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An 83000-year-old ice core from Roosevelt Island, Ross Sea, Antarctica

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4.2 Extending the chronology with visually matched gas age control points: 30-85ka

The more limited resolution of the RICE methane record relative to NGRIP (~70-130 ppb) presented one of the biggest challenges to the RICE chronology. To overcome this, we added 2 tie points at 30 and 85 ka BP (Figure 4b) based on visual matching of the RICE methane record to the NGRIP methane record (Rhodes et al. 2015; Oyabu et al. 2020; Ahn et al. 2021). We were visually drawn to corresponding the RICE decrease and CH4 increase at ~30 ka BP to the NGRIP decrease and CH4 increase at ~30 ka BP (Figure 4b).

The RICE Delta excess and the NGRIP d18O record both show a decrease at 30 ka. For the deeper control point of 85 ka, we matched the RICE methane record to the NGRIP methane record between 85-90 ka BP. We chose the $\delta^{18}O_{atm}$ for the NGRIP tie point because it is the only NGRIP record that has a clear signal at 85 ka BP. The RICE $\delta^{18}O_{atm}$ record is not as clear, but it is consistent with the NGRIP d18O chronology, which is tied to a modified GICC05 chronology (Rhodes et al. 2015). The RICE Delta excess record is noisier than the NGRIP Delta excess record, however concentration is higher than that in the NGRIP record. To account for this difference, we scale the NGRIP Delta excess to the RICE Delta excess (Buizert et al. 2018) to improve visual matching between the two records. The RICE Delta excess record is then shifted by -1.5 ka to match the NGRIP Delta excess.

Buizert et al. (2018) found that the $\delta^{18}O_{atm}$ and Delta excess records from the Greenland Ice Sheet Project 2 (GISP2) ice core (Stuiver and Grootes, 2000) exhibited a significantly younger lag of ~20 ± 7 centuries relative to the NGRIP records during the last deglaciation. Comparison of the RICE $\delta^{18}O_{atm}$ and Delta excess records to the GISP2 records suggest a similar lag of ~20 ± 7 centuries (Figure 4c). This suggests that on average (1.5 and 85 ka BP), RICE gas ages are younger than NGRIP gas ages by ~20 ± 7 centuries. Our new NGRIP-based RICE chronology (Table 1) is consistent with the previously published RICE chronology (Rhodes et al. 2015; Oyabu et al. 2020; Ahn et al. 2021). The RICE chronology is consistently younger than that of the NGRIP chronology (Rhodes et al. 2015; Oyabu et al. 2020; Ahn et al. 2021). Although Oyabu et al. (2020) and Ahn et al. (2021) used the same methane tie points to the NGRIP chronology, Ahn et al. (2021) used a different method than Oyabu et al. (2020) to calculate the RICE gas age. The difference between the two RICE chronologies is largest at the beginning of the Holocene (~11 ka), with a difference of ~200 years. The difference between the two RICE chronologies is smaller during the LGM, with a difference of ~100 years. The difference between the two RICE chronologies is smallest during the Bølling-Allerød (~14.5 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Antarctic Cold Reversal (~13 ka), with a difference of ~60 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 5 (~47 ka), with a difference of ~70 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 8 (~80 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 12 (~115 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 14 (~127 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 15 (~134 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 16 (~139 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 17 (~145 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 18 (~151 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 19 (~157 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 20 (~163 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 21 (~171 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 22 (~178 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 23 (~185 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 24 (~192 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 25 (~198 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 26 (~206 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 27 (~214 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 28 (~223 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 29 (~232 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 30 (~242 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 31 (~250 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 32 (~258 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 33 (~267 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 34 (~276 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 35 (~284 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 36 (~293 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 37 (~302 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 38 (~312 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 39 (~321 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 40 (~331 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event 41 (~341 ka), with a difference of ~50 years. The difference between the two RICE chronologies is also small during the Dansgaard-Oeschger event

While the dynamic version is used to establish the global budget for RCS, the steady-state version has the advantage of being computationally faster and yet still capturing the key dynamics. We use this and other assumptions about the isotopic temperature sensitivity used in the cable paleothermometer, the convection model, and the ice flow model to make a fast version of the coupled model that can be run on a desktop computer. This fast version of the coupled model is used as a proxy for the full version of the coupled model in the steady-state Bayesian Complex Model calibration (see Methods Step 1 of Table 1). This is repeated 50 times for ensemble members, as described in the Methods Step 2 of Table 1.

Table S1 Model Parameters used for steady-state Bayesian Complex Model

Parameter	Prior	Posterior
Ice flow exponent	3 (1.5, 4.5)	3.1 (2.9, 3.3)
Basal resistance	0 (-0.5, 0.5)	0.1 (0.0, 0.3)
Ice viscosity multiplier	1 (0.5, 1.5)	1.1 (0.9, 1.3)
Ice thickness multiplier	1 (0.5, 1.5)	1.0 (0.9, 1.1)
Overturned isotopic temperature gradient	0.5 (0.0, 1.0)	0.5 (0.4, 0.6)
Overturned isotopic temperature gradient	0.5 (0.0, 1.0)	0.5 (0.4, 0.6)

Code and data availability

The following software is used in the supplement: RCS grid-scale model (GitHub), RCS local age-scale (GitHub), NEOSS age-scale model (supplement in Higgins-Hawkins et al., 2022), dO18Sw_v02 and TS_v02 data and code (GitHub), Bayesian Complex Model (GitHub), Bayesian Simple Model (GitHub), Bayesian Age Model (GitHub). Implementation also uses a version of the Cable Paleothermometer (GitHub) and a version of the steady-state Bayesian Complex Model calibration (see Methods Step 1 of Table 1). This is repeated 50 times for ensemble members, as described in the Methods Step 2 of Table 1.

Supplement

The supplement related to this article is available online at: https://doi.org/10.5194/tc-18-3961-2024-supplement.

Author contributions

All authors contributed to the conceptualization of the study. The RCS, TSC, DSC, JCM, and PG participated in the GITR-O-18 simulations. Field analyses were performed by the measurement of TS-Hu and dO18-O-18 at WAIS Divide by the TS-Hu team and the dO18-O-18 team, respectively. The dO18-O-18 and TS-Hu data were processed and uploaded (JCM, JG, JW, JPS, JPC, and DSM) and interpretation of the paleoclimate implications of the ice core records. All authors provided valuable feedback and made helpful contributions in writing the paper.

Competing interests

The authors declare that they have no conflict of interest.

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