Pinpointing circulation changes with $\delta^{18}O$ and $\delta^{13}C$ since the last glaciation in a core from the Indian Sector of the Southern Ocean

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Introduction and Motivation

The Southern Ocean is one of the primary locations where CO_2, sequestered in the deep ocean by the biological pump, is exchanged with the atmosphere and released through upwelling. This exchange is a dynamic interaction between ocean circulation and atmospheric processes. It is well established in the palaeoceanographic community that ocean circulation changed in the past affecting this dynamic. It is therefore important to understand past circulation changes that would affect this release of CO_2 that ultimately affects global climate. Today the easterly flow in the Southern Ocean, called the Antarctic Circumpolar Current (ACC), is driven by the westerly winds and is composed of three fronts (Figure 1).

Shifted westerly winds during the Last Glacial Maximum (LGM), along with greater sea ice extent, are believed to have moved the ACC north (2, 3). This diminished the release of CO_2 in the Southern Ocean (1). The shallowing of North Atlantic Deep Water (NADW) to Glacial North Atlantic Intermediate water (GNAIW: 4) fundamentally altered the Global Overturning Circulation (GOC) enhancing the sequestration of CO_2 in the deep ocean (2).

The shift from LGM to modern climate was punctuated by a sequence of climatic events. LGM (~23-19ka) was the last time the earth's ice sheets were at their greatest extent; Heinrich Stadial 1 (HS1; ~17.5- 14.5) was a period of abrupt cooling in the northern hemisphere and warming in the southern hemisphere attended by sea ice and glacial retreat. The Antarctic Cold Reversal (ACR; ~14.5 -12.9 ka) was period of south-ern hemisphere cooling attended by increased sea ice lesser than the LGM. The Younger Dryas (YD) was a period of northern hemisphere cooling but in the southern hemisphere it was a time of warming into the Holocene. Northern GOC did not start producing NADW again until after the YD. Therefore, changes in the Southern Ocean before the Holocene are believed to be independent of the GOC (2).

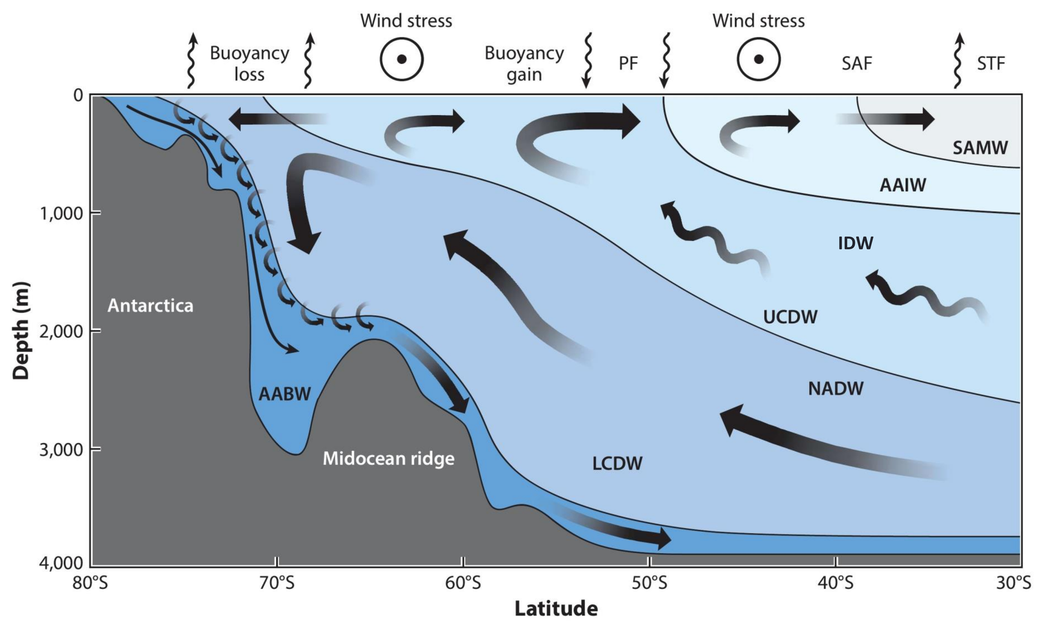


Figure 1. Cross-section of Southern Ocean Circulation. The Subtropical Front (STF) is the northern boundary of the Southern Ocean. At the Polar Front (PF) deep waters are upwelled to the surface, driving CO_2 release from the deep ocean and increased biological productivity due to upwelled nutrients. From the PF the surface water moves north toward the Subantarctic Front (SAF), releasing sequestered ^{12}C (increasing $\delta^{13}C$). This creates a $\delta^{13}C$ gradient across the Southern Ocean. At the SAF, surface waters subduct beneath formed Antarctic Intermediate Water and Subantarctic Mode Water (AAIW, SAMW). Figure from Gent (5)

Objectives

Past behaviors of the Atlantic and Pacific sectors of the Southern Ocean are well studied, however information about the Indian sector is scarce. Here we explore sediment cores from the Indian Sector to develop a clearer understanding of how the Southern Ocean upwelling has changed since the LGM relative to the atmospheric CO_2 rise and influence of GOC .

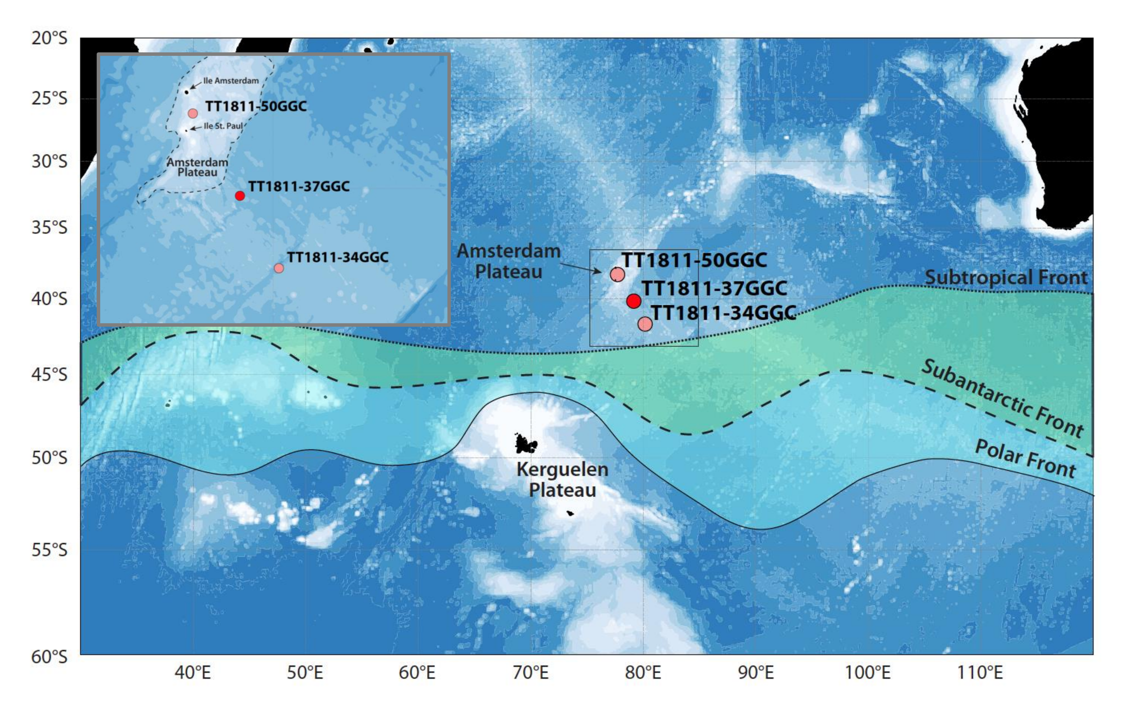


Figure 2. Study Location. Cores collected from the Indian Sector of the Southern Ocean during the CROCCA-2S expedition (red dots). Modern summer frontal locations are indicated . Figure produced by Ryan H. Glaubke.

Surface $\delta^{13}C$ in the Southern Ocean is an indicator for upwelling and productivity. The record of this is preserved in $CaCO_3$ fossils in the sediments. Three sediment cores were collected from the Indian Sector of the Southern Ocean during the Coring to Reconstruct Ocean Circulation and Carbon-dioxide Across 2 Seas (CROCCA-2S) expedition in 2018 (Figure 2).

Core 37GGC was the primary focus of this study. The first objective of this work was to Increase sampling in this core, as it was previously sampled every 4 cm for $\delta^{18}O$ and $\delta^{13}C$ analysis, and to create a high-resolution record by creating an age model from LGM to present. This enabled the second objective: to compare this record to other cores to generate a regional planktic $\delta^{13}C$ signature and answer the question of how/when the frontal location and/or upwelling changed since the last glaciation.

Results

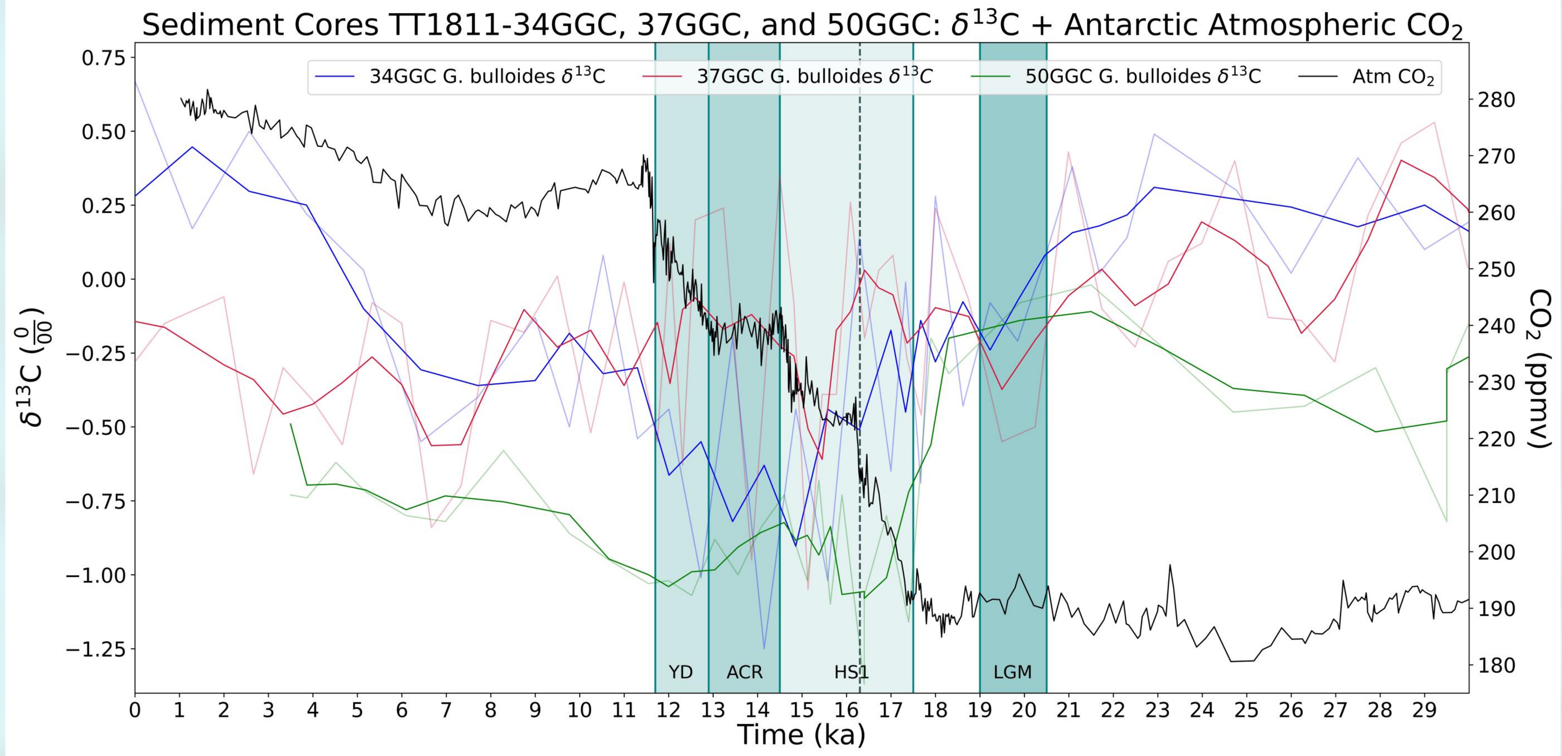


Figure 5. $\delta^{13}C$ results compared to atmospheric CO_2. Comparison of planktic $\delta^{13}C$ in sediment cores TT1811-34GGC (blue), TT1811-37GGC (red), and TT1811-50GGC (green) to Antarctic Atmospheric CO_2 (black) (6). Thick line represent the 3-point moving average of the planktic *(G. bulloides)*. $\delta^{13}C$ raw data are displayed in the same but faded colors. Millennial deglacial climatic events represented by shaded boxes YD = Younger Dryas, ACR = Antarctic Cold Reversal, HS1 = Heinrich Stadial 1, LGM = Last Glacial Maximum. Note that large decreases in $\delta^{13}C$ coincide with the increases in Atmospheric CO_2 .

Last Glacial Maximum (LGM):

Relative to modern, $\delta^{13}C$ is slightly depleted in cores 34GGC and 37GGC. This likely indicates a northward shift of the ACC relative to present, placing the cores in the Southern Ocean. This is consistent with our understanding of the LGM, with extensive sea-ice covering and north-shifted and stronger westerly winds.

Heinrich Stadial 1 (HS1):

Core 50GGC became rapidly depleted in $\delta^{13}C$ at the start of HS1, reaching maximum depletion at ~16.3 ka. This coincided with a rapid increase in atmospheric CO_2. Core 37GGC $\delta^{13}C$ drops in the second half of HS1, with 34GGC following shortly after coincident with continued increase in atmospheric CO_2. This indicates a southward shift of the ACC relative to LGM placing first 50GGC, then 37GGC in the axis of intense upwelling favorable winds and the release of CO_2 to the atmosphere in this location.

Antarctic Cold Reversal (ACR):

$\delta^{13}C$ abruptly increased in core 37GGC during the ACR, indicating decreased upwelling. This infers a shift of the ACC northward relative to HS1 but still south relative to the LGM. This is supported by evidence of greater sea-ice covering and shifted fronts in the ACR than at present, but less than at the LGM.

Younger Dryas (YD) through Holocene:

$\delta^{13}C$ in all three cores gradually enriched from the YD through the Holocene. This indicates the degassing of respired CO_2 moved to another region as NADW production resumed in the YD.

Conclusions

- In HS1: $\delta^{13}C$ considerably decreased, suggesting maximum upwelling and releasing CO_2 at our core location.
- During the LGM: $\delta^{13}C$ depletion indicates a north ACC, placing our cores in the Southern Ocean.
- We tentatively believe the release of CO_2 into the atmosphere occurred before NADW production reappeared, suggesting the Southern Ocean dynamics were responsible for CO_2 release in the first half of the deglaciation in advance of the resumption of the deep GOC.

Stratigraphy and Proxies

Changes in temperature and, on long time scales, global ice volume affect the $\delta^{18}O_{sw}$ (ratio of $^{18}O/^{16}O$ relative to a standard) of sea water. Thus, the $\delta^{18}O$ of a Calcium Carbonate ($CaCO_3$) shell is a function of temperature and the $\delta^{18}O_{sw}$ in which the shell was precipitated and can therefore be used for stratigraphy. $\delta^{13}C$ (ratio of $^{13}C/^{12}C$ relative to a standard) of the dissolved inorganic carbon (DIC) is a function of air-sea gas exchange and biological productivity. The $\delta^{13}C$ of a $CaCO_3$ shell is an indicator of carbon uptake versus release and can therefore be used to trace the ventilation of CO_2, which paints a picture of air-sea gas exchange changes over time.

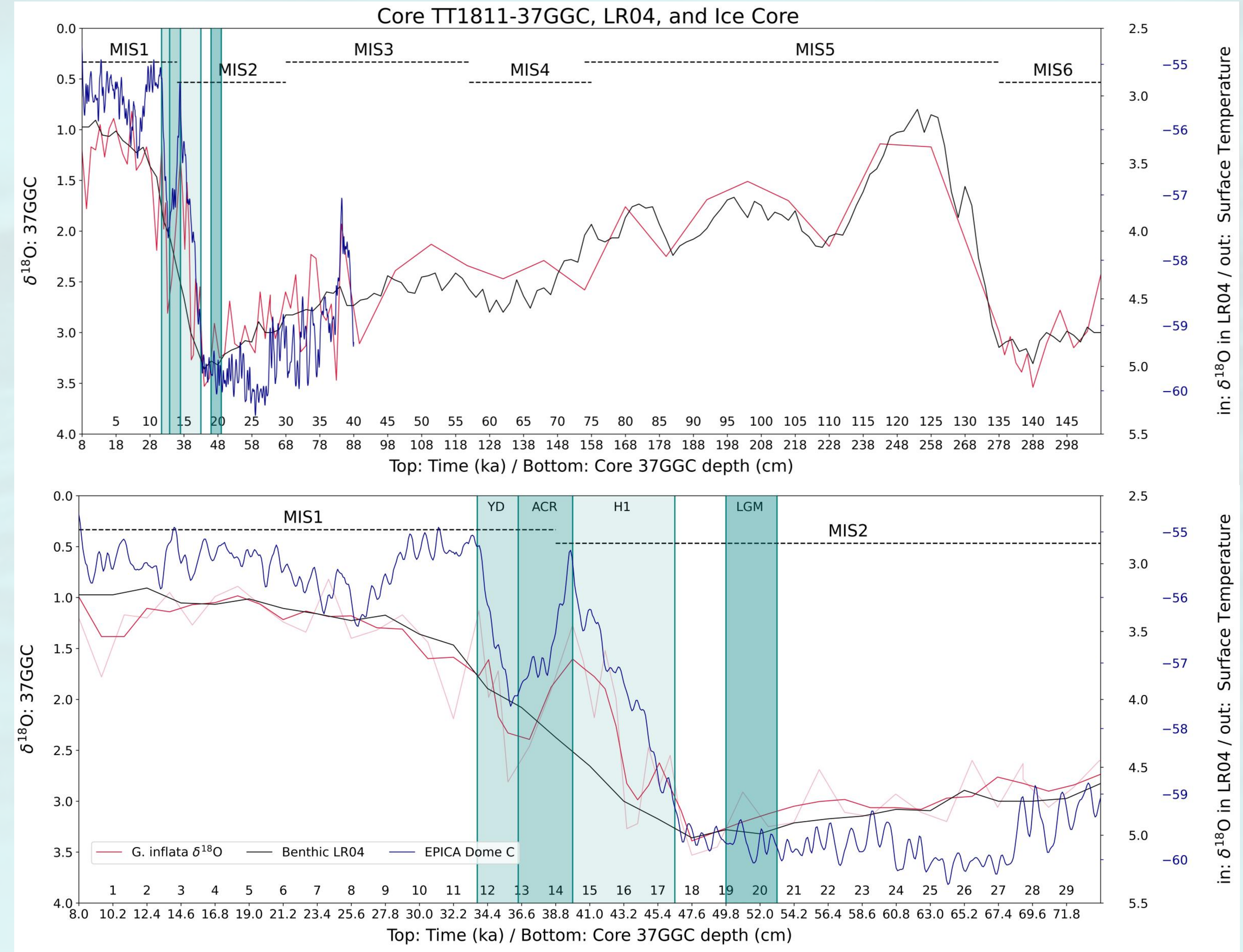


Figure 4. Age model for core TT1811-37GGC. Conversion of core depths to age were generated based on tuning of *G. inflata* $\delta^{18}O$ analyses to Marine Isotope Stage (MIS) chronology using tie points from the "LR04" stack of benthic $\delta^{18}O$ records (7) and the EPICA Dome C (6) ice core surface temperature records.
Top panel: Present to 150 ka. Bottom panel: Present to 30ka with dark red representing the 3-point moving average of $\delta^{18}O$ raw data (faded red).

Laboratory Methods

Sediment Sampling and Foraminifera Picking

- Increased stable isotope analysis from 4 cm to 1 cm for first 50 cm of core.
- Sediment samples oven dried at 35°C and weighed & wet sieved to 63µm.
- Foraminifera dry sieved to 250-355µm.
- *Globigerina bulloides* and *Globoconella inflata* morphologically speciated using stereomicroscope.

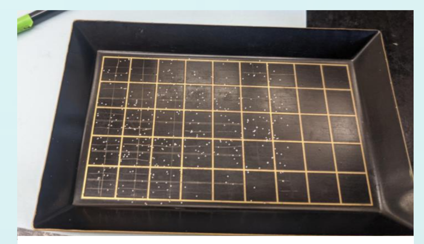
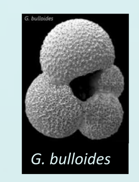


Figure 5. Foraminifera prepared for speciation

Stable Isotope ($\delta^{13}C$ and $\delta^{18}O$) Analysis

- Stable Isotope analyses performed on CO_2 released from 30-50µg of $CaCO_3$ shell material extracted from ~5 *G. bulloides* and *G. inflata* individuals.
- Isotopic ratios measured at the University of Florida Light Stable Isotope Mass Spectrometry Laboratory using a Finnigan-MAT 252 isotope mass spectrometer with a Kiel III device.
- Measurement precision were assessed with NBS-19 standard.



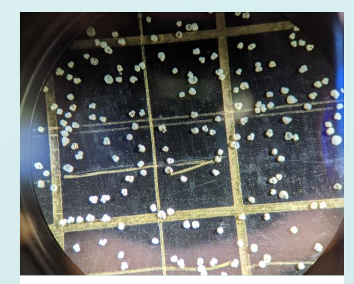


Figure 6. Foraminifera viewed through stereomicroscope

Acknowledgements

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