Wind-driven evolution of the North Pacific subpolar gyre over the last deglaciation

supporting information

Using planktic foraminiferal $\delta^{18}O_{calcite}$ to trace the gyre boundary

Our ability to use the planktic foraminiferal $\delta^{18}O_{calcite}$ to trace the gyre boundary comes from the dominance of the temperature signal over that of $\delta^{18}O_{water}$ in driving the meridional pattern of $\delta^{18}O_{calcite}$ across the basin; the temperature signal is ~5 times greater than the $\delta^{18}O_{water}$ (~salinity) signal (Figure 1). As the spatial temperature pattern across the basin is primarily governed by the gyre circulation, with the steepest meridional temperature gradient (and thus meridional $\delta^{18}O_{calcite}$ gradient) at the gyre boundary, we can use the meridional profiles of temperature (~$\delta^{18}O_{calcite}$) to track the movement of the gyre boundary. Coupled climate models demonstrate a very tight coupling between the LGM-PI change in latitude of gyre boundary (defined where barotropic stream function = 0) and LGM-PI change in the latitude of maximum latitudinal gradient in sea surface temperature (SST) (Figure S1). As no mechanism exists to drive changes in $\delta^{18}O_{water}$ of the same magnitude as the changes in $\delta^{18}O_{calcite\text{-}water}$ fractionation from the large temperature difference between the gyres (Figure 1d), the temperature signal will always dominate over the $\delta^{18}O_{water}$ signal in determining the spatial pattern of $\delta^{18}O_{calcite}$ (Figure 1e) across the basin and the maximum meridional $\delta^{18}O_{calcite}$ gradient (Figure 1f); thus, while there are likely to be local changes in $\delta^{18}O_{water}$ across the basin, the steepest part of the meridional $\delta^{18}O_{calcite}$ gradient will always be determined by temperature, allowing us to use meridional profiles of $\delta^{18}O_{calcite}$ to track the position of the gyre boundary through time.

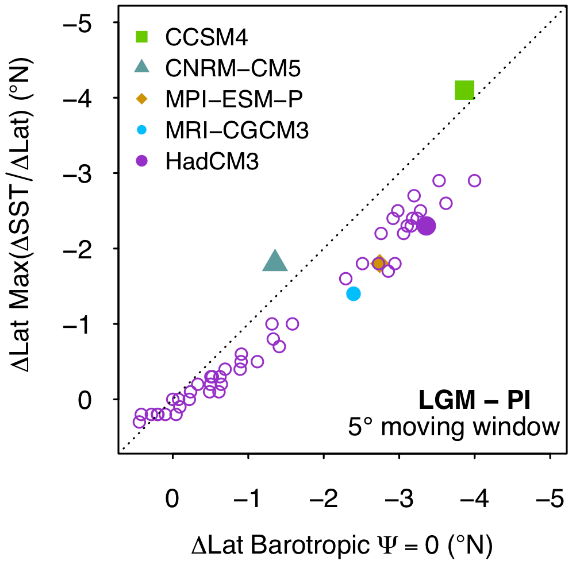

Figure S1 Modelled zonal mean LGM-pre-industrial (PI) change in latitude of gyre boundary (defined where barotropic stream function = 0) versus LGM-PI change in latitude of maximum meridional gradient in sea surface temperature (SST) within a 5° moving window; the close relationship demonstrates past changes in the position of the maximum gradient in SST/Lat (and thus ~$\delta^{18}O_{calcite}$/Lat) can be used to trace changes in the position of the gyre boundary.

We model the $\delta^{18}O_{calcite}$ data as a function of latitude, using a general additive model (GAM) (Wood, 2011; Wood *et al.*, 2016) in the *mgcv* package in R (R core Team) at 500 yr timesteps from 18.5 to 10.5 ka (the time interval for which we have sufficient spatial and temporal resolution in our dataset; Figure 1),

$$\delta^{18}O_{calcite} = \beta + f(Lat) + \varepsilon$$

where f(Lat) is the sum of the underlying basis functions (Wood, 2011; Wood et al., 2016). The smoothing term (λ) was determined using generalised cross validation (GCV). We tested the models fitted using GCV by fitting models with an identical form, however using Reduced Maximum Likelihood (REML), which can sometimes be a preferable method to GCV (Reis and Ogden, 2009; Wood *et al.*, 2016), to determine the smoothing term; both GCV and REML result in identical smoothing terms, very similar degrees of freedom (4.06 with GCV versus 4.19 with REML), and indistinguishable model fits.

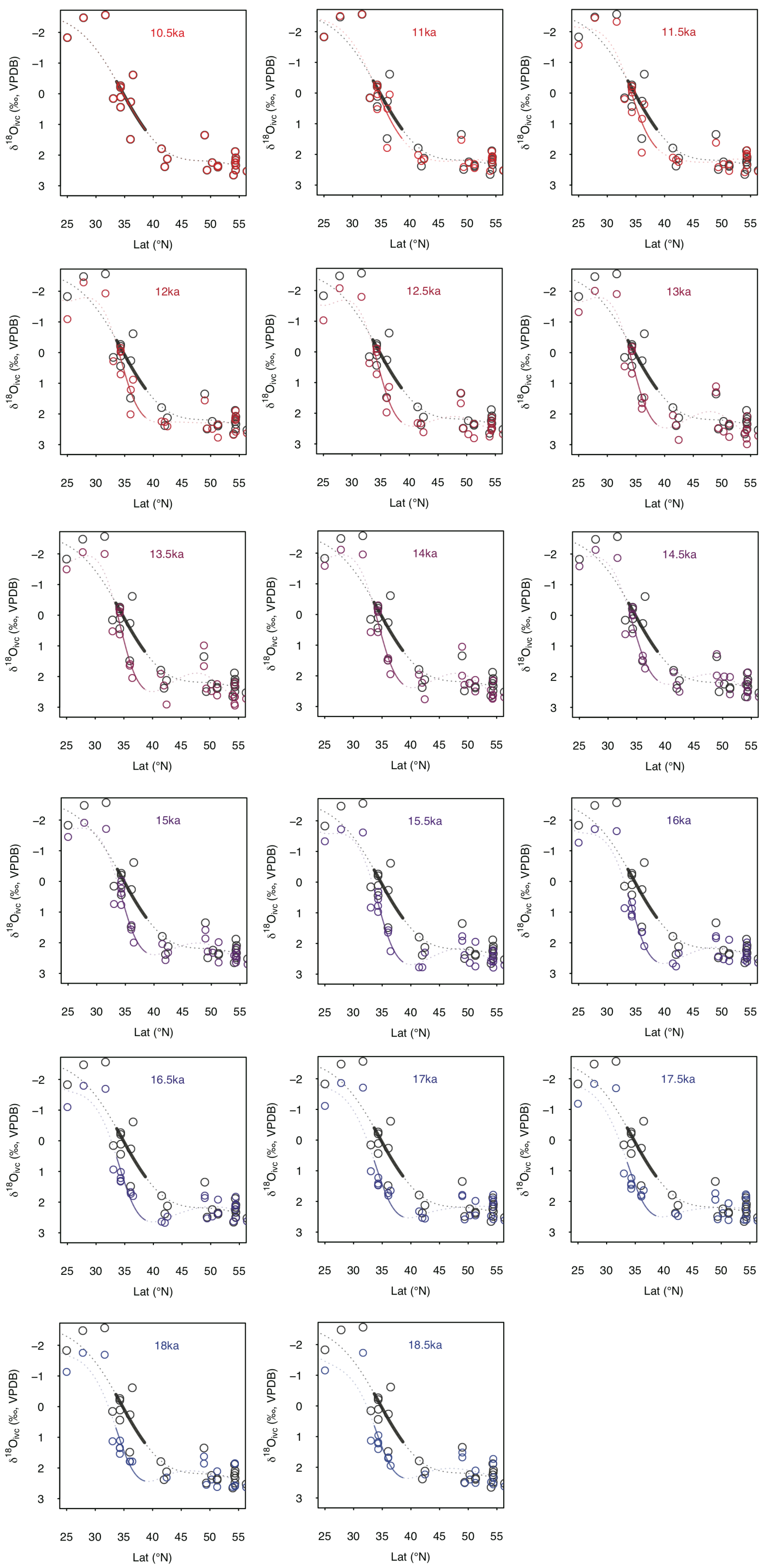

Figure S2 GAM fits to $\delta^{18}O_{calcite}$ data as a function of latitude at 500 year timesteps from 18.5 to 10.5 ka (colours); the GAM fit to Holocene $\delta^{18}O_{calcite}$ data (10.5 ka) is shown in grey. The portion of the curve within the latitudinal band used to calculate the shift in gyre position is shown by the solid line; at each timestep we calculate the latitudinal shift that minimises the Euclidian distance between the solid part of the coloured curve and the solid part of the grey curve. Data are the combined east-west dataset (marked ALL on Figure 4).

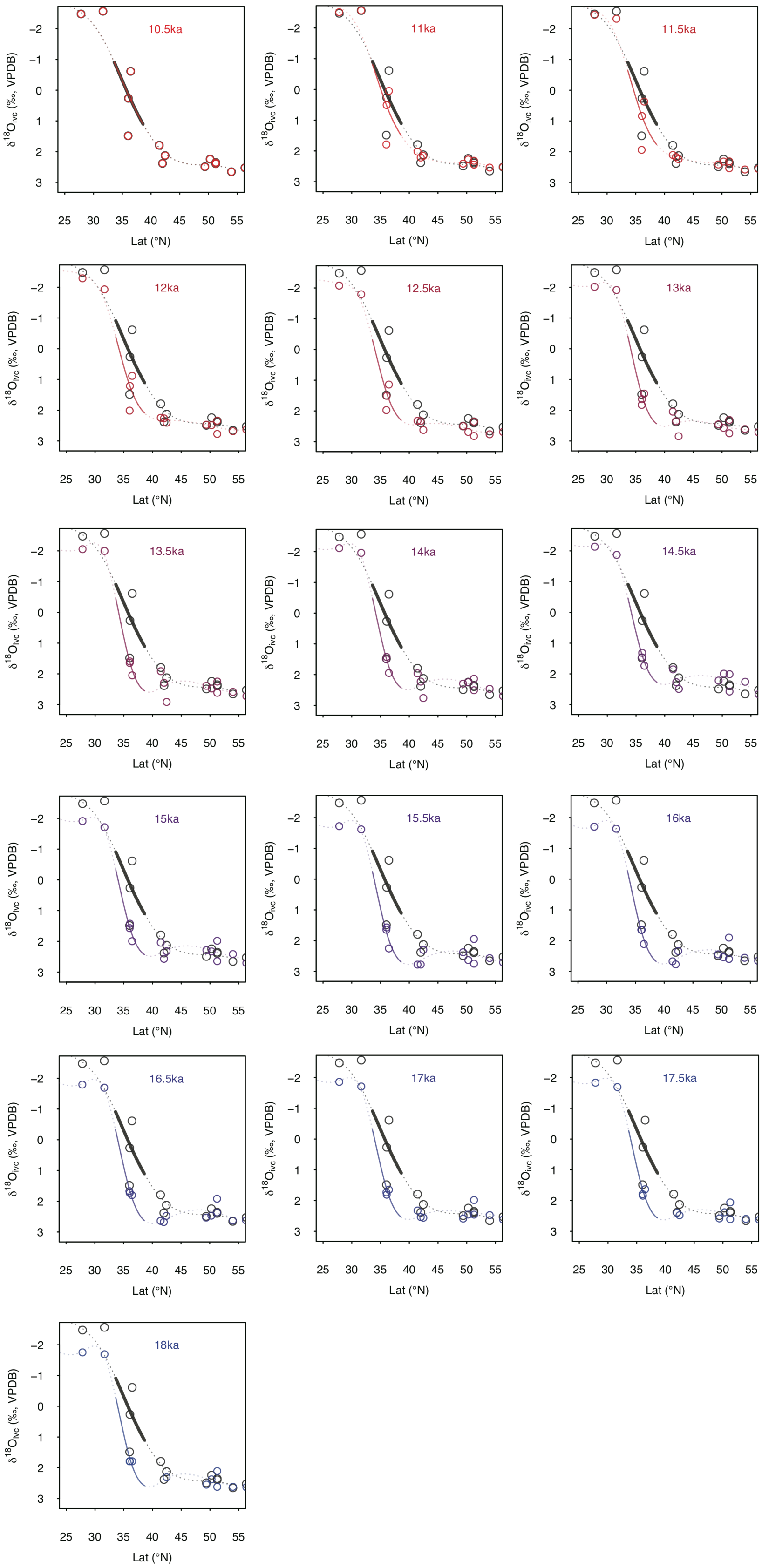

Figure S3 As figure SX, however data are from west of 180°.

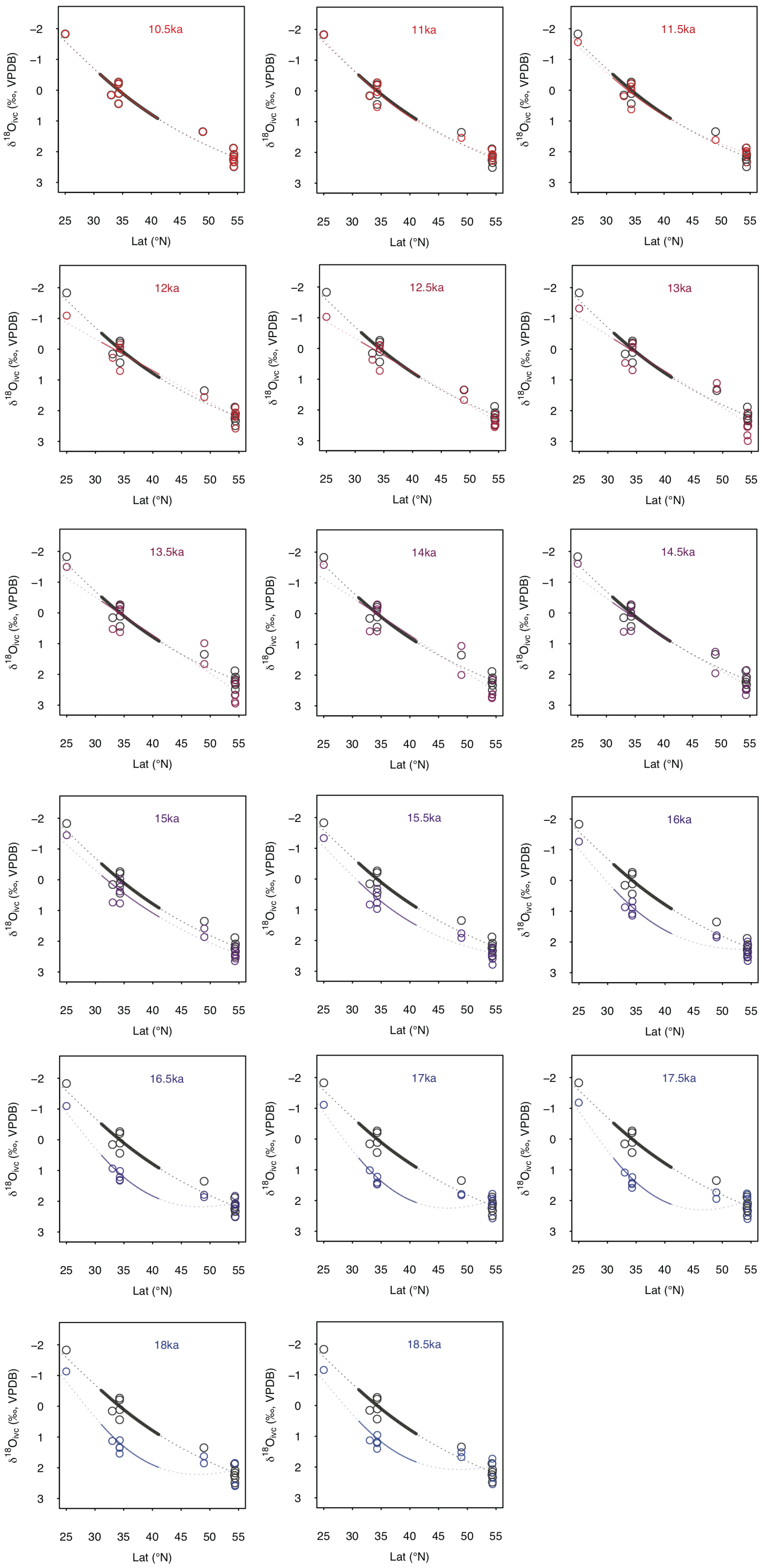

Figure S4 As figure SX, however data are from east of 180°.

We calculate the change in gyre boundary position over deglaciation as the latitudinal shift (x°) that minimises the Euclidian distance (L^2) between the Holocene (taken as 10.5±0.5 ka) $\delta^{18}O_{calcite}$~latitude GAM fit and the GAM fit to each time step, within a latitudinal band spanning the gyre boundary; this latitudinal band is centred around the maximum gradient in $\delta^{18}O_{calcite}$ versus latitude in the Holocene data within a 5° moving window (36.1 °N). In the combined dataset from the east and west, and the data from the west only, we calculate the latitudinal shift using a 5° latitudinal band (i.e. 33.6 to 38.6 °N), and we note the size of this latitudinal band has only a negligible effect on our results (Fig. SX); as the gyre boundary (and thus meridional temperature and $\delta^{18}O_{calcite}$ gradient) is more diffuse in the east, we use a slightly larger window of 10° (i.e. 31.1 to 41.1 °N).

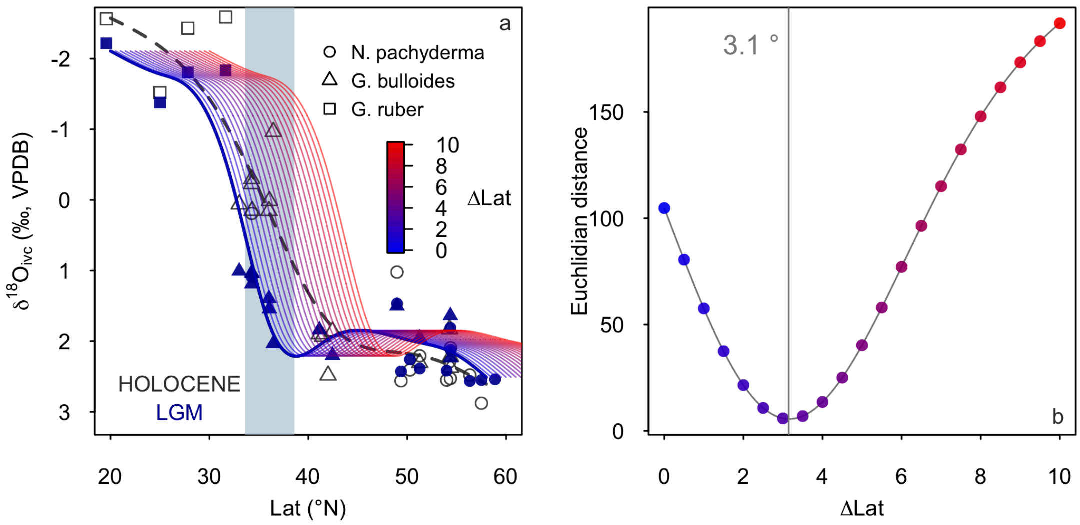

Figure S5 method used to calculate the shift in gyre boundary position **(a)** at each time step (here LGM, 18.5 ka) we calculate the gyre boundary shift as the latitudinal shift (x°, in 0.1 ° increments from 0 to 10 degrees) that minimises the Euclidian distance **(b)** within a specified latitudinal band (grey box in (a) between the GAM fit to the timestep and the Holocene in data is calculated. The coloured lines in (a) show the LGM GAM fit shifted north in 0.5° increments, and the coloured dots in (b) show the Euclidian distance at each increment, with the colour indicating the degree to which the curve has been shifted.

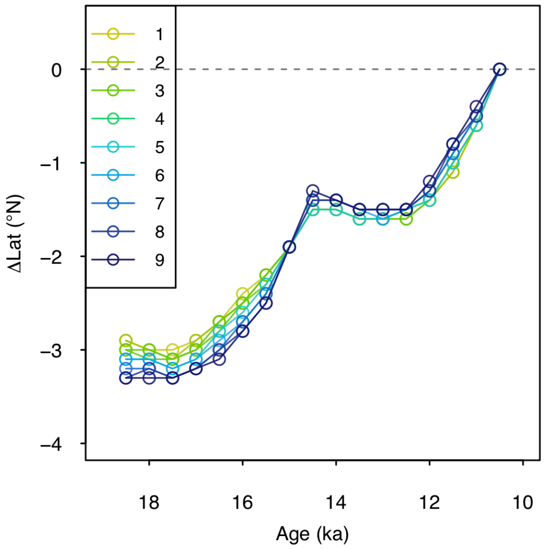

Figure S6 (a) calculated change in the position of the gyre boundary using different sizes of latitudinal band (between 1° and 9°) in which the Euclidian distance is calculated; the size of latitudinal band (the grey box in figure SXa above) has very little effect on the results.

We note that the steepest part of the Holocene curve (~36.1 °N) using the combined dataset from the east and west, is further south than the zonal mean position of the gyre boundary today (~40 °N). This is due to the westward bias within the dataset (i.e. there are many more sites in the west relative to the east within the dataset), and the gyre boundary is located slightly further south in the west relative to the zonal mean; the maximum meridional gradient in mean annual SST is found at ~36 °N along the western margin of the basin (Boyer et al., 2013), in good agreement with our reconstruction.

We also note that if we use a totally different method to calculate the change in position of the gyre boundary, simply calculating the change in latitude in the steepest part of the meridional $\delta^{18}O_{calcite}$ gradient (within a 5° moving window), we arrive at a very similar estimate of a ~2.6° southward shift between the Holocene and LGM. This method is more prone to anomalous values at the latitudinal extremes, hence we opt for the method of calculating the latitudinal shift that minimises the Euclidian distance between timesteps within a defined latitudinal band described above; however, the agreement between the two methods is reassuring.

Planktic foraminiferal $\delta^{18}O_{calcite}$ compilation

We compiled all available planktic foraminiferal calcite $\delta^{18}O$ from cores across the North Pacific. All data were kept on the original age models, except in the case when data were only available on uncalibrated ^{14}C age models, in which case the ^{14}C data were recalibrated using INTCAL13 (Reimer et al., 2013) using an average of the modern reservoir age at each site and a regional glacial increase of +400 years with large uncertainties (±500 years). All $\delta^{18}O_{calcite}$ data along with the core, location, water depth, species, sediment depth, age, and original data reference are given in Table S1. We only include cores spanning the interval between 10.5 to 18.5 ka with an average resolution of >1 point per ka. We exclude core EW0408-26/66JC from the compilation (Praetorious and Mix, 2014); this core is located in close proximity to the terminus of a glacier and comparing the $\delta^{18}O_{calcite}$ data of this core to other cores within the subpolar gyre demonstrates planktic foraminiferal $\delta^{18}O_{calcite}$ data from this core primarily reflect local meltwater changes, rather that wider oceanographic conditions in the subpolar gyre (Figure S3). The compiled dataset will be available on Pangea.

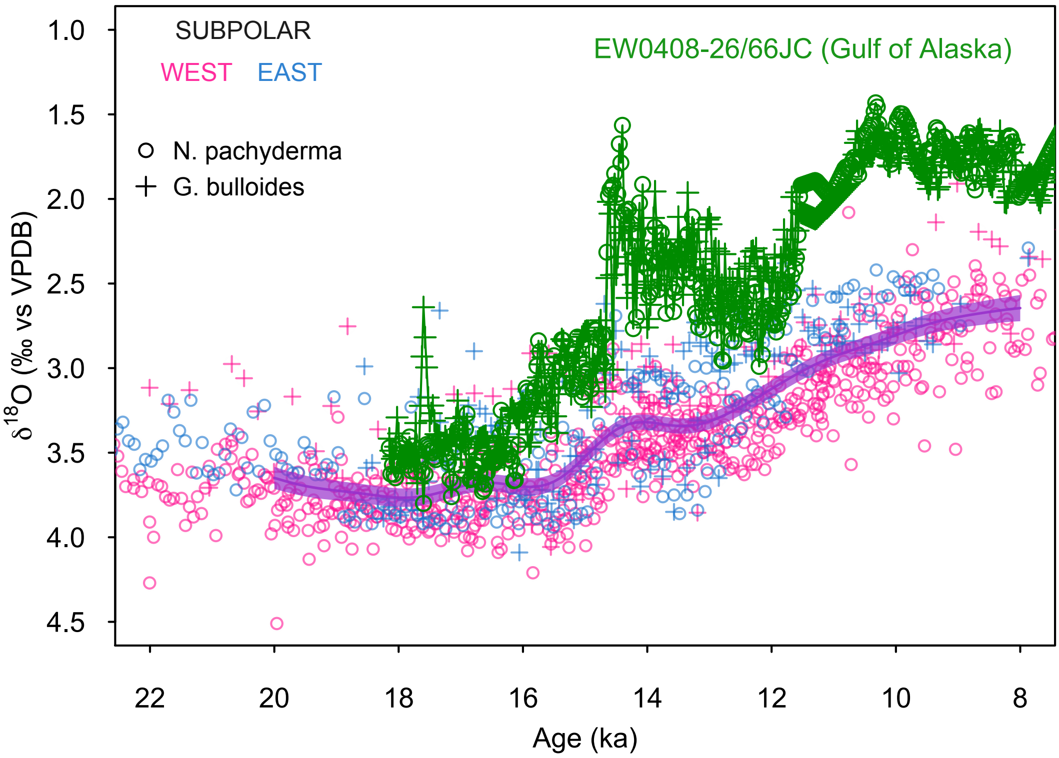

Figure S7 Foraminiferal $\delta^{18}O_{calcite}$ from the subpolar gyre over deglaciation. A GAM fit with to all the data (excluding core EW0408-26/66JC) is shown by the purple line, with standard error of the fit shaded. Data from core EW0408-26/66JC (Praetorius and Mix, 2014) is shown in green.

Seasonality of planktic foraminifera

Our approach assumes that any change in seasonal bias relating to the habitat preference of foraminifera are small relative to the change in temperature due to the movement of the gyre boundary. The validity of this approach is supported by sites where $\delta^{18}O_{calcite}$ has been measured on more than one species of foraminifera, such as core ODP Site 893 (Figure 1 and Figure 2). At this site, foraminiferal species with habitat temperature preferences that are known to be different (*G. bulloides* and *N. pachyderma*, e.g. Taylor *et al*., 2018) show very similar changes down core, with a Holocene-LGM change that is identical (within error); this suggests any changes relating to changes seasonal bias are likely to be insignificant in our reconstruction.

Sea surface temperature compilation

We compiled Mg/Ca and $U^{K'}_{37}$ sea surface temperature (SST) data from across the North Pacific (Mg/Ca: Reitdorf et al., 2013; Gebhardt et al., 2008; Rodriguez Sanz et al., 2013; Taylor et al., 2015; Sagawa et al., 2006; Sagawa et al., 2008; Pak et al., 2012; Kubota et al., 2010; Gray et al, 2018. $U^{K'}_{37}$: Minoshima et al., 2007; Seki, 2004; Harada et al., 2004; Harada, 2006; Harada et al., 2008; Inagaki et al., 2009; Herbert et al., 2001; Sawada et al., 1998; Yamamoto et al., 2004; Isono et al., 2009). All age models are as given in the original publication. All Mg/Ca and $U^{K'}_{37}$ data were recalibrated (see below) and the temperature change during the LGM is given as a difference to both proxy temperature in the Holocene, and to mean annual climatological temperature from the WOA13 (Boyer et al., 2013).

While the direct temperature sensitivity of Mg/Ca in planktic foraminifera is ~6% per °C (Gray et al., 2018b; Gray and Evans, 2019), due to the effect of temperature on pH through the disassociation constant of water (K_w), the 'apparent' Mg/Ca temperature sensitivity is higher (Gray et al., 2018b). Thus, we calculate the change in temperature from the change in Mg/Ca at each site using a temperature sensitivity of 8.8%, derived from laboratory cultures (Kisakürek et al., 2008), which encompasses both the direct temperature effect and the temperature-pH effect, with a Mg/Ca-pH sensitivity of ~ -8% per 0.1 pH unit (Lea et al., 1999; Russell et al., 2004; Evans et al., 2016; Gray et al., 2018b; Gray and Evans, 2019). Mg/Ca is also influenced by salinity, with a sensitivity of ~4% per PSU (Hönisch et al, 2013; Gray et al., 2018b; Gray and Evans, 2019). We make no attempt to account for the effects of salinity (due to sea level) or pH downcore (due to lower atmospheric CO_2). The combined effect of the whole-ocean increase in salinity (due to sea level), and the increase in surface ocean pH (due to lower atmospheric CO_2) means changes in temperature derived from changes in Mg/Ca are likely to be cold-biased by ~1.5 °C during the LGM (Gray and Evans, 2019). For $U^{K'}_{37}$, the change in temperature at each site was calculated using the calibration of Prahl et al., 1988; the temperature range in this study is too low to be substantially effected by the non-linearity of $U^{K'}_{37}$ (e.g. Tierney and Tingley, 2018).

General Circulation Models

We assess differences in North Pacific barotropic stream function, wind stress curl, zonal wind stress, and SST between LGM and pre-industrial conditions as represented by five coupled climate models (CCSM4, CNRM-CM5, MPI-ESM-P and MRI-CGCM3). All models are part of the Coupled Model Intercomparison Project phase 5 (CMIP5, Taylor et al., 2012). We only used models where both wind stress and barotropic stream function data are available. Orbital parameters, atmospheric greenhouse gas concentrations, coastlines and ice topography for the LGM simulations are standardized as part of the Paleoclimate Model Intercomparison Project phase 3 (PMIP3) (Braconnot *et al*. 2012, Taylor *et al*. 2012). Ensemble means are computed by first linearly interpolating to a common grid.

Using a single model (HadCM3) we look at runs where the model greenhouse gas, ice sheet albedo, ice sheet topography are changed individually ('Green Mountains, White Plains') as described in Roberts and Valdes (2017). The 'Green Mountains, White Plains' runs use the ICE5G ice sheet reconstruction (Peltier *et al*., 2004), whereas the deglacial 'snapshot' runs (below) use the ICE6G ice sheet reconstruction (Peltier *et al*., 2015).

We also explore changes through time over the deglaciation using a series of HadCM3 equilibrium-type simulations where all forcings and model boundary conditions are changed at 500-year intervals broadly adhering to the PMIP4 last deglaciation protocol (Ivanovic et al., 2016). These simulations use the ICE6GC ice sheet reconstruction and 'melt-uniform' scenario for ice sheet meltwater; i.e. freshwater from the melting ice sheets is NOT routed to the ocean via coastal outlets. Instead, water is conserved by forcing the global mean ocean salinity to be consistent with the change in global ice sheet volume with respect to present. Note, these deglacial simulations are not transient, but are equilibrium-type experiments that begin from the end of the 1750-year long simulations run by Singarayer et al. (2011). At each 500-year interval (21.0 ka, 20.5 ka, 20.0 ka…0.5 ka, 0.0 ka), all boundary conditions and forcings are updated according to the more recent literature (presented by Ivanovic et al., 2016) and held constant for the full 500-year duration of the run. The climate means and standard deviations used here are calculated from the last 50 years of each simulation (i.e. year 451-500, inclusive). More information on these runs can be found in the supplement to Morris et al. (2018), noting that we use the raw model output and not the downscaled and bias-corrected data used in the previous publication.

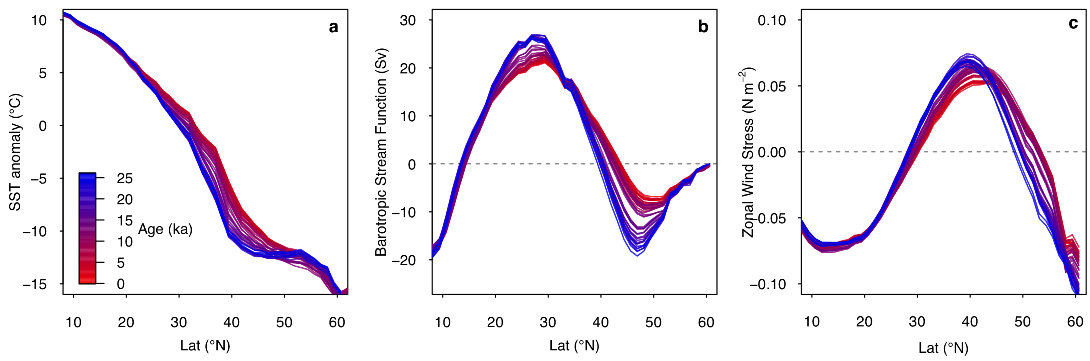

Figure S8 Deglacial evolution of zonal mean **(a)** SST anomaly (relative to global mean) **(b)** barotropic stream function **(c)** zonal wind stress in the HadCM3 simulations.

Eastern boundary test

To test if there is an influence of coastal upwelling on the data in the east (i.e. a signal of some other control on latitudinal temperature anomaly [and thus latitudinal $\delta^{18}O_{calcite}$ anomaly] besides change in gyre position) we compare the ensemble mean SST along the eastern boundary of the basin (taken as the first oceanic grid point west of land during the LGM) to the zonal mean, and zonal mean east of the dateline (Fig. S9). The models show no indication of a strong influence of coastal upwelling, which would manifest as an anomalous cooling relative to the zonal mean. This analysis suggests coastal upwelling is unlikely to be having a significant effect on our results, although the simulated coastal upwelling may be poorly represented due to the resolution of the models. A further argument against a strong influence of upwelling on the data in the East Pacific is that sites that are ~15° apart from each other latitudinally, such that they are in different upwelling regimes today and are likely to have undergone very different changes in upwelling since the LGM, display very similar patterns of change in $\delta^{18}O_{calcite}$ over deglaciation, with no differences in timing (Fig. 1).

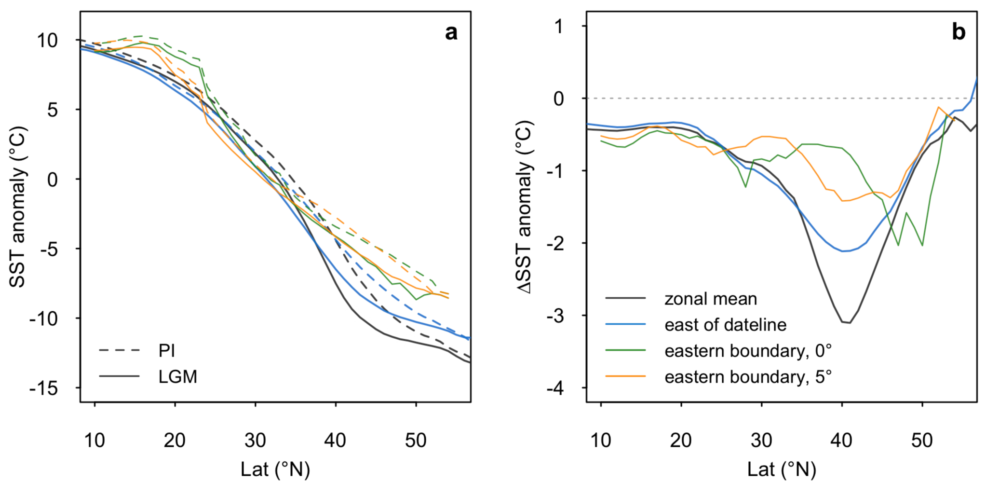

Figure S9 (a) LGM and PI SST anomaly (from global mean), and **(b)** LGM-PI SST anomaly in different longitudinal bins; zonal mean (grey), zonal mean east of the dateline (180°, blue), along the eastern boundary of the basin (green), and 5° seaward from the eastern boundary of the basin (orange). Note, the gyre boundary s located slightly further north along the eastern margin relative to the zonal mean and zonal mean east of the dateline.

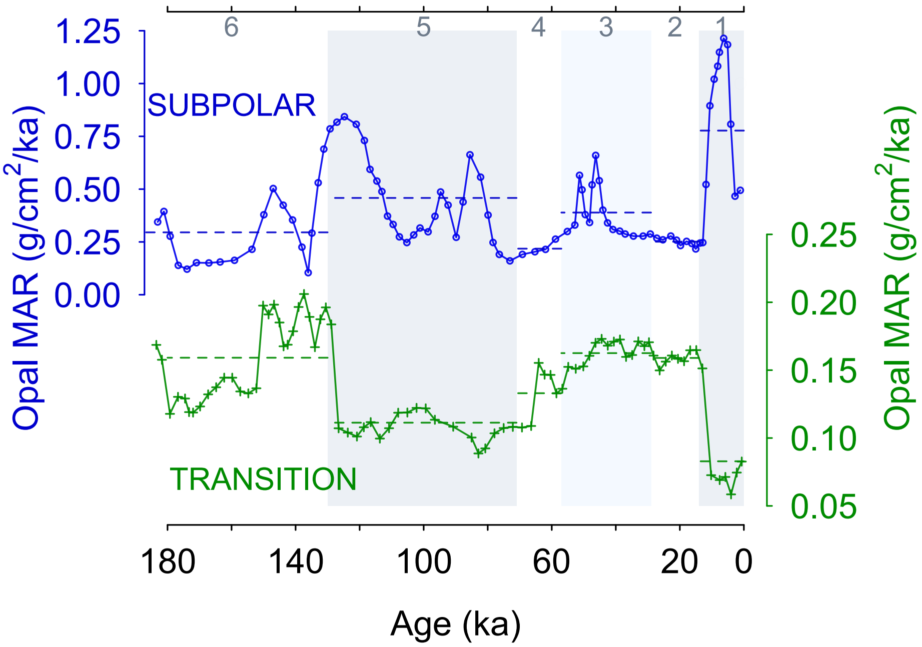

Figure S10 Opal Mass Accumulation Rate data from core KH99-03 in the SPG (Narita et al., 2002) and core NCG108 in the transition zone (Maeda et al., 2002). Dashed lines show mean value for each marine isotope stage (MIS). Grey shading shows MIS 1, 3 and 5. Transition zone and subpolar waters show an anti-phased relationship in Opal MAR over the last glacial cycle.

HS1 Freshwater test

The release of large amounts of freshwater into the eastern subpolar North Pacific has been suggested over deglaciation, at ~17.5 ka (Maier *et al* 2018). The release of freshwater into the eastern subpolar North Pacific is evident in an increase in the $\delta^{18}O_{calcite}$ difference between the mixed-layer dwelling species *G. bulloides* and the slightly deeper-dwelling species *N. pachyderma* in core MD02-2489 (54.39°N, -148.92°E) at this time; during this interval *G. bulloides* becomes ~0.6 ‰ more depleted than *N. pachyderma*. To test if this release of freshwater may be influencing our gyre boundary reconstruction we re-run the gyre-boundary analysis, however removing the *G. bulloides* data from core MD02-2489; the results are identical to the gyre boundary reconstruction including the *G. bulloides* data demonstrating that the effect of freshwater release has very little effect on our gyre boundary reconstruction. This is because the change in $\delta^{18}O_{calcite}$ from the freshwater release (~0.6 ‰, equivalent to ~2

PSU freshening) is very small compared to the large change in $\delta^{18}O_{calcite}$ resulting from the temperature difference between the gyres (6 ‰). Localised freshwater inputs, while having a large effect locally, do very little to change the pattern of $\delta^{18}O_{calcite}$ at the basin scale.

Table S1 Compiled planktic foraminiferal $\delta^{18}O_{calcite}$ records. The compiled will be made available on Pangea.

Core	Lat (°N)	Lon (°E)	Species	Reference
MD02-2489	54.39	-148.921	N. pachyderma	Gebhardt et al 2008
MD02-2489	54.39	-148.921	G. bulloides	Gebhardt et al 2008
PAR87A-10	54.363	-148.4667	G. bulloides	Zahn et al 1991
PAR87A-10	54.363	-148.4667	N. pachyderma	Zahn et al 1991
PAR87A-02	54.29	-149.605	G. bulloides	Zahn et al 1991
PAR87A-02	54.29	-149.605	N. pachyderma	Zahn et al 1991
MD02-2496	48.967	-127.033	N. pachyderma	Taylor et al 2015
MD02-2496	48.967	-127.033	G. bulloides	Taylor et al 2015
ODP1017	34.32	-121.6	G. bulloides	Pak et al 2012
ODP893	34.2875	-120.03667	N. pachyderma	Hendy et al 2002
ODP893	34.2875	-120.03667	G. bulloides	Hendy et al 2002
MD02-2503	34.28	-120.04	G. bulloides	Hill et al 2006
AHF-28181	33.011667	-119.06	G. bulloides	Mortyn et al 1996
MD05-2505	25	-112	G. ruber	Rodríguez-Sanz et al 2013
SO201-2-101	58.883	170.683	N. pachyderma	Reitdorf et al 2013
SO201-2-85	57.505	170.413167	N. pachyderma	Reitdorf et al 2013
SO201-2-77	56.33	170.69883	N. pachyderma	Reitdorf et al 2013
SO201-2-12	53.992667	162.375833	N. pachyderma	Reitdorf et al 2013
MD01-2416	51.268	167.725	N. pachyderma	Gebhardt et al 2008
MD01-2416	51.268	167.725	G. bulloides	Gebhardt et al 2008
VINO-GGC37	50.28	167.7	N. pachyderma	Keigwin 1998
LV29-114-3	49.375667	152.877933	N. pachyderma	Reitdorf et al 2013
KT90-9_21	42.45	144.3167	G. bulloides	Oba and Murayama 2004
GH02-1030	42	144	G. bulloides	Sagawa and Ikehara 2008
CH84-14	41.44	142.33	G. bulloides	Labeyrie 1996
CH84-04	36.46	142.13	G. bulloides	Labeyrie 1996
MD01-2420	36.067	141.817	G. bulloides	Sagawa et al 2006
MD01-2421	36.01667	141.7833	G. bulloides	Oba and Murayama 2004
KY07_04_01	31.6391667	128.944	G. ruber	Kubota et al 2010
A7	27.82	126.98	G. ruber	Sun et al 2005
ODP184-1145	19.58	117.63	G. ruber	Oppo and Sun 2005

Table S2 Reconstructed change in gyre boundary latitude. Uncertainty is 1σ.

age	DLat	DLat_error	DLat_west	DLat_west_error	Dlat_east	DLat_east_error
10.5	0.0	1.0	0.0	1.3	0	1.0
11.0	-0.6	0.9	-0.7	1.2	-0.3	0.9
11.5	-1.0	0.9	-1.1	1.1	-0.5	1.0
12.0	-1.4	0.9	-1.7	1.1	-0.5	1.1
12.5	-1.5	0.9	-1.9	1.0	-0.8	1.1
13.0	-1.6	0.9	-1.8	1.0	-0.2	1.3
13.5	-1.6	0.9	-1.8	1.0	0	1.3
14.0	-1.5	0.9	-1.7	1.0	0.2	1.3
14.5	-1.5	0.9	-1.7	1.0	-0.5	1.2
15.0	-1.9	0.8	-1.9	1.0	-2.4	1.0
15.5	-2.3	0.8	-2.1	1.0	-3.9	1.0
16.0	-2.6	0.8	-2.1	1.0	-5	0.9
16.5	-2.8	0.9	-2.0	1.0	-5.9	0.9
17.0	-3.1	0.9	-2.0	1.0	-6.3	0.9
17.5	-3.2	0.9	-2.0	1.0	-6.3	1.0
18.0	-3.1	0.9	-2.0	1.0	-6.4	1.1
18.5	-3.1	0.9	NA	NA	-6	1.1

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