



*Supplement of*

## **Impact of the temperature-cloud phase relationship on the simulated Arctic warming during the Last Interglacial**

**Nozomi Arima et al.**

*Correspondence to:* Masakazu Yoshimori ([masakazu@aori.u-tokyo.ac.jp](mailto:masakazu@aori.u-tokyo.ac.jp))

The copyright of individual parts of the supplement might differ from the article licence.

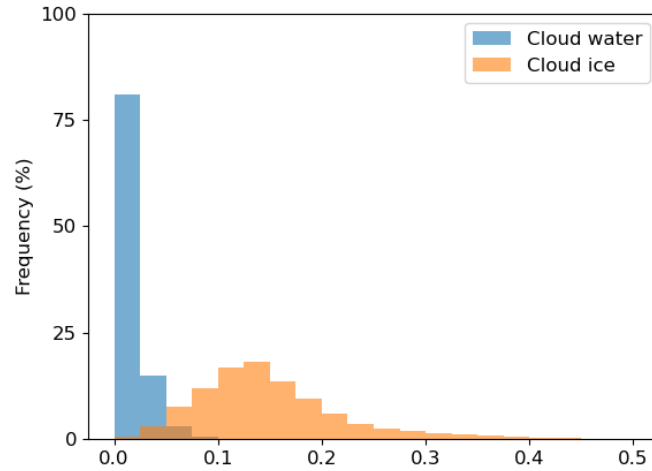
The list of experiments is provided in Table 2 of the main text. Their description is given in Sect. 3 of the main text and is briefly repeated here. A set of four experiments was conducted with MIROC4mV, an atmosphere-ocean general circulation model with a dynamic vegetation component, and they are referred to as PIVS, PIVL, LIGvS, and LIGvL. Here, PI and LIG denote preindustrial and Last Interglacial, respectively. “S” and “L” denote two different sets of cloud parameters, in which “S” and “L” are named after more solid and liquid water at the same temperature, respectively. Another set of four experiments was conducted with MIROC4m, an atmosphere-ocean general circulation model with prescribed, fixed vegetation distributions, and they are referred to as PIfS, PIfL, LIGfS, and LIGfL.

### 1. The average autoconversion rate of cloud particles

The parameterization of rain rate is described in Sect. 2.2 of the main text. Another autoconversion process, the snowfall rate is parameterized as

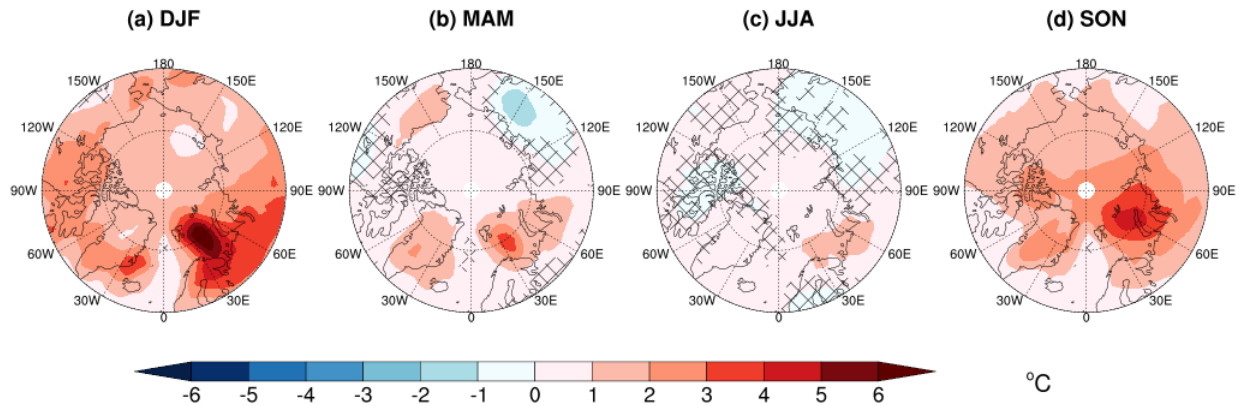
$$P_{ice} = -\frac{\partial l_F}{\partial t} = C_t \left[ 1 - \exp \left\{ -\left( \frac{l}{l_c C} \right)^2 \right\} \right] l_F + C_c F_p l_F, \quad (\text{S1})$$

where  $l$  is the cloud condensate content,  $l_c$  the critical cloud condensate content that leads to rapid snow formation,  $C$  the cloud amount, and  $C_t$  is a constant. We examined the mean lifetime of cloud particles for the autoconversion processes by computing the rate of fractional changes  $\frac{1}{l} \frac{\partial l}{\partial t}$  in Eq. (2) of the main text and  $\frac{1}{l_F} \frac{\partial l_F}{\partial t}$  in Eq. (S1) internally in the model for the Arctic lower troposphere and the result is shown in Fig. S1.



20 **Figure S1:** Histograms of the monthly mean autoconversion rate ( $-1/L \cdot dL/dt$ ) of cloud particles with  $L$  being the cloud liquid or solid water content for PIVS using MIROC4mV. The data represent grid points below the 680 hPa level in the Arctic. The unit of the horizontal axis is 1/hour. The vertical axis is the fraction of the total number of grid points. The results for PIVL, LIGvS, and LIGvL are qualitatively similar.

## 2. Seasonal difference in surface air temperature in the preindustrial simulations



25 **Figure S2:** Difference in surface air temperature between PIVL and PIVS ( $^{\circ}\text{C}$ ): (a) December-January-February; (b) March-April-May; (c) June-July-August; and (d) September-October-November. Grid cells for which the difference is not statistically significant at the 5% level are hatched.

### 3. Alternative definition of calendar

30 **Table S1: Mid-month dates defined by day of the year in the alternative calendar in which the ecliptic longitude with respect to the fixed vernal equinox (21<sup>st</sup> of March) is closest between PI and LIG, following Kutzbach and Gallimore (1988). Each month is defined as 31 days, including 15 days before and after the newly defined mid-month dates (allowing day overlap).**

Month	PI	LIG (127 ka)
January	15	11
February	44	42
March	74	74
April	104	104
May	135	133
June	165	160
July	196	188
August	227	216
September	257	244
October	288	275
November	318	307
December	349	341

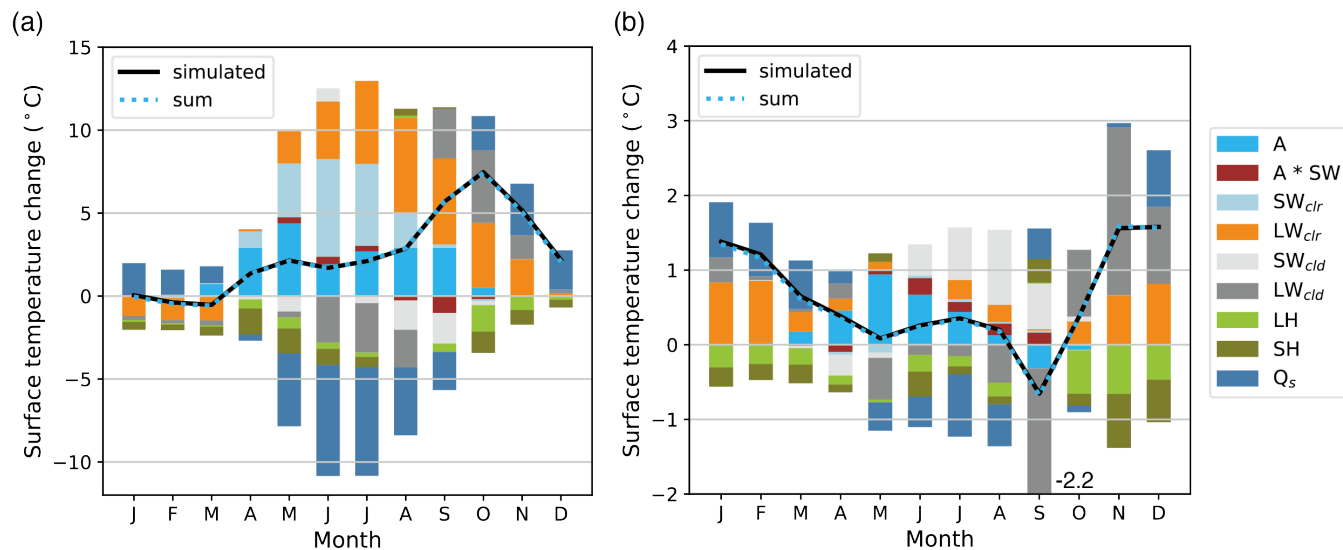


Figure S3: Same as in Fig. 9 of the main text, but with a different definition of the monthly calendar (Table S1).

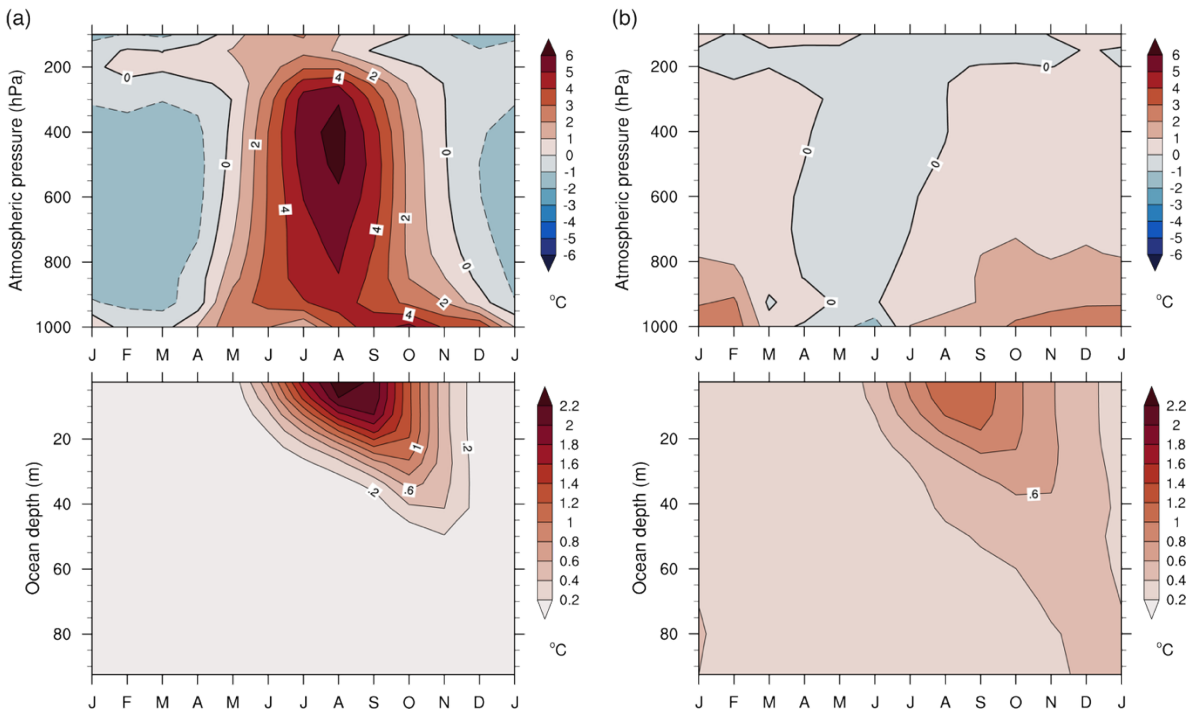
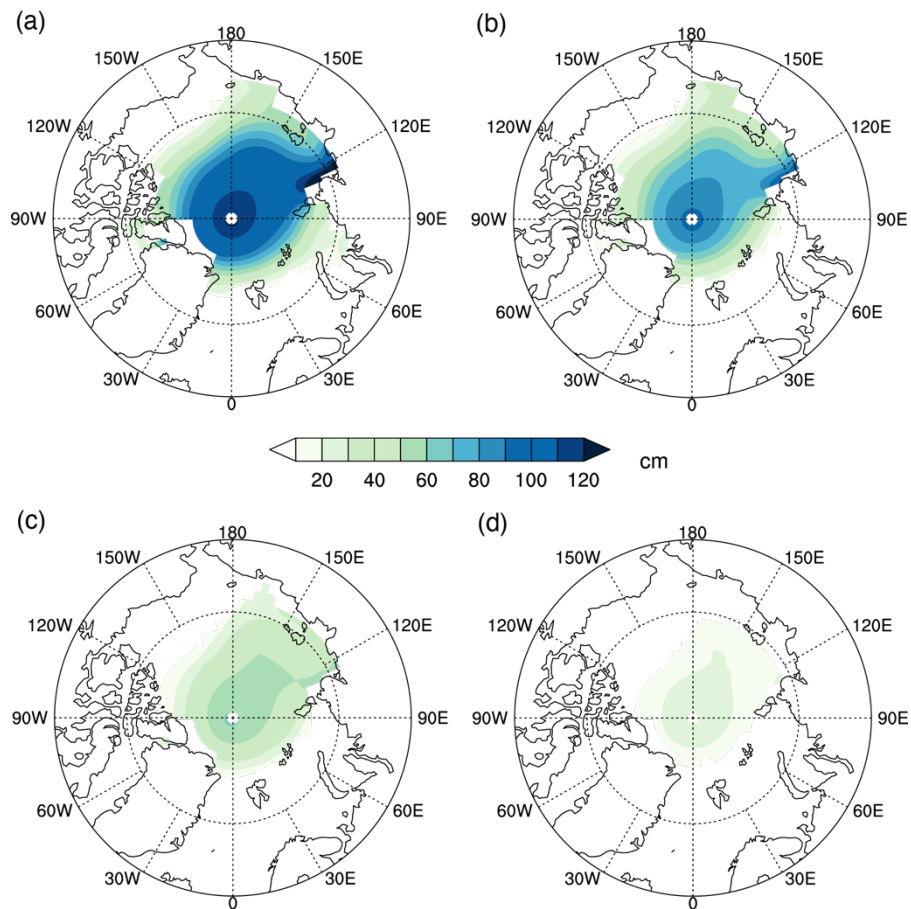


Figure S4: Same as in Fig. 12 of the main text, but with a different definition of the monthly calendar (Table S1).

#### 4. AOGCM results without a dynamic vegetation component (MIROC4m)



45 **Figure S5: September sea-ice thickness (cm) in the Arctic with MIROC4m: (a) P1fS; (b) P1fL; (c) L1GfS; and (d) L1GfL. Note that grid cells where the ice concentration is less than 0.15 are not coloured. This figure corresponds to Fig. 7 of the main text, which presents the MIROC4mV results.**

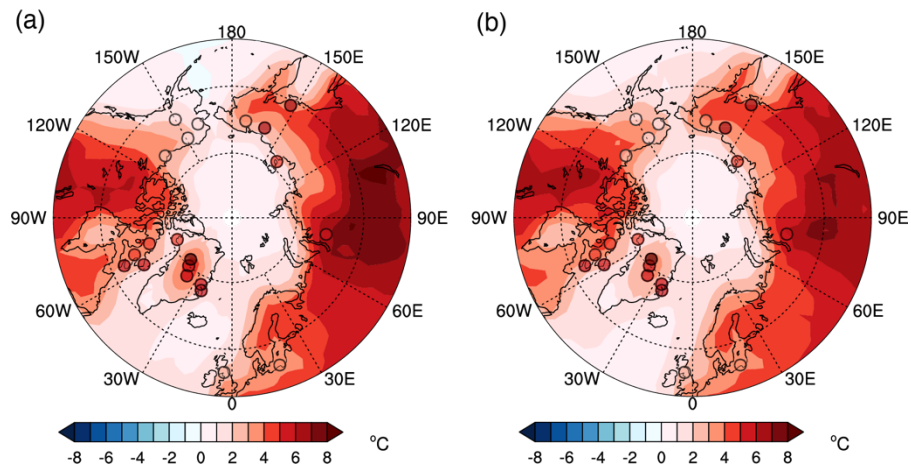


Figure S6: Comparison of simulations with proxies for the  $\Delta$ LIG (LIG-PI) summer SAT difference (June-July-August): (a)  $\Delta$ LIGfS; and (b)  $\Delta$ LIGfL. The circles represent proxy data from Guarino and Sime (2022). This figure corresponds to Fig. 8 of the main text, which presents the MIROC4mV results.

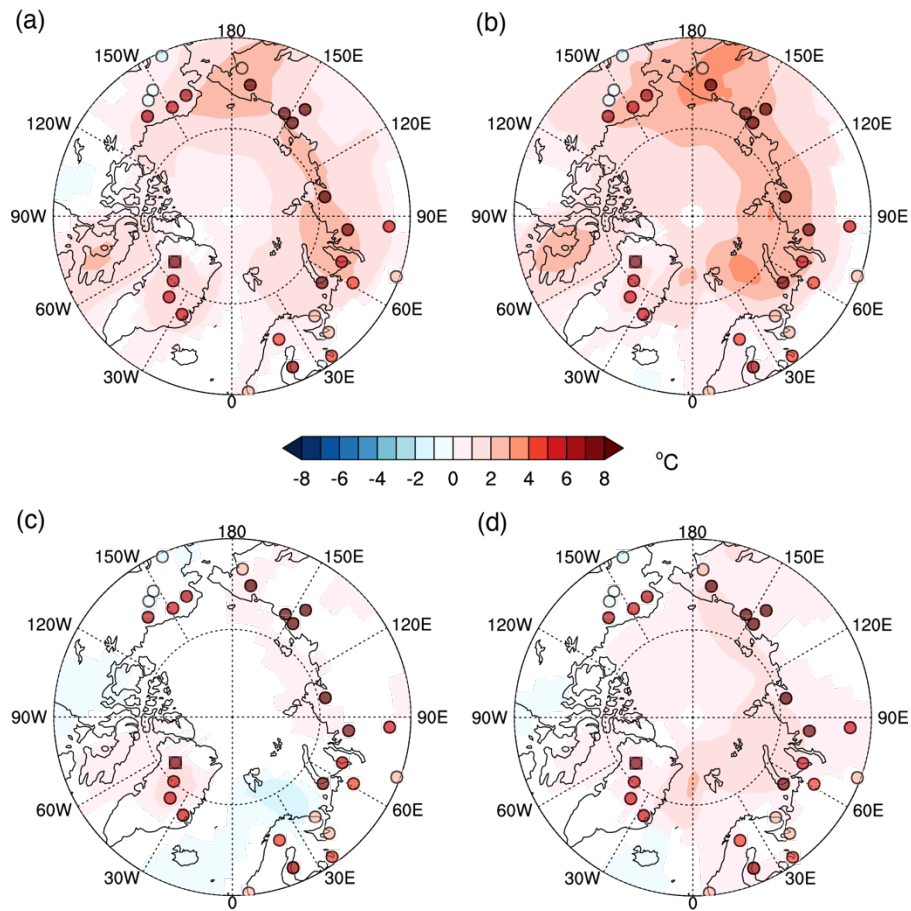
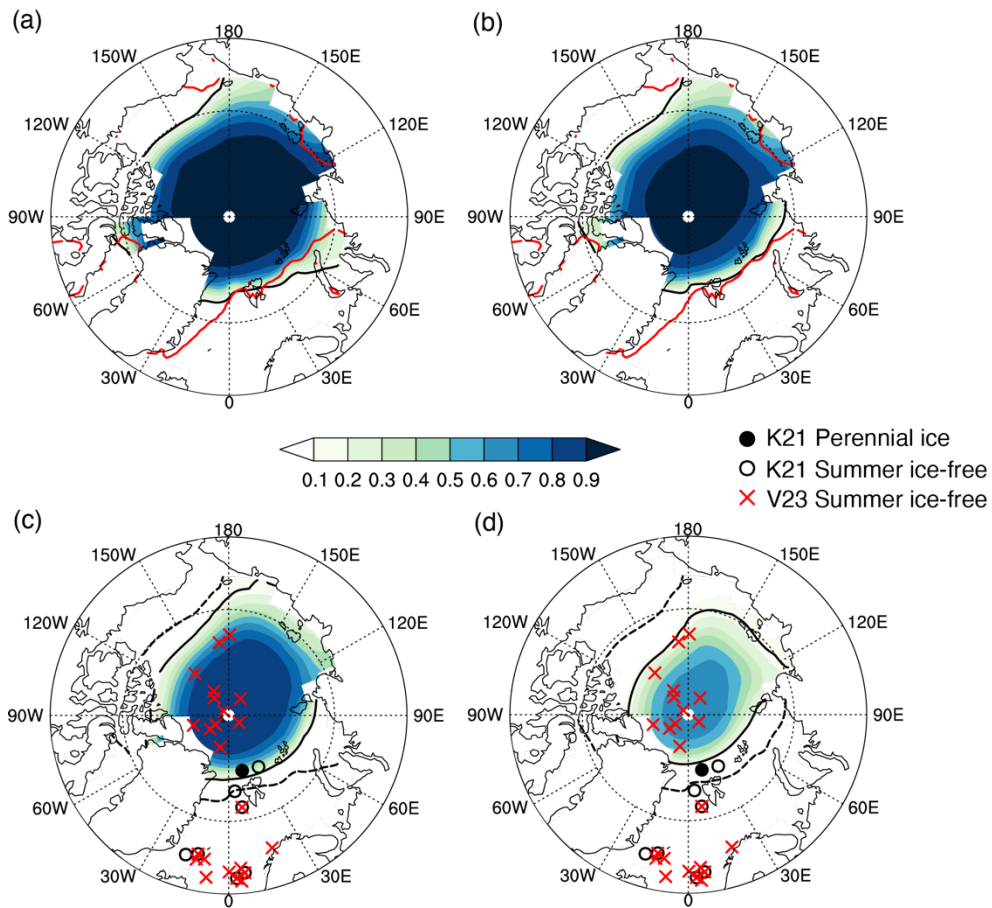


Figure S7: Comparison of simulations with proxies for the  $\Delta$ LIG (LIG-PI) annual mean SAT difference: (a)  $\Delta$ LIGvS; (b)  $\Delta$ LIGvL; (c)  $\Delta$ LIGfS; and (d)  $\Delta$ LIGfL. Only grid cells for which the difference is significant at the 5% level are coloured, using Student's t-test on 100 samples from the last 100 years of each experiment. The circles represent proxy data from Turney and Jones (2010), and the squares represent proxy data from Capron et al. (2017).



60 **Figure S8: September sea-ice concentration in the Arctic: (a) PIfS; (b) PIfL; (c) LIGfS; and (d) LIGfL. In (a) and (b), black lines**  
**denote the simulated boundaries for the ice concentration of 0.15, while red lines denote the observed ones (HadISST2 by Titchner**  
**and Rayner, 2014). In (c) and (d), black solid lines denote the simulated boundaries for the ice concentration of 0.15, while black dashed lines denote those in the corresponding preindustrial simulations. The year-round ice cover (solid circles) and summer ice-**  
**free conditions (empty circles) suggested by proxy data from Kageyama et al. (2021), and summer ice-free conditions (red cross**  
65 **marks) from Vermassen et al. (2023) are also plotted. Note that only proxies claimed as good chronological control are shown for**  
**Kageyama et al. (2021), and whether the data from Vermassen et al. (2023) actually represent LIG has been questioned, as stated**  
**in the Introduction. This figure corresponds to Fig. 6 of the main text, which presents the MIROC4mV results.**

## References

- 70 Capron, E., Govin, A., Feng, R., Otto-Bliesner, B. L., and Wolff, E. W.: Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions, *Quaternary Science Reviews*, 168, 137-150, <https://doi.org/10.1016/j.quascirev.2017.04.019>, 2017.
- Guarino, M. V. and Sime, L. C.: Last Interglacial summer air temperature observations for the Arctic (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre. <https://doi.org/10.5285/9AB58D27-596A-472C-A13E-2DCD68612082>, 2022.
- 75 Kageyama, M., Sime, L. C., Sicard, M., Guarino, M.-V., de Vernal, A., Stein, R., Schroeder, D., Malmierca-Vallet, I., Abe-Ouchi, A., Bitz, C., Braconnot, P., Brady, E. C., Cao, J., Chamberlain, M. A., Feltham, D., Guo, C., LeGrande, A. N., Lohmann, G., Meissner, K. J., Menviel, L., Morozova, P., Nisancioglu, K. H., Otto-Bliesner, B. L., O'Ishi, R., Ramos Buarque, S., Salas y Melia, D., Sherriff-Tadano, S., Stroeve, J., Shi, X., Sun, B., Tomas, R. A., Volodin, E., Yeung, N. K. H., Zhang, Q., Zhang, Z., Zheng, W., and Ziehn, T.: A multi-model CMIP6-PMIP4 study of Arctic sea ice at 127 ka: sea ice data compilation and model differences, *Climate of the Past*, 17, 37-62, <https://doi.org/10.5194/cp-17-37-2021>, 2021.
- 80 Kutzbach, J. E. and Gallimore, R. G.: Sensitivity of a coupled atmosphere/mixed layer ocean model to changes in orbital forcing at 9000 years B.P. *Journal of Geophysical Research*, 93, 803-821, <https://doi.org/10.1029/JD093iD01p00803>, 1988.
- 85 Titchner, H. A., and Rayner, N. A.: The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations, *J. Geophys. Res. Atmos.*, 119, 2864-2889, <https://doi.org/10.1002/2013JD020316>, 2014.
- Turney, C. S. M. and Jones, R. T.: Does the Agulhas Current amplify global temperatures during super-interglacials?, *Journal of Quaternary Science*, 25, 839-843, <https://doi.org/10.1002/jqs.1423>, 2010.
- 90 Vermassen, F., O'Regan, M., de Boer, A., Schenk, F., Razmjooei, M., West, G., Cronin, T. M., Jakobsson, M., and Coxall, H. K.: A seasonally ice-free Arctic Ocean during the Last Interglacial, *Nature Geoscience*, <https://doi.org/10.1038/s41561-023-01227-x>, 2023.