**SUPPLEMENT TO**

**Sea Level controls on Agulhas Leakage Salinity and the Atlantic Overturning Circulation**

Sophie Nuber\* (1, 2, 3), James W. B. Rae (2), Morten B. Andersen (1), Xu Zhang (4), Bas de Boer (5), Matthew D. Dumont (2), Yuchen Sun (6), Huw T. Mithan (3), Ian R. Hall (1), Stephen Barker (1).

(1) Cardiff University, (2) University of St. Andrews, (3) National Taiwan University, (4) Institute of Tibet Plateau Research, Chinese Academy of Science, (5) Vrije Universiteit Amsterdam, (6) Alfred Wegener Institute

METHODS

1. *SST and relative salinity reconstruction using Mg/Ca and δ18Osw*

Globigerinoides *ruber* (G. *ruber*) samples were picked from U1476, then crushed and homogenised. An aliquot of 5 foraminifera was analysed for δ18O on a MAT253 with a Kiel IV preparation device at Cardiff University. The remaining samples were cleaned and dissolved in a fume hood equipped with HEPA filters under clean laboratory conditions according to Barker et al. (2003). Analysis of Mg/Ca was conducted partially on a Thermo Element XR at Cardiff University, partially on an Agilent Triple Quadrupole at the University of St. Andrews. The instruments were cross-calibrated using the same in-house standard. In both institutions, long term reproducibility of in-house standards yielded RSDs of 1-3%.

SST were calculated from G. *ruber* Mg/Ca using the transfer function and R-script from Gray & Evans (2019)

where T is sea surface temperature, S is salinity, and pH is the negative decadic logarithm of H+ ions. SST uncertainties were processed using Monte Carlo propagation analysis.

Ice volume-corrected seawater δ18O (δ18Osw-ivc)has been previously used as a proxy for changes in relative seawater salinity in the surface Indian Ocean (e.g. Kiefer et al., 2006). We therefore correct our δ18Ocarbonate according to

δ18Osw-ivc = δ18Ocarbonate – δ18Otemperature – δ18Oice volume

to reflect local δ18Osw and interpret the results as changes in relative salinity. δ18Otemperature was calculated from Mg/Ca-based temperatures and δ18OG. *ruber* using the transfer function of Bouvier-Soumagnac & Duplessy (1985) for Indian Ocean planktonic foraminifera with a correction factor of +0.20 (Pearson, 2012). To determine the best correction curve for δ18Oice volume across the last 1.2Ma, we tested the sensitivity of 4 different sea level reconstructions on the resulting δ18Osw-ivc (Figure S6). Reconstructions of δ18Oice volume from de Boer et al. (2014b) based on the LR04 stack gave representative results over the last ~500 kyr where different sea level reconstructions can be readily compared and also extends for the ~1.2 Myr duration of our record, and was therefore usedto determine δ18Osw-ivc.

The resulting δ18Osw-ivc was detrended per glacial cycle using the respective glacial cycle’s mid-termination δ18Osw-ivc. We identified the mid-point of each termination as the middle between the maximum and minimum δ18Obenthic value using the δ18Obenthic data from van der Lubbe et al. (2021). Then, we defined the half-point of each glaciation as the middle between minimum δ18Obenthic and the following maximum. We finally collected the δ18Osw-ivc value during each termination mid-point and subtracted it from all δ18Osw-ivc values within that glacial cycle. A glacial cycle was defined from one glacial half-point to the next, with the respective termination mid-point in the centre.

The lead-time of δ18Osw-ivc to δ18Obenthic was calculated by subtracting the “termination” midpoint-time of δ18Osw-ivc from the termination midpoint-time of δ18Obenthic. Using this method, we receive an average lead time of δ18Osw-ivc to δ18Obenthic of 15kyr. For comparison, we also performed a cross spectral analysis between δ18Osw-ivc and δ18Obenthic. Both records were first clipped to 1350kyr, then subsampled to 1kyr. The resulting cross spectral analysis calculated an average lead time of 18kyr in the δ18Osw-ivc to δ18Obenthic at the 95% confidence interval.

1. *SST and* δ18Osw *stack formation*

The data for the SST, δ18Osw-ivc, and δ18Obenthic stacks was taken from 8 cores within the Indian Ocean. These include the Agulhas Bank Slice (Martinez-Mendez et al., 2010), MD96-2048 (Caley et al., 2012), U1476 SST, δ18Osw-ivc (this study) and U1476 δ18Obenthic (van der Lubbe et al., 2021), WIND 28K (Kiefer et al., 2006), TY93-929/P (Barker et al., 2003), MD90-0963 (Rostek et al., 1997; Bassinot et al., 1994), GeoB10038-4 (Mothadi et al., 2010), and MD01-2378 (Xu et al., 2006; Zuraida et al., 2009). The SST, δ18Osw-ivc, and respective δ18Obenthic stacks were created by first mitigating sampling bias through resampling each of the records at high frequency (10yrs) by linear interpolation. All the resampled records were then combined and a gaussian function (sigma = 8/5kyr) was used to smooth the combined data into a single continuous record with a sampling frequency of 100yrs. The δ18Obenthic stacks were created to allow lead-lag analysis between the SST and δ18Osw-ivc stacks and their respective δ18Obenthic data. By making an Indian Ocean-specific δ18Obenthic stack, age-model errors are equal between surface and benthic stacks, which makes lead-lag analyses possible.

1. *Indian Ocean source water analysis*

To test whether the salinification process is also evident in Indian Ocean source waters, we additionally analysed SST core data from the western Pacific warm pool (ODP806) (de Gardiel-Thoron et al., 2005) and the South China Sea (ODP1146) (Herbert et al., 2010) for lead-lag against their respective δ18Obenthic using cross spectral analysis. For the analysis, SST and δ18Obenthic data from the cores was clipped to 6-1168kyr, then subsampled at 1kyr. The cross spectral analysis was conducted between the SST data and their respective δ18Obenthic from the same core using the resampled data. Neither core ODP806 or ODP1146 showed a significant SST lead at the 95% confidence interval.

1. *Age model*

The age model for U1476 was taken from van der Lubbe et al. (2021) who aligned U1476 δ18Obenthic to the δ18Obenthic probability stack (Ahn et al., 2017).

1. *ANICE-SELEN sea level-topography model*

To gain understanding of the land surfacing and flooding rates around the Indonesian archipelago, we ran a time-transient simulation of RSL calculated in the ice-sheet model ANICE (de Boer et al., 2013), which was then fed into the topography model SELEN (de Boer et al., 2014a). ANICE uses an inverse forward modelling approach where δ18Obenthic is split into ice volume and bottom water temperature components through global ice mass conservation calculations. The approach assumes that changes in NH mid latitude-to-subpolar surface-air temperatures (ΔTNH) are strongly related to changes in ice volume and deep-water formation. Changes in ΔTNH are derived from the difference between modelled δ18O at time t, and foraminiferal δ18Obenthic at time t+100 years. The changes in ΔTNH are subsequently fed into a 3D ice sheet and deep-water temperature model whose outputs influence the determination of modelled δ18O. Relative sea level is calculated in parallel from changes in the resulting ice volume component of δ18O. The sea level height information was then fed into SELEN which calculates above-sea level topography using ice sheet chronology and a solid Earth rheology model accounting for changes in RSL as well as gravitational changes linked to water and ice load, influences of earth’s rotation, glacial isostatic adjustment of the solid earth, and migration of coastlines across the globe. Model coupling is complete, such that SELEN informs the ANICE model about basal topography prior to the next timestep. To increase model-run efficiency, the fully coupled version was run for 599 kyr with a map every 1 kyr, producing 598 global topography maps (see supplementary Figure S7). The spatial resolution per map is 1 pixel per ⁓5000 km2. To cover a greater number of glacial cycles in 600kyr of model run time, we chose to run 10 glacial cycles between 651kyr and 1250ky assuming that changes in the outline of continents and islands stay constant across the last 1.2Ma. Therefore, any correlations between changes in the land-ocean ratio and RSL should also be valid for younger glacial cycles.

To calculate changes in above-sea level topography, all maps were processed in Python and cut to the same size, zooming in on the Indonesian archipelago (Figure S4a). Each pixel was given a value of 0, 1, or NaN for ocean, land, or unidentifiable, respectively. Then, land-to-ocean ratios were calculated for each map as

Changes in the ratio land-to-ocean ratio with respect to sea level stand [m] were calculated as

To identify trends linked to rising and falling sea level, the data was grouped into ratios at times of rising, and ratios at times of falling sea level, respectively.

1. *Salinity influence on AMOC in comprehensive climate model COSMOS*

Ocean circulation experiments were conducted in COSMOS (Zhang et al., 2013). For glacial state control settings see Zhang et al. (2013). Based on the equilibrium state of the Last Glacial Maximum, we disturbed the glacial ocean circulation by imposing a constant 0.15Sv freshwater perturbation over the ice-rafted debris belt in the North Atlantic for 500 years (LGM015) (see also Zhang et al., 2013). This weakened AMOC state serves as a climate background comparable to early deglacial Heinrich stadial. We then investigated effects of additional salinity perturbations on the Agulhas plateau by removing freshwater from the region through enhanced evaporation. Two salt-water perturbation experiments with strengths of 0.05Sv (LGM015 SA\_005) and 0.1Sv (LGM015 SA\_01) were integrated for 800 years based on LGM015 (i.e. under the background climate of persistent freshwater input in the North Atlantic). In addition, LGM015 is continued for additional 800 years to provide a direct reference for AMOC changes in LGM015 SA\_005 and LGM015 SA\_01.

SUPPLEMENTARY FIGURES

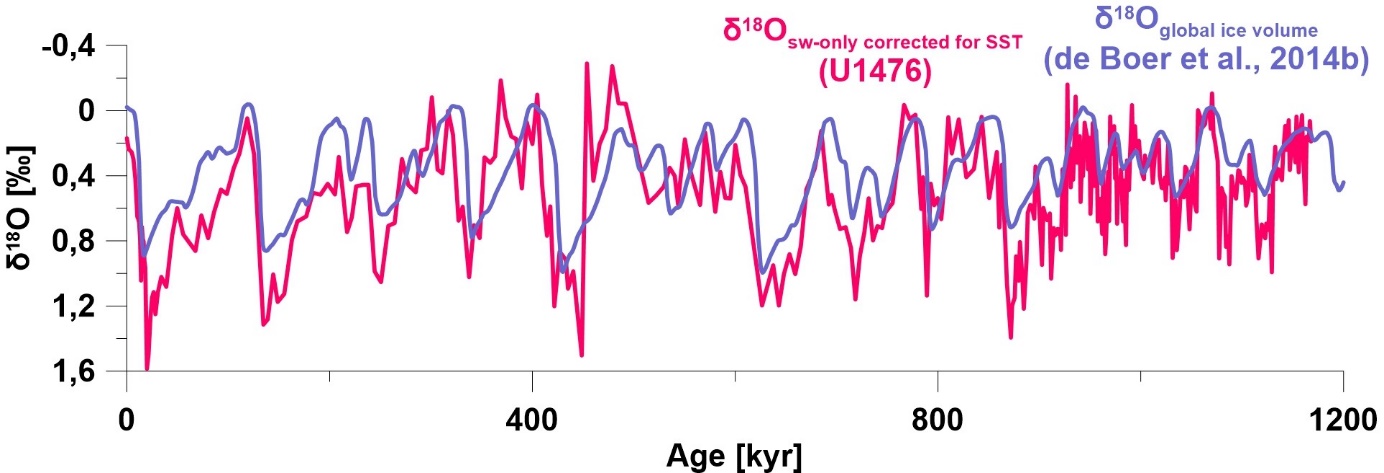


Figure S1. Reconstructed δ18Osw-SST (SST corrected only) from U1476 (pink) and δ18O from global ice volume changes (de Boer et al., 2014). In each glacial cycle, the change in surface water δ18Osw-SST at U1476 exceeds global changes during peak glacial conditions. The average glacial-interglacial difference across all glacial cycles is roughly 50% lower in the δ18Oglobal ice volume than in the δ18Osw-SST.

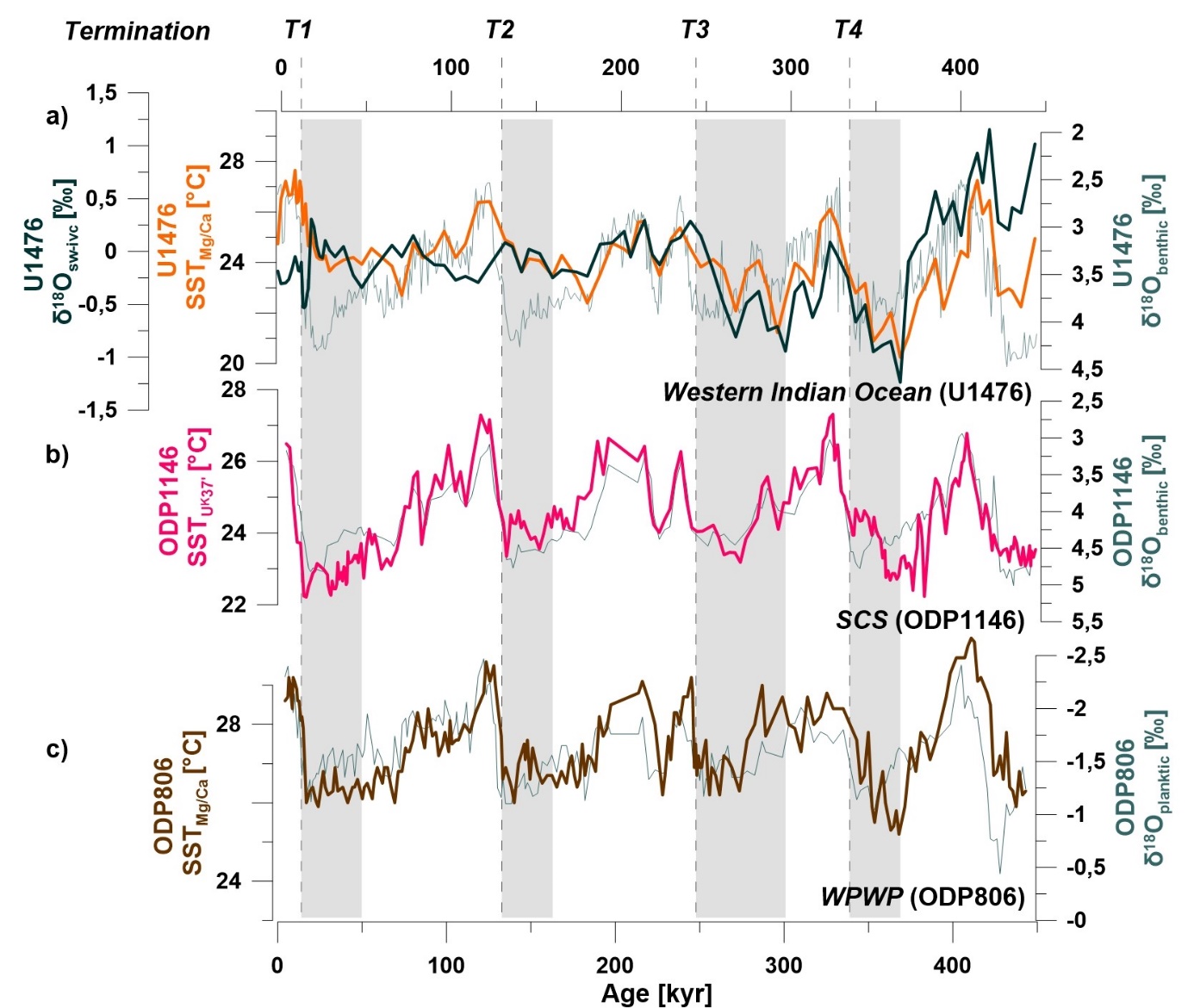


Figure S2. Surface hydrography in the source regions of the ITF and the Indian Ocean. (a) U1476 δ18Osw-ivc (dark green), U1476 Mg/Ca-derived sea surface temperatures (orange), and U1476 δ18Obenthic (thin blue line) (van der Lubbe et al., 2021) from the western Indian Ocean. (b) Alkenone-derived sea surface temperatures (light pink) and δ18Obenthic (thin blue line) from the South China Sea (Herbert et al., 2010). (c) Mg/Ca-derived sea surface temperatures (brown) and δ18Obenthic (thin blue line) from the western Pacific warm pool (de Gardiel-Thoron et al., 2012). Onset of U1476 glacial salinification highlighted in grey bars. Note that both South China Sea, and western Pacific warm pool records do not show a similarly consistent lead-lag pattern between their respective SST and δ18Obenthic data.

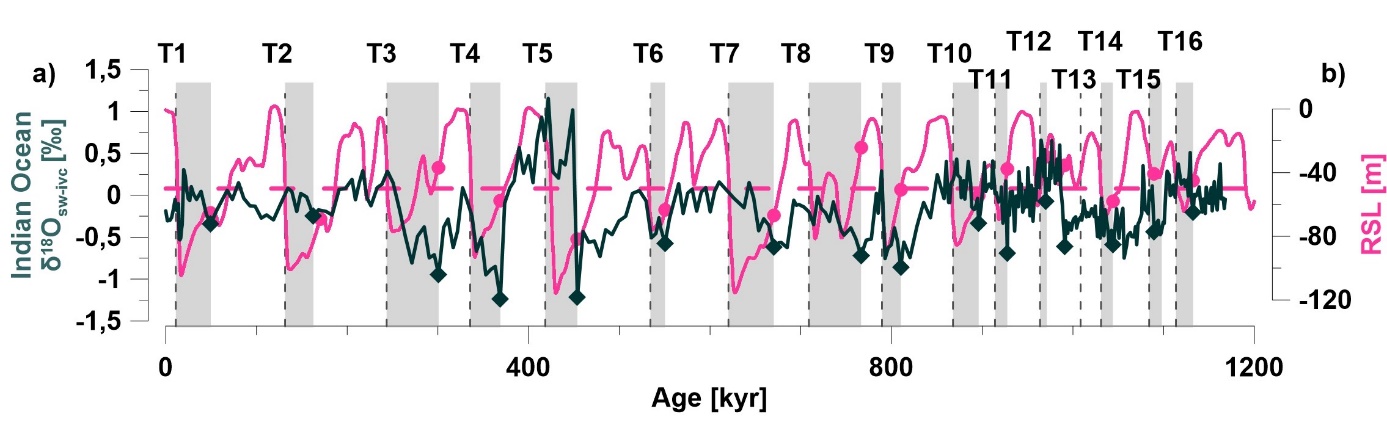


Figure S3. (a) U1476 ice volume-corrected δ18Osw (green line) for the surface Ocean, with the onset of δ18Osw-ivc increases indicated by green diamonds. (b) Relative sea level (de Boer et al., 2014) (pink line), with pink dots indicating the RSL-stands at times of onset of δ18Osw-ivc increases (e.g. pink dots mark RSL at the time of the green diamonds in δ18Osw-ivc). The average RSL-stand corresponding to increased δ18Osw-ivc is indicated with a horizontal dashed pink line. This yields very similar results to the analysis of the whole Indian Ocean stack shown in Figure 3.

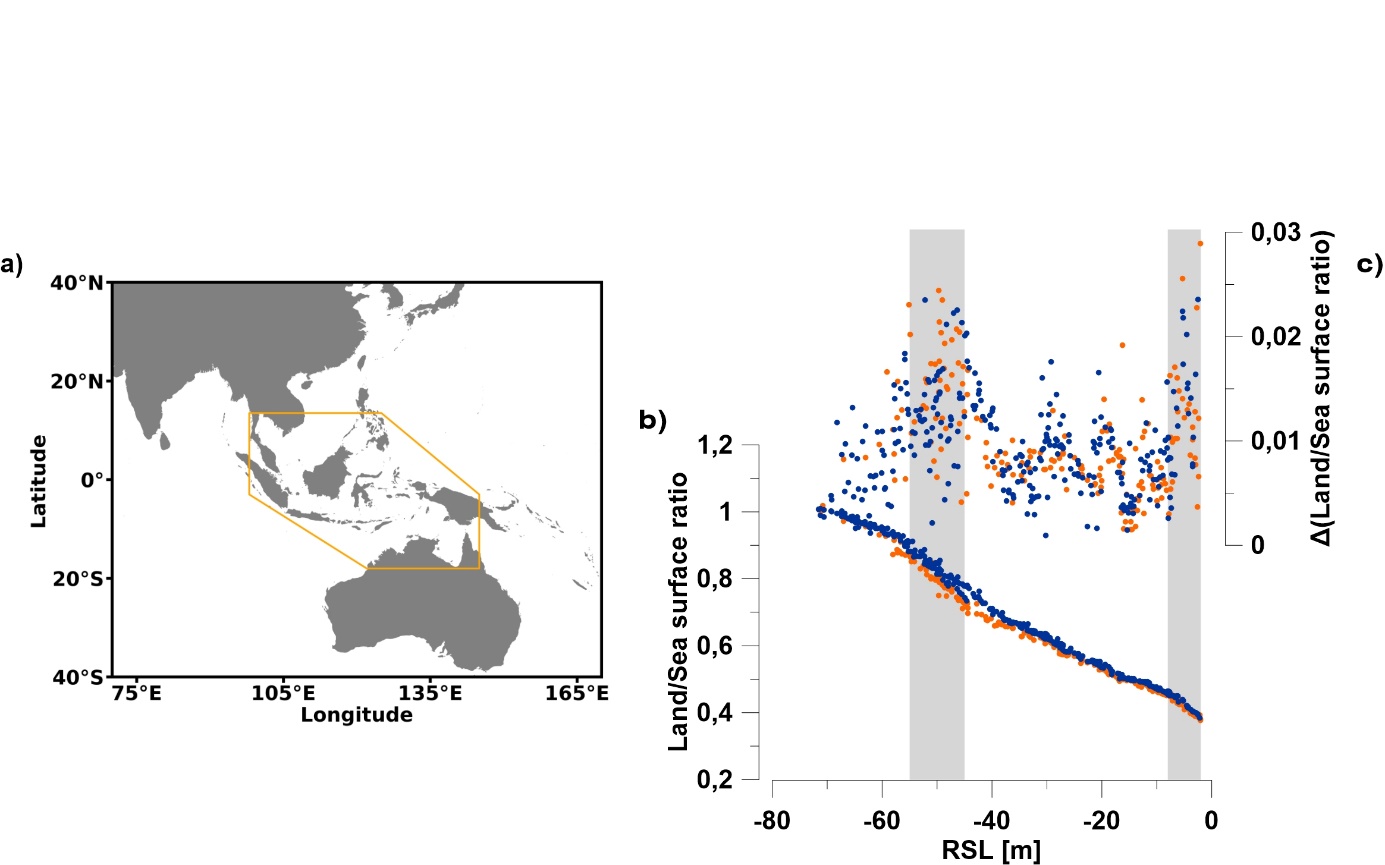


Figure S4. Changes in land surfacing in the Indonesian Archipelago as a function of changes in sea level. (a) The pixels occurring within the orange polygon were used to calculate the land/sea ratio in each time-slice map created by the ANICE-SELEN model. (b) Change in land to sea surface ratio in the Indonesian archipelago as modelled by the coupled ice sheet-topography model ANICE-SELEN for a subset of 9 glacial-interglacial cycles in respect to relative sea level. Changes occurring from falling and rising sea level are plotted in blue and orange respectively. (c) Slope of the land/sea surface ratio as a function of RSL to highlight specific sea levels at which the rate of land exposure during sea level fall, or land flooding during sea level rise, is particularly fast. This occurs at around 0-8m and 45-50m (highlighted with vertical grey shaded bars).

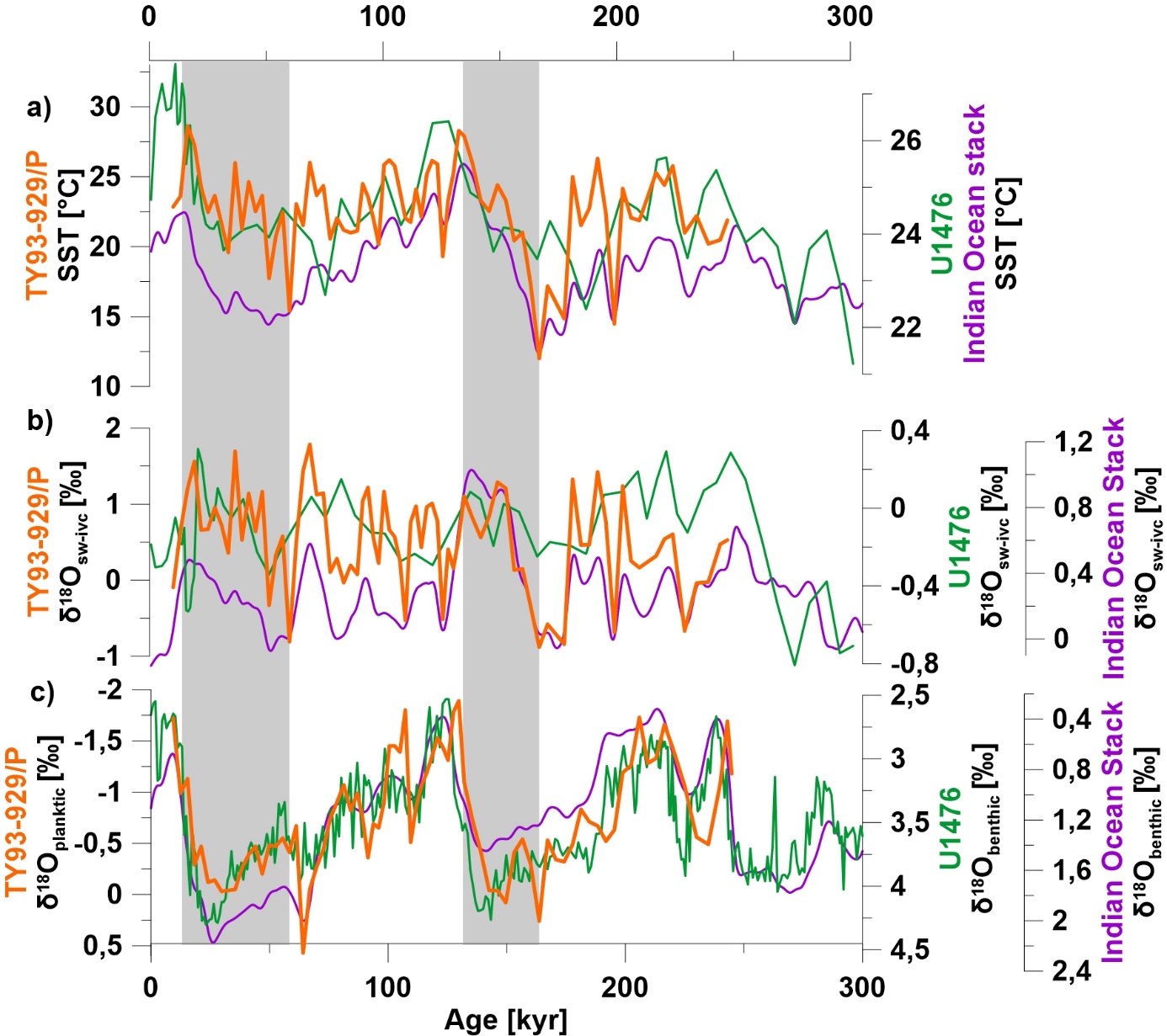


Figure S5. Consistent evolution of SST (a) and δ18Osw-ivc (b) from the western Indian Ocean (U1476, green line) (this study), Arabian Sea (TY93-929/P, orange line) (Barker et al., 2003), and the whole Indian Ocean SST and δ18Osw-ivc stacks (purple line) (this study). Raw benthic and planktic δ18O data are also shown (c) as a measure of chronological consistency. Grey bars highlight the early increase in SST and δ18Osw-ivc prior to terminations as seen in δ18Obenthic.

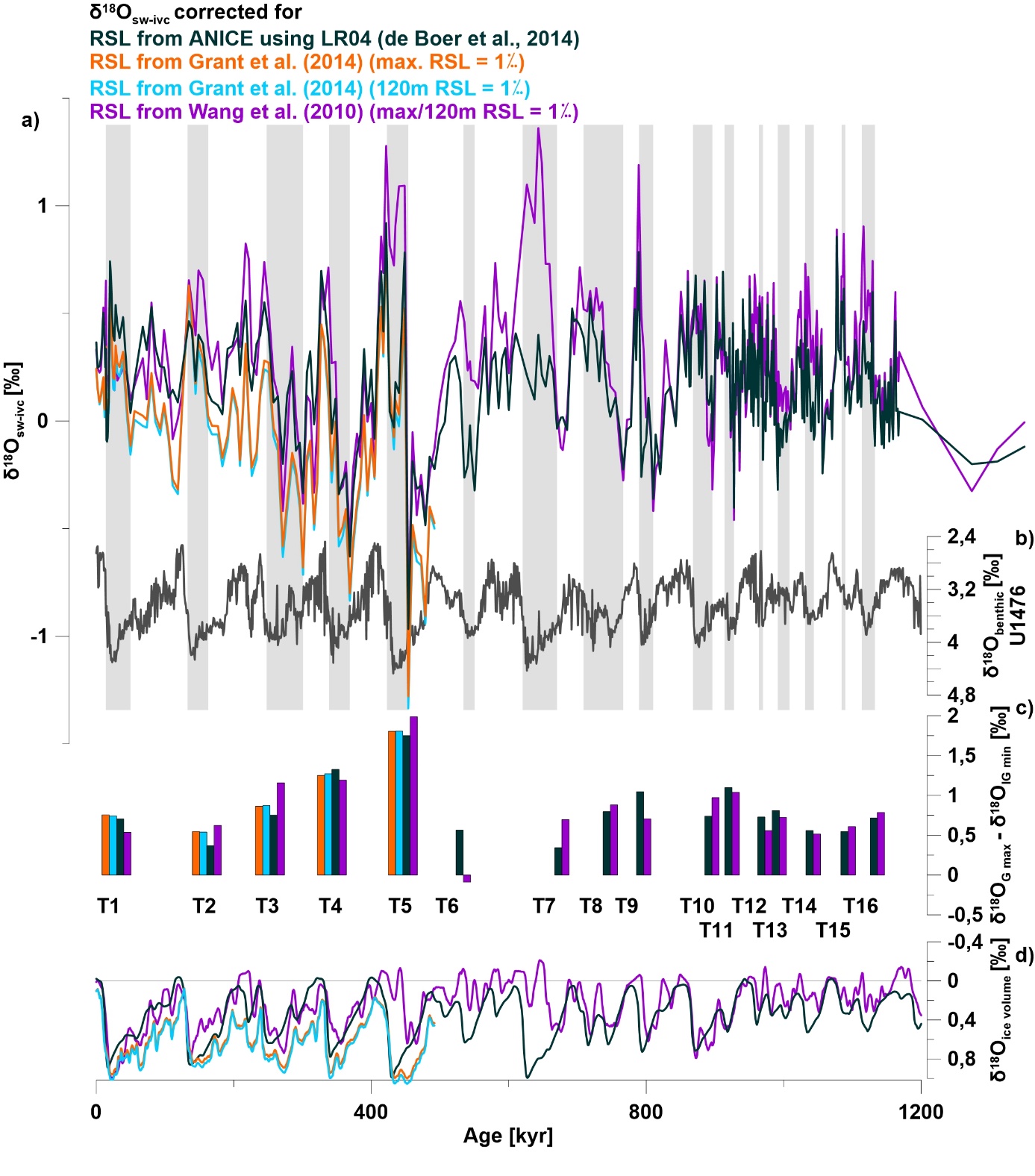


Figure S6. (a) Resulting δ18Osw-ivc records using 4 different RSL reconstructions for the ice volume correction. U1476 δ18Obenthic (van der Lubbe et al., 2021) is plotted in b) for lead-lag comparison. Grey bars highlight the early increase in δ18Osw-ivc prior to terminations. The de Boer et al. (2014) ice volume correction allowed modelled ice volume δ18O to be used (dark green). For other RSL reconstructions, a change of 1% in δ18Obenthic per 120m RSL was assumed. The colour of each δ18Osw-ivc record corresponds with the referenced scenario below. (c) Absolute δ18Osw-ivc amplitude of the glacial δ18Osw-ivc maxima compared to the preceding minima for all 4 δ18Osw-ivc scenarios. The colours of the bars correspond to the referenced scenarios in (a). Note that differences between different scenarios are small. (d) Corresponding ice volume δ18O curves for the 4 RSL reconstructions. The colours of each line correspond with the referenced scenario in (a).

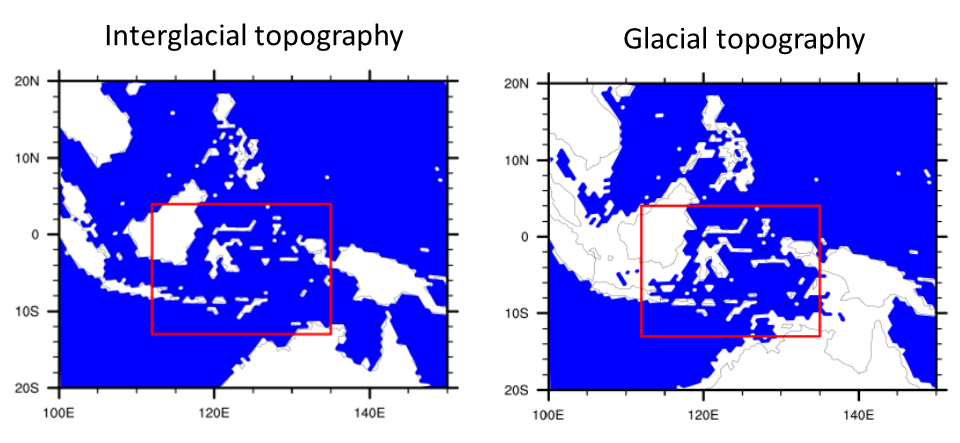


Figure S7. Example output maps from ANICE-SELEN coupled ice-sheet topography model showing coastline topography in the Indonesian archipelago during a representative interglacial (1067kyr) and representative glacial (873kyr).

ADDITIONAL REFERENCES

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