperthermal events during the Mesozoic–Paleogene hyperthermal events (He et al., 2023)

1.3 Carbon emission trajectory

- Left: emission mass → How much carbon released?
- Right: isotopic signature → What is the carbon source?

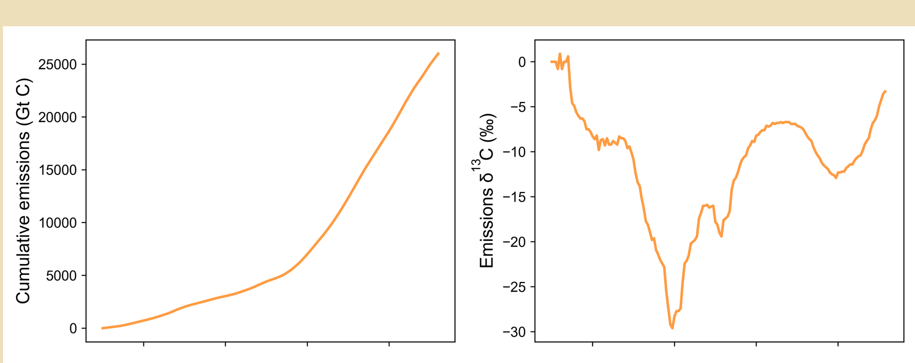

Figure 2. An example of carbon emission trajectory across a specific event.

1.4 Current method

- Combination of proxy records and the carbon cycle model
  - $x_{model}(t) = f(fcinp(t))$

Emission trajectory $fcinp(t)$ → Carbon cycle model (f) → Modeling proxy $x_{model}(t)$

1.5 Aim: Inversion model development

Proxy records $x_{obs}(t)$ (pCO_2, pH …) → Inversion model → Emission trajectory $fcinp(t)$

$$fcinp(t) = argmin \sum_{i=1}^{n} \left| \frac{x_{model}(t_i) - x_{obs}(t_i)}{x_{obs}(t_i)} \right|$$

2. Model development

2.1 Base model: LOSCAR

- Atmosphere, Ocean, Sediments
- Efficient: several seconds for a 200-kyr experiment

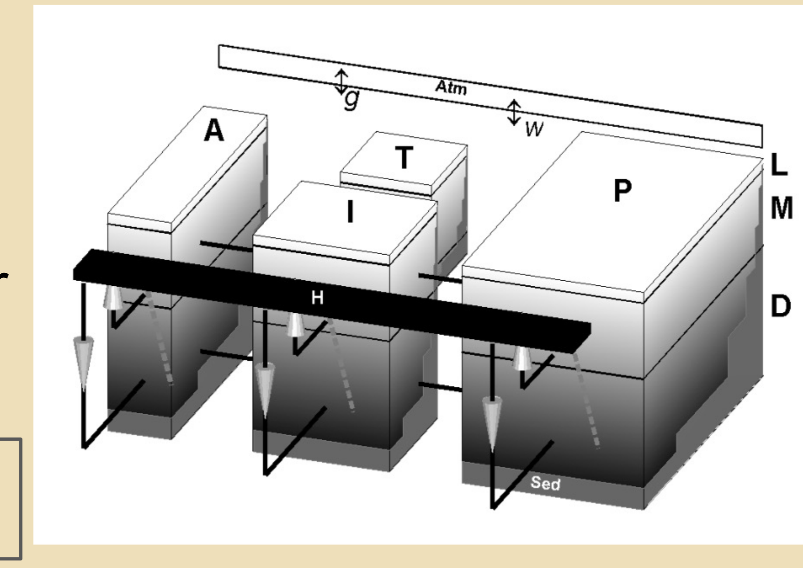

Figure 3. Architecture of the LOSCAR model (Zeebe, 2012).

2.2 Inversion algorithm

i. Divide the proxy data to n intervals and assume a constant emission rate within each interval, i.e.:

$$\begin{aligned} fcinp(t) &= k_1 \quad (if\ t_0 \le t \le t_1) \\ &= k_2 \quad (if\ t_1 < t \le t_2) \\ &\dots \\ &= k_n \quad (if\ t_{n-1} < t \le t_n) \end{aligned}$$

ii. Start from the (t_0, t_1) interval and k_1 is the only free parameter that can control the modeled pCO_2 at $t = t_1$

iii. Employ numerical methods to determine k_1

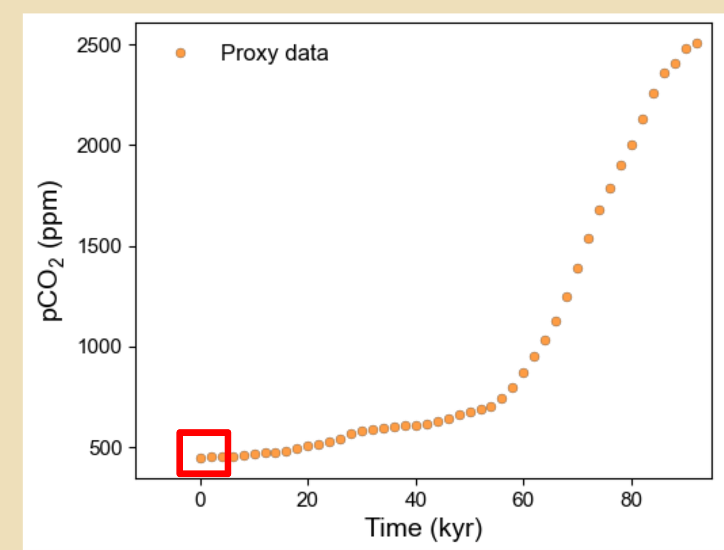

Figure 4. An example of pCO_2 records for the inversion model.

iv. Save the corresponding $\vec{y}(t_1)$ as the initial $\vec{y}$ 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‰ $\delta^{13}C$ decrease
- Low-latitude 8-10℃ 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: pCO_2 and $\delta^{13}C$
  - Ideal for model intercomparison

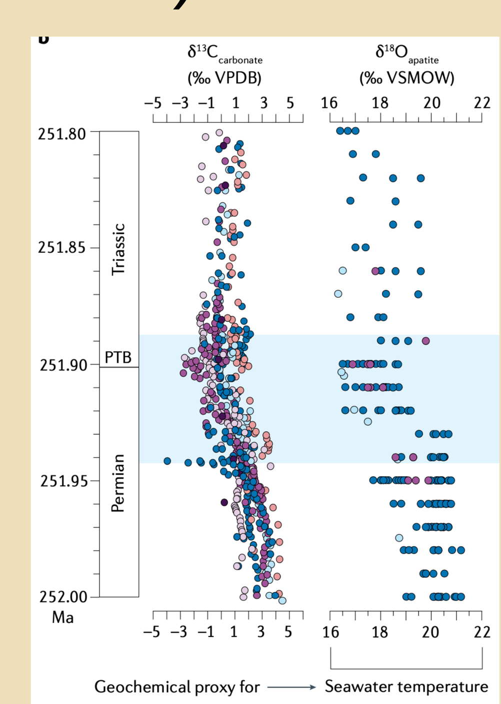

Figure 5. Compiled $\delta^{13}C$ and $\delta^{18}O$ records across the EPME, after Corso et al., 2022.

Results

- Modeling results align with proxy pCO_2 and sea surface $\delta^{13}C$ data
- Results mirror findings from Wu et al., 2023
  - ~21,000 Gt C emission
- Running time: ***13.6 min*** vs ***1-2 months*** in cGENIE

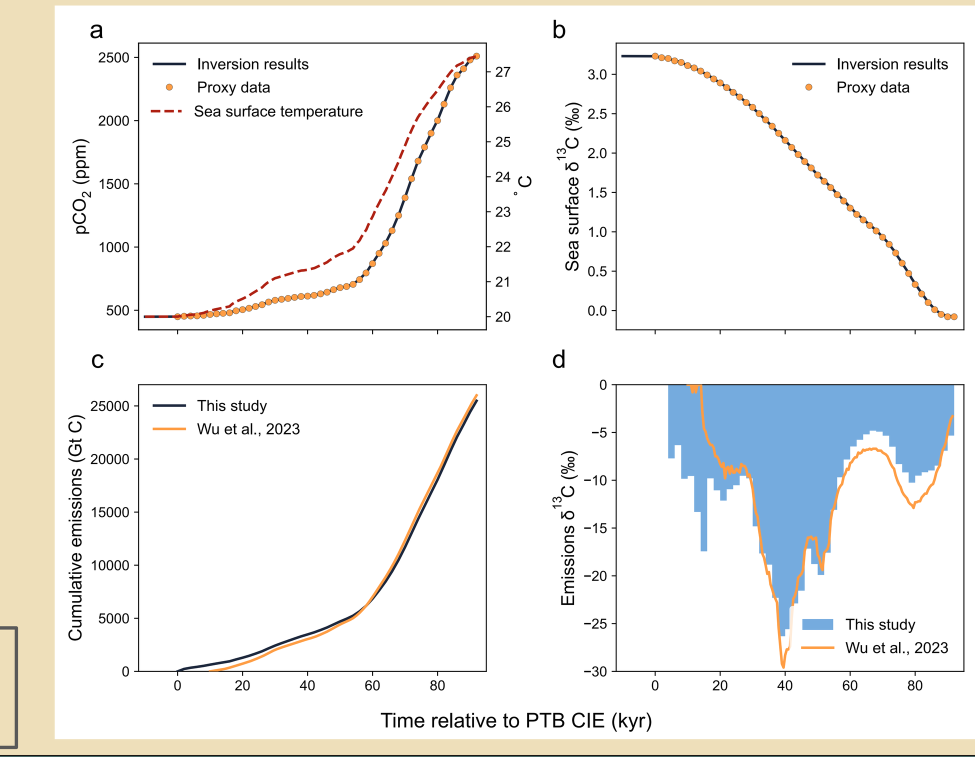

Figure 6. Inversion modeling results for the EPME.

4. Case study

Event: Kasimovian–Gzhelian boundary (~304 Ma)

- $\delta^{13}C$ decreased, pCO_2 increased, and global warming (Chen et al., 2022)
- Paleo-glacial state

Inversion experiment

- Input: pCO_2, Sea surface $\delta^{13}C$
- Modeling results align with proxy records
- ~9,000 Gt C emission
- Two new features
  - Negative C emission → Organic C burial
  - A gradual decrease in $\delta^{13}C_{source}$

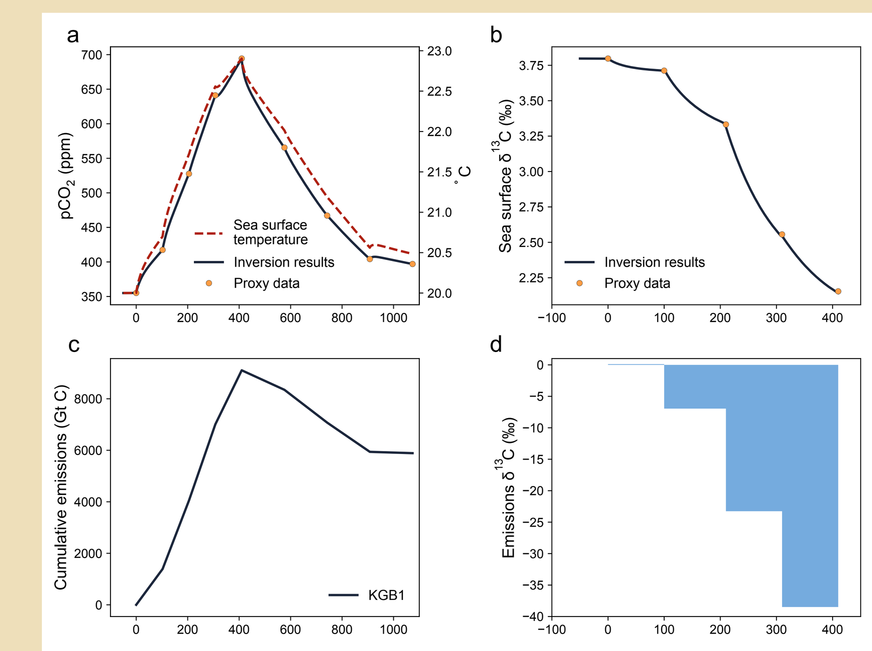

Figure 7. Inversion modeling results for the KGB.

5. Summary and outlook

iLOSCAR 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

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