NEGATIVE CARBON ISOTOPE EXCURSIONS: an interpretative framework

Supplementary Information

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Figure S1. Zonally averaged overturning circulation strengths in the symmetric pole-to-pole continental configuration used in this study (top) compared to the late Paleocene as per Panchuk et al. (2008).

Table S1. Carbon reservoirs and carbon pumps during cGENIE initial steady-state conditions

|                | Symmetric (this study) | Panchuk et al. 2008 |
|----------------|------------------------|---------------------|
| DIC pool       | ~30,000 Pg C           | ~30,000 Pg C        |
| DOC pool       | ~6.7 Pg C              | ~5.8 Pg C           |
| POC export     | 6.96 Pg C yr⁻¹         | 5.95 Pg C yr⁻¹      |
| CaCO₃ export   | 1.39 Pg C yr⁻¹         | 1.19 Pg C yr⁻¹      |

Table S2. Surface water properties during cGENIE initial steady state conditions

|                  | Symmetric (this study) | Panchuk et al. 2008 |
|------------------|------------------------|---------------------|
| Global mean SST  | 25.75°C                | 27.02°C             |
| Global mean SSS  | 34.09 psu              | 33.76 psu           |
| Global mean pH   | 7.72                   | 7.74                |
Figure S2. Gross C input over the nCIE onset for nCIEs that vary in duration, nCIE size, duration symmetry, and carbon source. Subplots a-d are scenarios in which nCIEs have a rapid onset, slow recovery (25% vs 75% of total duration). Subplots e-h are scenarios in which nCIEs have a symmetric shape with equal onset and recovery duration (50% vs 50%). Subplots i-l are scenarios in which nCIEs have a slow onset, rapid recovery (75% vs 25% of total duration). Variations in size symmetry are excluded because the ending δ¹³C value does not influence gross C input over the experiment onset. The subplot columns from left to right are nCIEs forced with carbon of δ¹³C -6.0‰, -12‰, -22‰ and -60‰, respectively. Within each subplot the gross carbon input required to generate nCIEs with various total durations and sizes is shown and color coded.
Figure S3. Cross-plots between the maximum sustained carbon flux, gross carbon input, and atmospheric CO$_2$. a) The mass of carbon input versus the maximum sustained flux of carbon, b) The mass of carbon input versus the maximum rise in atmospheric CO$_2$, and c) the maximum sustained flux of carbon versus the maximum rise in atmospheric CO$_2$ for all simulated nCIEs. For each set of simulations of certain nCIE size and carbon source, the direction of increasing onset duration is indicated with an arrow.
Figure S4. Net carbon input (carbon input minus removal) throughout the total nCIE duration required to match the prescribed nCIE profile. nCIEs are forced with carbon with a carbon isotopic signature of -6‰ (top left), -12‰ (top right), -22‰ (bottom left), and -60‰ (bottom right). Subplot rows from top to bottom are scenarios in which nCIEs have a rapid onset and slow recovery (25% vs 75% of total duration), a symmetric shape with equal onset and recovery duration (50% vs 50%) or have a slow onset and rapid recovery (75% vs 25% of total duration). The subplot columns from left to right are nCIEs with an overshoot, ‘no shoot’ and undershoot, respectively. Within each subplot the net carbon input required to generate nCIEs with various total durations and sizes is shown and color coded.
Figure S5. Change in mass of carbon in the exchangeable reservoir from nCIE onset to end to match the prescribed CIE profile. nCIEs are forced with carbon with a carbon isotopic signature of -6‰ (top left), -12‰ (top right), -22‰ (bottom left), and -60‰ (bottom right). Subplot rows from top to bottom are scenarios in which nCIEs have a rapid onset and slow recovery (25% vs 75% of total duration), a symmetric shape with equal onset and recovery duration (50% vs 50%) or have a slow onset and rapid recovery (75% vs 25% of total duration). The subplot columns from left to right are nCIEs with an overshoot, ‘no shoot’ and undershoot, respectively. Within each subplot the carbon inventory of the exchangeable reservoir at the end of a nCIE relative to the initial conditions is shown and color coded.
Figure S6. Maximum carbon input rates during nCIE onset phase required to match the prescribed nCIE profile. Subplots a-d are scenarios in which nCIEs have a rapid onset, slow recovery (25% vs 75% of total duration). Subplots e-h are scenarios in which nCIEs have a symmetric shape with equal onset and recovery duration (50% vs 50%). Subplots i-l are scenarios in which nCIEs have a slow onset, rapid recovery (75% vs 25% of total duration). Variations in size symmetry are excluded because the ending $\delta^{13}$C value does not influence gross C input and associated fluxes over the experiment onset. The subplot columns from left to right are nCIEs forced with carbon of -6.0‰, -12‰, -22‰ and -60‰, respectively. Within each subplot the maximum carbon input fluxes required to generate nCIEs with various total durations and sizes is shown.
Figure S7. Maximum increases in atmospheric carbon dioxide (CO$_2$) concentrations during the nCIE peak. Subplots a-d are scenarios in which nCIEs have a rapid onset, slow recovery (25% vs 75% of total duration). Subplots e-h are scenarios in which nCIEs have a symmetric shape with equal onset and recovery duration (50% vs 50%). Subplots i-l are scenarios in which nCIEs have a slow onset, rapid recovery (75% vs 25% of total duration). Variations in size symmetry are excluded because the final $\delta^{13}C$ value at the end of the recovery phase does not influence C input over the nCIE onset or and associated CO$_2$ (atm) concentrations. The subplot columns from left to right are nCIEs forced with carbon of -6.0‰, -12‰, -22‰ and -60‰, respectively. Within each subplot the maximum increase in CO$_2$ (atm) associated with the nCIEs of various total durations and sizes is shown.
Figure S8. Maximum change in pH and calcite saturation state (Ω_{cal}) reached during the nCIE peak. Subplots a-d are scenarios in which nCIEs have a rapid onset, slow recovery (25% vs 75% of total duration). Subplots e-h are scenarios in which nCIEs have a symmetric shape with equal onset and recovery duration (50% vs 50%). Subplots i-l are scenarios in which nCIEs have a slow onset, rapid recovery (75% vs 25% of total duration). Variations in size symmetry are excluded because the final δ^{13}C value at the end of the recovery phase does not influence carbonate chemistry at the nCIE peak. The subplot columns from left to right are nCIEs forced with carbon of -6.0‰, -12‰, -22‰ and -60‰, respectively. Within each subplot the relative changes in pH and Ω_{cal} are shown as a proportion of the maximum changes across all experiments (max. ΔpH = 1.7 and max. ΔΩ_{cal} = 5.0), associated with the nCIEs of various total durations and sizes. pH changes are adjusted to a linear scale in order to compare pH and Ω_{cal}. The top left triangle shows maximum pH change while the bottom right triangle shows maximum change in Ω_{cal} for each experiment. Yellow colors indicate maximum change, blue colors indicate little or no change.
Figure S9. Maximum global mean sea surface temperature (SST) increase during the nCIE peak. Subplots a-d are scenarios in which nCIEs have a rapid onset, slow recovery (25% vs 75% of total duration). Subplots e-h are scenarios in which nCIEs have a symmetric shape with equal onset and recovery duration (50% vs 50%). Subplots i-l are scenarios in which nCIEs have a slow onset, rapid recovery (75% vs 25% of total duration). Variations in size symmetry are excluded because the final $\delta^{13}C$ value at the end of the recovery phase does not influence gross C input and associated temperature rise. The subplot columns from left to right are nCIEs forced with carbon of -6.0‰, -12‰, -22‰ and -60‰, respectively. Within each subplot the maximum increase in global mean SST associated with nCIEs of various total durations and sizes is shown.
Figure S10. nCIE onset duration versus six carbon cycle and environmental variables at the nCIE peak. Subplots for each nCIE size are gross carbon input, change in atmospheric CO$_2$, change in surface ocean saturation state ($\Omega_{\text{cal}}$), change in surface ocean pH, change in sea surface temperature (SST), and the change in marine sedimentary wt% CaCO$_3$ for nCIEs with a size of (a) 0.5‰, (b) 1.0‰, (c) 3.0‰, and (d) 6.0‰.

Figure S11. Carbon cycle evolution and environmental impacts of nCIEs with a size of 3‰ and durations of (a) 300 kyr and (b) 100 kyr. In the left upper panel, (a) bulk $\delta^{13}$C record of the OAE-1a from Resolution Guyot (Jenkyns, 1995) with linear interpolation between nCIE onset, peak and end, based on the age model from Malinverno et al. (2010) (black line) and the simulated nCIE that best matches this record: symmetric in time with a total duration of 300 kyr (red line). In the right upper panel, (b) bulk $\delta^{13}$C record of the PETM from Site 1001A (Bralower et al., 1997) (black line) and the simulated nCIE that best matches this record: a 100 kyr-long nCIE with rapid onset (red line). Below, the evolution of the gross carbon input (solid), change in atmospheric CO$_2$ (dashed), change in surface ocean calcite saturation state ($\Omega_{\text{cal}}$, solid) and surface ocean pH (dashed), change in global mean sedimentary wt% CaCO$_3$ (solid), percentage of change in rock weathering rate relative to initial conditions (dashed), and the change in sea surface temperature (SST) for 3‰ nCIEs, forced with $\delta^{13}$C -6‰, -12‰, -22‰, and -60‰ $\delta^{13}$C carbon.
Figure S12. Climate sensitivity of cGENIE experiments in this study. Maximum temperature is compared to the maximum atmospheric CO$_2$ increase in terms of the number of doublings from an initial concentration of 834 ppm.