

# **Model-data comparison of Antarctic winter sea-ice extent and Southern Ocean sea-surface temperatures during Marine Isotope Stage 5e**

M. Chadwick<sup>1,2\*</sup>; L.C. Sime<sup>1</sup>; C.S. Allen<sup>1</sup> & M.-V. Guarino<sup>1,3</sup>

<sup>1</sup> British Antarctic Survey, Cambridge, UK

<sup>2</sup> Ocean and Earth Science, University of Southampton, Southampton, UK

<sup>3</sup> Earth System Physics Section, International Centre for Theoretical Physics, Trieste, Italy

\*Corresponding author: [m.chadwick@cornwall-insight.com](mailto:m.chadwick@cornwall-insight.com), British Antarctic Survey, High Cross, Madingley Rd., CB3 0ET, Cambridge, UK

## **Key points**

- Different areas of the Southern Ocean show different consistency between model simulations and proxy data.
- Inclusion of Heinrich 11 meltwater forcing improves the match between model simulations and proxy data.

## **Abstract**

Marine Isotope Stage (MIS) 5e (130-116 ka) represents a ‘process analogue’ for future anthropogenic warming. Climate model simulations for MIS 5e have previously failed to produce Southern Ocean sea-surface temperatures (SST) and sea-ice extent reconstructed from marine sediment core proxy records. Here we compare state of the art HadGEM3 and HadCM3 simulations of Peak MIS 5e Southern Ocean summer SST and September sea-ice concentrations with the latest marine sediment core proxy data. The model outputs and proxy records show the least consistency in the regions located near the present-day Southern Ocean gyre boundaries, implying that model simulations are currently unable to fully realise changes in gyre extent and position during MIS 5e. Including Heinrich 11 meltwater forcing in Peak MIS 5e climate simulations improves the likeness to proxy data but it is clear that longer (3-4 ka) run times are required to fully test the consistency between models and data.

## **Plain Language Summary**

Investigating past warm periods can provide us with an analogue for how climate will respond to future warming. In this study we compare the latest computer simulations of Southern Ocean sea-surface temperatures and Antarctic winter sea-ice extent from 130,000 years ago with data from marine sediment cores. The simulations and sediment core data show the least match in the areas near the boundaries of the present day Southern Ocean gyres (large, circulating ocean currents),

implying that changes in the position and size of the gyres are not fully recreated in the computer simulations. The inclusion of ice sheet meltwater into the North Atlantic improves the comparison between the simulations and sediment core data but it is clear that longer simulation run times are required to fully test their consistency.

## **Keywords**

Last interglacial; Southern Ocean; sea ice; sea-surface temperatures; model-data comparison

## **1. Introduction**

In the present day, Antarctic winter sea ice covers an area of  $\sim 1.8 \times 10^6 \text{ km}^2$  and forms a critical component of the global climate system (Maksym 2019). Sea ice has a high albedo or ‘reflectivity’ (Hall 2004), and seasonal growth in sea ice influences the strength of Southern Ocean (SO) and global overturning circulation through the formation of dense Antarctic shelf and bottom waters (Abernathy et al. 2016, Rintoul 2018). Rising atmospheric greenhouse gas concentrations are driving current global warming, with a predicted reduction of 24-34 % in the Antarctic winter sea-ice extent (WSIE) by 2100 (Meredith et al. 2019). The short length of the observational record for Antarctic sea ice, coupled with the complex climate dynamics involved in changes to modern WSIE (Hobbs et al. 2016, Purich et al. 2016) mean that model simulations have been unable to faithfully replicate recent changes in Antarctic sea ice unless they use unrealistically reduced warming (Rosenblum & Eisenman 2017). Marine Isotope Stage (MIS) 5e proxy records offer valuable evidence of a ‘warmer-than-present’ climate, and the opportunity to improve our understanding/prediction of the impacts of future climate change.

During MIS 5e (130-116 ka) both mean annual global atmospheric temperatures and mean annual SO sea-surface temperatures (SSTs) peaked at  $\sim 2^\circ \text{C}$  warmer than preindustrial (PI) (Capron et al. 2017, Fischer et al. 2018). Global sea levels were also 1.2-5.3 m higher than the present day (Dyer et al. 2021). Unlike future anthropogenic warming, MIS 5e warming is forced by orbital changes, alongside a variety of internal ocean-ice-atmosphere feedbacks, rather than being driven by increasing atmospheric greenhouse gas concentrations. However, MIS 5e represents an important ‘process analogue’ for understanding the climatic mechanisms and feedbacks active under warmer-than-present climates (Stone et al. 2016).

Model simulations of the Peak MIS 5e climate at 127 ka are a part of the Coupled Model Intercomparison Project (CMIP6) and Paleoclimate Modelling Intercomparison Project (PMIP4) (Otto-Bliesner et al. 2017). Analysis of the short (50-100 years) orbitally forced CMIP6-PMIP4 ensembles indicate that these simulations exhibit SO summer  $\text{SST}_{\text{model}}$  (SSSTs) which were  $\sim 0.5^\circ \text{C}$  cooler during

Peak MIS 5e than the PI and that there was an average reduction of ~5-8 % in WSIE at 127 ka relative to the PI (Otto-Bliesner et al. 2021). These simulation results are a poor match for published Peak MIS 5e proxy records from SO marine sediment cores, which indicate a  $SSST_{proxy}$  warming of 0-5 °C relative to the PI (Capron et al. 2017, Otto-Bliesner et al. 2021). The SO model-data discrepancy is hypothesised to be due to the absence of the Heinrich 11 (H11) meltwater event in CMIP6-PMIP4 Tier 1 simulations (Otto-Bliesner et al. 2021). Though we also note that model-data comparisons of MIS 5e Antarctic WSIE have been limited by the location of most published marine sediment core records: they are located north of the modern WSIE, and likely also north of the 127 ka WSIE (Holloway et al. 2017, Chadwick et al. 2020).

The published syntheses of proxy records from SO marine sediment cores in Capron et al. (2017) and Chadwick et al. (2020) indicate Peak MIS 5e  $SSST_{proxy}$  were between 0 and 5 °C warmer than the present and PI, with this warming anomaly decreasing towards the South Pole. The most southerly marine cores in these syntheses have  $SSST_{proxy}$  anomalies for Peak MIS 5e of <1.5 °C (40 °W – 40 °E), but there are no MIS 5e marine records located south of the modern Antarctic Polar Front (APF) for most of the SO (80 °E – 40 °W).

Whilst most proxy records of Antarctic sea ice are located too far north to precisely constrain the Peak MIS 5e  $WSIE_{proxy}$ , a recent reconstruction suggests that the winter sea-ice (WSI) edge was located 1-2° south of its modern position in the Pacific sector and >5° south of its modern position in the Atlantic sector (Chadwick et al. 2022a).

This study presents a new model-data comparison for the Southern Ocean during MIS 5e. Peak MIS 5e Antarctic September sea-ice concentrations ( $SIC_{model}$ ) and SO  $SSST_{model}$  from the latest UK fully-coupled HadGEM3-GC3.1 (hereafter HadGEM3) numerical simulations, both with and without the H11 meltwater event (Guarino et al. 2022, *in review*), and from the H11 meltwater-hosed HadCM3 numerical simulations in Holloway et al. (2018) are compared with the latest diatom transfer function estimates of September  $SIC_{proxy}$  and  $SSST_{proxy}$  from nine marine sediment cores (Chadwick et al. 2021, Chadwick et al. 2022a) to answer the following:

- Can we now tell if different areas of the Southern Ocean show more or less consistency between model simulations and proxy data during MIS 5e?
- Is H11 meltwater forcing necessary for the models to match the proxy records?
- Are our current state of the art models capable of simulating the proxy data?

## **2. Materials and methods**

### **2.1. *Numerical simulations***

HadGEM3 is a global coupled atmosphere-land-ocean-ice model which combines the Unified Model Atmosphere model (Walters et al. 2017), the JULES land surface model (Walters et al. 2017), the NEMO ocean model (Madec et al. 2019) and the CICE sea-ice model (Ridley et al. 2018b). The PI control run is presented in Menary et al. (2018) and uses a constant 1850 climate forcing (see Menary et al. (2018) for further details).

The standard Peak MIS 5e simulation (hereafter referred to as LIG\_HG) is published in Guarino et al. (2020) and the H11 simulation is published in Guarino et al. (2022, *in review*). They were run using the protocol described in Otto-Bliesner et al. (2017) for Tier 1 and Tier 2 PMIP4 simulations. The Peak MIS 5e climate was simulated by forcing the HadGEM3 model with constant last interglacial orbital and greenhouse gas boundary conditions (see Guarino et al. (2022, *in review*) for further details). In the H11 run, the H11 meltwater event is simulated by adding a constant freshwater flux equal to 0.2 Sv, evenly across the North Atlantic between 50 and 70 °N (Otto-Bliesner et al. 2017). The H11 simulation was run for 250 years with the climatological averages from the final 100 years (150-250 years) presented here (hereafter referred to as H11(250)\_HG).

HadCM3 is a faster running, but older and lower resolution, UK model than HadGEM3. The HadCM3 simulations are published in Holloway et al. (2018), with 0.25 Sv freshwater forcing to the North Atlantic applied for 1600 years. We use the climatological averages for years 150-250 of the model run (hereafter referred to as H11(250)\_HC), to match the length of the run performed for HadGEM3, and the last 100 years (1500-1600 years)(hereafter referred to as H11(1600)\_HC), to examine how  $SSST_{\text{model}}$  and  $SICs_{\text{model}}$  evolved after a longer period of H11 type forcing.

MIS 5e  $SSST_{\text{model}}$  (average January to March) are presented as anomalies relative to the PI control runs whereas September  $SICs_{\text{model}}$  are presented as absolute values.

### **2.2. *Marine sediment cores***

Modern Analog Technique diatom transfer function estimates of September  $SICs_{\text{proxy}}$  and  $SSSTs_{\text{proxy}}$  for Peak MIS 5e, reconstructed from nine marine sediment cores and published in Chadwick et al. (2022a), are compared to model output. The transfer function methodology is detailed in Chadwick et al. (2022a) and the data for all the cores is available from Chadwick et al. (2021). Reconstructed September  $SICs_{\text{proxy}}$  have a Root Mean Square Error of Prediction (RMSEP) of 0.09 and  $SSSTs_{\text{proxy}}$  have a RMSEP of 1.1 °C. For PI  $SSSTs_{\text{proxy}}$  at each core site the average January-March  $SST_{\text{proxy}}$  from 1870-1900 was calculated from the HadISST1 dataset (Rayner et al. 2003). The average  $SSST_{\text{proxy}}$  and

September SIC<sub>proxy</sub> in the 130-128 ka interval is considered to represent Peak MIS 5e conditions. This time interval is chosen as it is within the chronological uncertainty ( $\pm 2$  ka) of both the peak  $\delta^{18}\text{O}$  in the EPICA Dome C ice core record at  $\sim 128$  ka (Sime et al. 2009) and the termination of the H11 meltwater event at 130 ka (Marino et al. 2015).

### **3. Results**

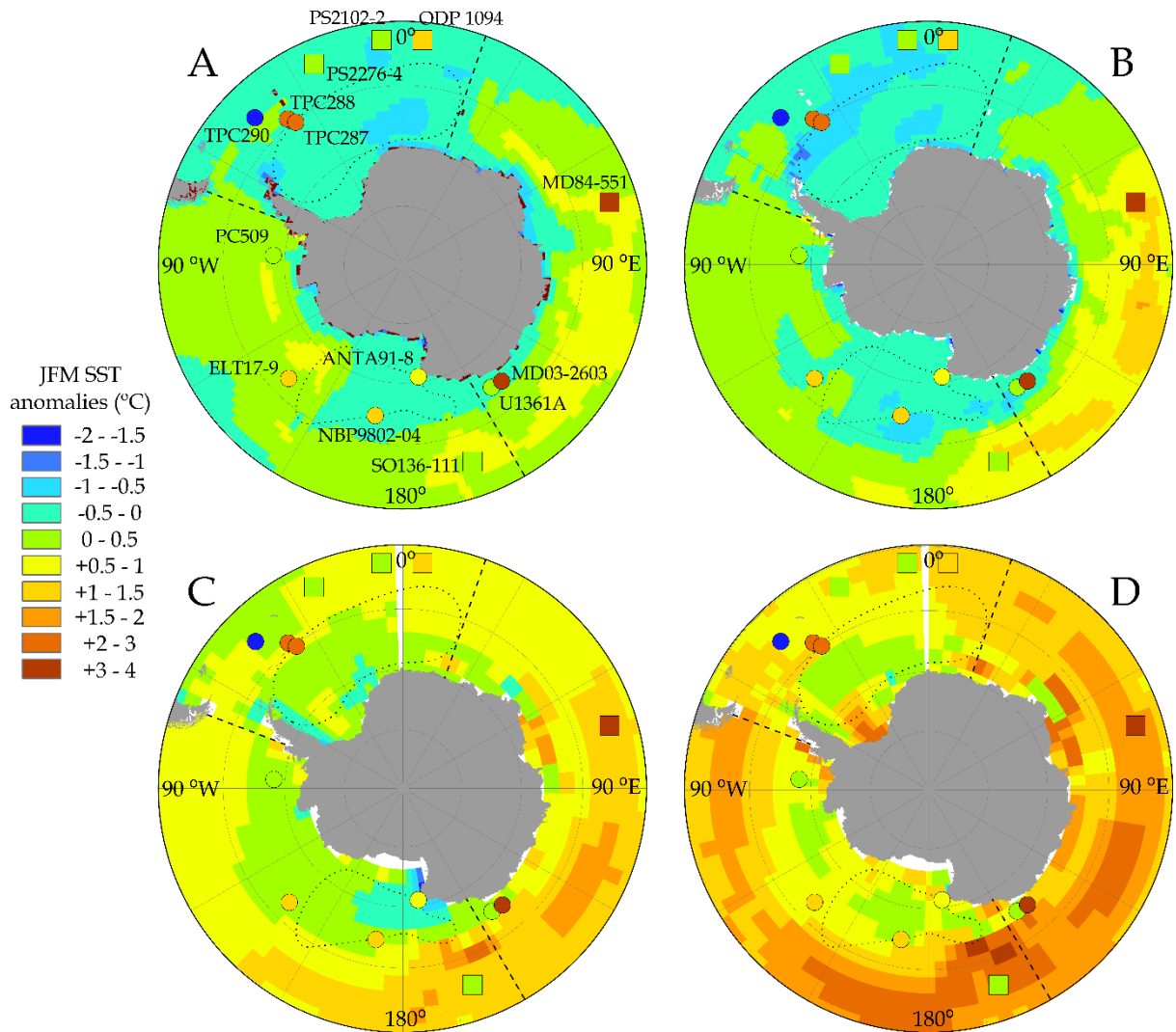
#### **3.1. SSST<sub>model</sub> anomalies**

In both the LIG\_HG and H11(250)\_HG simulations the pattern of SSST<sub>model</sub> anomalies for Peak MIS 5e relative to the PI is very similar (Figure 1a & b). Both runs show a cooling (0-1 °C) in the Atlantic sector (70 °W – 20 °E) and a warming (0-1.5 °C) in the Indian sector (20 – 150 °E) during Peak MIS 5e relative to the PI, with both trends more pronounced in the H11(250)\_HG run (Figure 1b). In the Pacific sector (150 °E – 70 °W), both the LIG\_HG and H11(250)\_HG simulations show a warming (0-1 °C) in the eastern region (120 – 70 °W) and a cooling (0-0.5 °C) in the western region, south of the modern WSIE (150 °E – 150 °W) but have diverging trends in the central area (150 – 120 °W) where the LIG\_HG run has a warming of up to 1 °C and the H11(250)\_HG run has a mixture of warming and cooling, all by less than 0.5 °C (Figure 1a & b).

The H11(250)\_HC and H11(1600)\_HC simulations both have greater warming trends than either of the HadGEM3 runs, with only a few localised areas of cooling in the H11(250)\_HC run and none in H11(1600)\_HC run (Figure 1c & d). In the H11(250)\_HC run, the area north of the modern WSIE had largely warmed by 0.5-1.5 °C, whereas the region within the modern WSIE was generally less than 0.5 °C warmer than PI (Figure 1c). In the H11(1600)\_HC run the SSST<sub>model</sub> anomalies have increased throughout the SO relative to the H11(250)\_HC run, with the region within the modern WSIE mainly 0.5-1.5 °C warmer than PI and the area to the north of the modern WSIE largely showing 1-3 °C warming (Figure 1d). All simulations show the greatest Peak MIS 5e warming in the 90-170 °E region, north of 60 °S (Figure 1).

#### **3.2. SSST<sub>proxy</sub> anomalies**

With the exception of core TPC290, the sediment cores all indicate warmer conditions during Peak MIS 5e than the PI (Table 1 & Figure 1). The Pacific sector cores have SSST<sub>proxy</sub> anomalies of less than 1.5 °C, with the more southerly cores showing a warming of less than 1 °C (Table 1). The nearby cores TPC288 and TPC287 in the Atlantic sector have similar SSST<sub>proxy</sub> anomalies to each other, whereas, in the Indian sector, the proximally located cores MD03-2603 and U1361A have very different SSST<sub>proxy</sub> anomalies to each other, with the SSST<sub>proxy</sub> anomaly for core MD03-2603 more than 3 °C warmer than the anomaly in core U1361A (Table 1 & Figure 1).



**Figure 1:** Maps of summer (JFM) SST<sub>model</sub> anomalies for Peak MIS 5e relative to the PI. **A** - LIG\_HG. **B** - H11(250)\_HG. **C** - H11(250)\_HC. **D** - H11(1600)\_HC. Coloured circles on all maps represent the JFM SST<sub>proxy</sub> anomalies from Chadwick et al. (2022a) and coloured squares represent the summer SST<sub>proxy</sub> anomalies from Capron et al. (2017). The dashed black lines mark the boundaries between the three SO sectors and the dotted black lines mark the modern extents of the Weddell Sea and Ross Sea gyres (positions of the Weddell Sea gyre is from Vernet et al. (2019) and the Ross Sea gyre is from Dotto et al. (2018)).

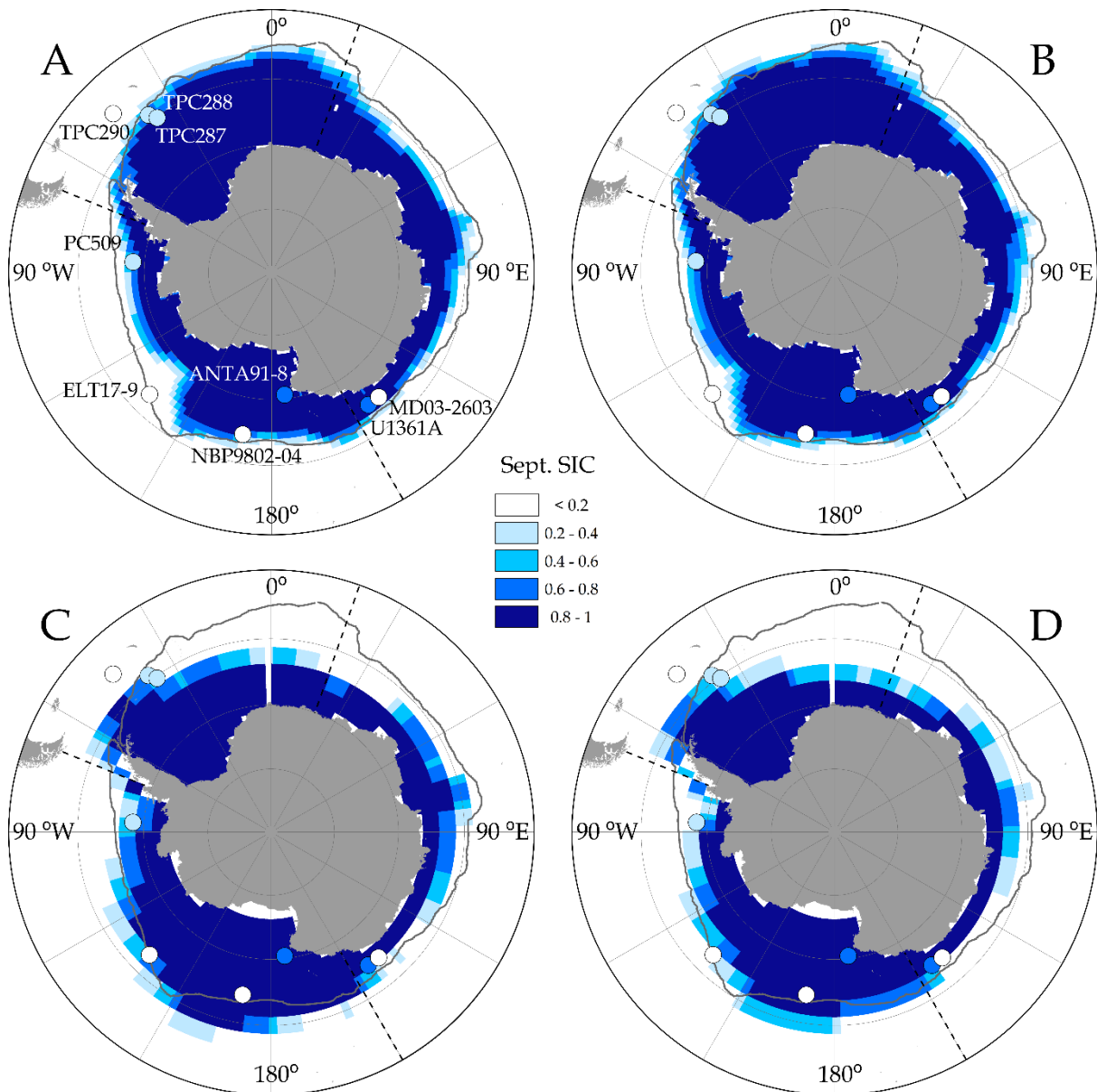
158 Within the  $\pm 1.1$  °C uncertainty on the diatom transfer function SSST<sub>proxy</sub> values and the standard  
 159 deviation of the model output, the Peak MIS 5e – PI SSST<sub>proxy</sub> anomalies in all Pacific sector cores match  
 160 the H11(250)\_HC and H11(1600)\_HC runs (Table 1, Figure 1c & d). Proxy data for cores PC509 and  
 161 ANTA91-8 also match the HadGEM3 model outputs (Table 1) and the proxy data in core ELT17-9  
 162 matches the LIG\_HG run (Table 1). The transfer function Peak MIS 5e SSST<sub>proxy</sub> anomaly in core U1361A  
 163 also matches, within uncertainty, the values from all four model runs (Table 1). The transfer function  
 164 SSST<sub>proxy</sub> anomalies in cores TPC288 and MD03-2603 only match the model output for H11(1600)\_HC  
 165 and in core TPC287 there is not a match with any of the model outputs considered here (Table 1).

166 Cores TPC288, TPC287 and MD03-2603 have SSST<sub>proxy</sub> anomalies >2 °C warmer than all the models and  
167 core TPC290 >1.5 °C cooler than all the models (Table 1).

	TPC290	TPC288	TPC287	ELT17-9	NBP9802-04	MD03-2603	U1361A	PC509	ANTA91-8	SO average (mean ± st. dev.)
<b>Latitude (°S), Longitude (°E)</b>	55.55, -45.02	59.14, -37.96	60.31, -36.65	63.08, -135.12	64.20, -170.08	64.28, 139.38	64.41, 143.89	68.31, -86.03	70.78, 172.83	-
<b>SSST<sub>proxy</sub> anomaly (°C)</b>	-1.70 ± 1.10	+2.65 ± 1.10	+2.75 ± 1.10	+1.24 ± 1.10	+1.43 ± 1.10	+3.13 ± 1.10	+0.04 ± 1.10	+0.24 ± 1.10	+1.00 ± 1.10	+1.56 ± 1.19
<b>LIG_HG SSST<sub>model</sub> anomaly (°C)</b>	-0.03 ± 0.67	-0.19 ± 0.90	-0.31 ± 1.02	+0.19 ± 0.91	-0.32 ± 1.06	-0.19 ± 1.05	-0.20 ± 1.18	+0.25 ± 1.01	-0.10 ± 0.29	-0.10 ± 0.04
<b>H11(250)_HG SSST<sub>model</sub> anomaly (°C)</b>	-0.16 ± 0.60	-0.50 ± 0.90	-0.78 ± 0.92	-0.03 ± 1.11	-0.55 ± 1.00	-0.50 ± 1.07	-0.66 ± 1.17	-0.02 ± 0.83	-0.13 ± 0.26	-0.37 ± 0.07
<b>H11(250)_HC SSST<sub>model</sub> anomaly (°C)</b>	+0.45 ± 0.72	+0.67 ± 0.82	+0.62 ± 0.81	+0.23 ± 0.61	+0.17 ± 0.60	+0.62 ± 0.89	+0.41 ± 0.74	+0.05 ± 0.52	-0.04 ± 0.74	+0.35 ± 0.06
<b>H11(1600)_HC SSST<sub>model</sub> anomaly (°C)</b>	+0.94 ± 0.72	+1.11 ± 0.92	+0.49 ± 0.84	+0.77 ± 0.63	+0.55 ± 0.66	+1.34 ± 0.84	+0.73 ± 1.00	+0.45 ± 0.54	+0.39 ± 0.73	+0.75 ± 0.09
<b>September SIC<sub>proxy</sub></b>	0.19 ± 0.09	0.23 ± 0.09	0.22 ± 0.09	0.13 ± 0.09	0.11 ± 0.09	0.19 ± 0.09	0.63 ± 0.09	0.34 ± 0.09	0.62 ± 0.09	0.30 ± 0.03
<b>LIG_HG September SIC<sub>model</sub></b>	0.00 ± 0.00	0.71 ± 0.62	0.89 ± 0.32	0.00 ± 0.00	0.67 ± 0.58	0.93 ± 0.12	0.93 ± 0.08	0.73 ± 0.58	0.96 ± 0.02	0.65 ± 0.13
<b>H11(250)_HG September SIC<sub>model</sub></b>	0.00 ± 0.00	0.79 ± 0.44	0.94 ± 0.10	0.01 ± 0.06	0.80 ± 0.42	0.94 ± 0.10	0.94 ± 0.06	0.85 ± 0.34	0.95 ± 0.02	0.69 ± 0.14
<b>H11(250)_HC September SIC<sub>model</sub></b>	0.00 ± 0.03	0.42 ± 0.28	0.42 ± 0.32	0.66 ± 0.32	0.96 ± 0.02	0.94 ± 0.13	0.95 ± 0.09	0.47 ± 0.36	0.97 ± 0.00	0.64 ± 0.10
<b>H11(1600)_HC September SIC<sub>model</sub></b>	0.00 ± 0.03	0.22 ± 0.25	0.22 ± 0.28	0.17 ± 0.35	0.94 ± 0.02	0.93 ± 0.13	0.94 ± 0.09	0.19 ± 0.33	0.97 ± 0.01	0.51 ± 0.16

**Table 1:** Diatom transfer function values and model output for Peak MIS 5e September SICs<sub>model/proxy</sub> and SSST<sub>model/proxy</sub> anomalies (Peak MIS 5e – PI) for nine marine sediment core locations and an average for the SO from the model/proxy values at the nine core sites. Diatom transfer function values for Peak MIS 5e are an average of the 130-128 ka interval and are presented in Chadwick et al. (2022a). For the model output, pink shading indicates conditions that are warmer/have less sea ice than the proxy values, blue shading indicates conditions that are colder/have more sea ice, and no shading indicates conditions that match the proxy values within uncertainty. The errors on the proxy data for each core are the RMSEP values for the diatom transfer function (section 2.2) and the errors on the model data at each core site are two standard deviations for the September SICs and one standard deviation for the SSST anomalies (cf. Guarino et al. 2020).

169 The patterns of September SICs<sub>model</sub> are very similar between the HadGEM3 simulations (Figure 2a &  
 170 b), with the main difference a greater WSIE<sub>model</sub> in the H11(250)\_HG run in the Pacific sector region  
 171 150-120 °W and in the Weddell Sea to the east of the Antarctic Peninsula (Figure 2b). The HadCM3  
 172 simulations both have a reduced WSIE<sub>model</sub> compared to the HadGEM3 runs, most notably in the  
 173 eastern Weddell Sea (30 °W – 30 °E) where the WSI edge is >5 ° latitude further south than either of  
 174 the HadGEM3 runs (Figure 2c & d). In the H11(1600)\_HC run, the September SICs<sub>model</sub> are reduced



**Figure 2:** Maps of September SICs<sub>model</sub> for Peak MIS 5e. **A** - LIG\_HG. **B** - H11(250)\_HG. **C** - H11(250)\_HC. **D** - H11(1600)\_HC. Coloured circles on all maps represent the September SICs<sub>proxy</sub> in Chadwick et al. (2022a). The grey line on all maps marks the modern (1981-2010) median September sea-ice extent (Fetterer et al. 2017) and the dashed black lines mark the boundaries between the three SO sectors.



compared to H11(250)\_HC run, with the WSI edge 2-5 ° latitude further poleward in the former (Figure 2d).

### **3.4. September SICs<sub>proxy</sub>**

Within the  $\pm 0.09$  uncertainty on the transfer function September SIC<sub>proxy</sub> values and two standard deviations of the model outputs, the Peak MIS 5e September SICs<sub>proxy</sub> for many of the cores (TPC290, MD03-2603, U1361A and ANTA91-8) do not match any of the model runs (Table 1 & Figure 2). The match between model and proxy September SICs in the other cores is largely due to the high standard deviations of the model output. The proxy data in cores TPC288, TPC287, ELT17-9 and PC509 are the closest match for the H11(1600)\_HC simulation (Table 1). The pattern of September SICs<sub>model</sub> in the H11(1600)\_HC simulation is also the best match with the transfer function values in the sediment cores (Figure 2d), with the greatest discrepancy evident in the expansion of western Pacific sector (150 °E – 150 °W) WSIE<sub>model</sub>, relative to the modern, in the H11(1600)\_HC run, compared with the WSIE<sub>proxy</sub> reduction evident in the sediment core data (Figure 2d).

## **4. Discussion**

### **4.1. SSST<sub>model/proxy</sub> anomalies**

For the Pacific sector core sites, the best model-data match for SSST<sub>model/proxy</sub> anomalies is with the H11(1600)\_HC run (Table 1 & Figure 1d), suggesting that the region south of 60 °S in this sector was largely 0.5-1 °C warmer than PI during Peak MIS 5e (Figure 1d). This SSST<sub>model</sub> anomaly is consistent with the more southerly SO core sites in Capron et al. (2017) and Chadwick et al. (2020) and suggests that the region south of the APF warmed less than the rest of the SO during MIS 5e. The better match between the proxy data and the H11(1600)\_HC simulation than between the proxy data and the H11(250)\_HC simulation supports the need to run meltwater-hosed simulations for a longer duration than the 250 years in both the H11(250)\_HG and H11(250)\_HC runs.

In the Indian sector, all the model runs in this study indicate warmer conditions at core site MD03-2603 than the nearby U1361A (Table 1), but none of them have a difference of more than 0.8 °C, whereas the transfer function SSST<sub>proxy</sub> anomalies are >3 °C warmer at core site MD03-2603 than U1361A (Table 1). The colder conditions around core U1361A could be due to increased melting of the Wilkes subglacial basin during MIS 5e (Wilson et al. 2018). The shelf bathymetry would likely funnel any colder glacial meltwaters towards U1361A rather than MD03-2603, promoting the difference in SSST<sub>model/proxy</sub> anomalies. However, this does not explain why the SSST<sub>proxy</sub> anomaly for core MD03-2603 is still >2 °C greater than any of the model results.

None of the model runs considered here are able to recreate the  $\sim 2.7$  °C SSST<sub>proxy</sub> anomaly in the Atlantic sector cores TPC288 and TPC287 (Table 1 & Figure 1). This discrepancy could be as a result of a poleward constriction of the northern limb of the Weddell Gyre not materialising in the model runs. A constriction of the Weddell Gyre would displace warm ( $>1.5$  °C) surface waters to the south during Peak MIS 5e, causing larger positive SSST<sub>proxy</sub> anomalies at cores TPC288 and TPC287 than if both cores had remained bathed by Weddell Sea surface waters during Peak MIS 5e. A CMIP3 and CMIP5 model ensemble by Wang (2013) identified that subpolar gyre areal extent displays a diverse response to warmer-than-present climatic conditions, with trends varying from a  $23 \times 10^{10} \text{ m}^2/\text{decade}$  decrease to a  $69 \times 10^{10} \text{ m}^2/\text{decade}$  increase between models. Our proxy-model comparison could further highlight the deficiencies of subpolar gyre evolution in models, with the greatest discrepancies for the core sites at the edges of the present-day gyre extents.

The  $>2$  °C SSST<sub>proxy</sub> anomalies in cores TPC288, TPC287 and MD03-2603 are greater than other published SSST<sub>proxy</sub> anomalies from the region south of the APF (Capron et al. 2017, Chadwick et al. 2020) and contrasts with the pattern of decreased SSST<sub>proxy</sub> anomalies towards the continent. The largest SSST<sub>proxy</sub> anomalies in the Capron et al. (2017) and Chadwick et al. (2020) syntheses were found in cores that were likely bathed by different surface water masses during MIS 5e compared to present/PI (Chadwick et al. 2020), indicating that this is likely also the case for core sites TPC288, TPC287 and MD03-2603. This difference in the surface water mass above the core sites was caused by either changes in gyre extent, in the case of cores TPC288 and TPC287, or by movement of Antarctic Circumpolar Current fronts, in the case of core MD03-2603 (Chadwick et al. 2022a). Comparing the SSST<sub>proxy</sub> anomalies in the Atlantic and Indian sectors with the Pacific sector shows that there is strong longitudinal heterogeneity in SSST<sub>proxy</sub> anomalies in addition to the latitudinal variation identified by Chadwick et al. (2020).

For the SO south of the APF, Capron et al. (2017) reconstructed a mean SSST<sub>proxy</sub> anomaly of  $+1.4 \pm 1.2$  °C during Peak MIS 5e relative to the PI and Chadwick et al. (2022a) reconstructed a mean SSST<sub>proxy</sub> anomaly of  $+1.6 \pm 1.2$  °C relative to the PI. Combining these syntheses indicates that the SO south of the APF averaged  $1.5 \pm 1.2$  °C warmer during Peak MIS 5e than the PI.

#### **4.2. September SICs<sub>model/proxy</sub>**

In the western Pacific (Ross Sea) sector all the model runs appear to overestimate Peak MIS 5e WSIE<sub>model</sub>, with the HadCM3 runs even indicating an expansion in WSIE<sub>model</sub> relative to the modern (Figure 2c & d). The eastern Pacific sector has better model-data agreement, especially for the H11(250)\_HG and H11(1600)\_HC runs (Figure 2b & d). The shape of modern Pacific sector WSIE is strongly influenced by the position of the APF and the shape and position of the Ross Sea Gyre (Nghiem

et al. 2016), with the proxy data indicating a poleward movement of the APF and contraction of the Ross Sea Gyre in the western Pacific sector which is less apparent in the models.

A similar poleward contraction of the Weddell Gyre during MIS 5e, as previously hypothesised with the  $SSST_{proxy}$  anomalies in cores TPC288 and TPC287 (section 4.1), would also help explain the shape of the  $WSIE_{model}$  in the HadCM3 runs (Figure 2c & d), with a longitudinal constriction of the Weddell Gyre during MIS 5e also supported by proxy data from the western Indian sector (Ghadi et al. 2020). The shape of the eastern Indian sector  $WSIE_{model}$  in the HadCM3 simulations in the proximity of cores MD03-2603 and U1361A (Figure 2c & d) is consistent with the greater Peak MIS 5e September  $SIC_{proxy}$  reconstructed for core U1361A. High glacial meltwater flux can promote increased  $WSIE$  (Merino et al. 2018) and the configuration of the eastern Indian sector  $WSIE$  therefore supports a large release of glacial meltwater from the Wilkes subglacial basin during MIS 5e (Wilson et al. 2018), which was channelled towards core U1361A rather than core MD03-2603, as discussed in section 4.1. Many of the estimates of Peak MIS 5e September  $SIC_{proxy}$  have a good visual similarity to the models (Figure 2) but do not match the models within the transfer function uncertainty (Table 1). This discrepancy is due to the steep gradient in  $SIC$  fraction, with values between 0.2 and 0.8 occupying only a small geographic area (Figure 3), and therefore small variations in the position of the  $WSI$  edge can make a large difference to the Peak MIS 5e September  $SIC_{model/proxy}$  at most of the core sites. This is supported by the high standard deviation of model output for September  $SICs_{model}$  between 0.2 and 0.8 (Table 1).

## 5. Conclusions

Reconstructed Peak MIS 5e September  $SICs_{proxy}$  and  $SSST_{proxy}$  anomalies display variation both within and between SO sectors (Figures 1 & 2). The greatest discrepancies between the proxy data and the simulation results are for the  $WSIE$  in the western Pacific sector and the  $SSSTs$  in the Atlantic sector (Figures 1 & 2), suggested to be due to a poleward contraction of the Ross and Weddell Gyres, respectively, which are seemingly not fully realised in the models.

Of the four HadGEM3 and HadCM3 simulations presented in this study, the best match to the proxy data is provided by the H11(1600)\_HC simulation (Figure 1d, Figure 2d & Table 1). The better model-data agreement for the H11(1600)\_HC run than for the H11(250)\_HC run supports the importance of including North Atlantic meltwater hosing in models of Peak MIS 5e climate and running the models for longer than 250 years. The short run length of the H11(250)\_HG simulation explains the poor match to the proxy data as the output is more likely reflective of the conditions at ~133 ka (Marino et al. 2015, Holloway et al. 2018) than 130-128 ka.

Running the meltwater hosed H11(250)\_HG simulation for a longer duration, ideally 3-4 ka (Marino et al. 2015), is crucial for investigating how well the latest simulations match with the Peak MIS 5e conditions reconstructed from marine sediment cores. Whilst the existing evidence suggests that H11 meltwater forcing is required to get a match between the models and proxy data, the current model run-duration is too short and likely needs to be run for at least 1500 years for us to know whether state of the art models are capable of matching the Peak MIS 5e conditions evidenced by the proxy data. Of particular interest in the analysis of longer HadGEM3 runs would be to assess whether the model would resolve the greater reduction in the Atlantic sector  $WSIE_{model/proxy}$  seen in both sediment core data (Chadwick et al. 2022a, b) and previous models (Holloway et al. 2017, Holloway et al. 2018) but absent from either the LIG\_HG or H11(250)\_HG simulations (Figure 2a & b). Additionally, for future model runs there potentially needs to be additional focus on how the Weddell Sea and Ross Sea gyres are realised in the simulations.

### **Open Research**

The MIS 5e September SIC and SSST data for the nine marine sediment cores, produced using the Modern Analog Technique, are available from PANGAEA (<https://doi.org/10.1594/PANGAEA.936573>) (Chadwick et al. 2021). All HadGEM3 and HadCM3 model output presented in this manuscript are available as netCDF files from the JASMIN group workspace web access site ([https://gws-access.jasmin.ac.uk/public/pmip4/EPSL\\_Chadwicketal\\_2022/](https://gws-access.jasmin.ac.uk/public/pmip4/EPSL_Chadwicketal_2022/)) and will be deposited in Mendeley by the time the article is accepted. Additionally the PI HadGEM3 output is available from the Earth System Grid Federation (<https://doi.org/10.22033/ESGF/CMIP6.419>) (Ridley et al. 2018a).

### **Author Contributions**

MC – Data curation, Formal analysis, Investigation, Methodology, Resources, Visualisation, Writing – original draft; LCS – Conceptualisation, Funding acquisition, Project administration, Supervision, Writing – review & editing; CSA – Conceptualisation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing; MVG – Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Writing – review & editing.

### **Competing interests**

The authors declare they have no competing interests.

### **Funding**

The Natural Environmental Research Council [grant number NE/L002531/1] supported this work. LCS and MVG acknowledge the financial support of National Environmental Research Council research

grants NE/P013279/1 and NE/P009271/1, respectively. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820970. This research also contributes to the British Antarctic Survey's "Polar Science for Planet Earth" programme.

## **Acknowledgements**

Our thanks to both Sentia Goursaud and Irena Malmierca Vallet for assisting in both accessing and formatting the HadCM3 output data from Holloway et al. (2018). This work used the ARCHER UK National Supercomputing Service (<http://www.archer.ac.uk>) and the JASMIN analysis platform (<https://www.ceda.ac.uk/services/jasmin/>).

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