Supplement of 'Northern Hemisphere ice sheets and ocean interactions during the last glacial period in a coupled ice sheet-climate model'

S1. Model parameters

Table S1a : Main parameters of the ECBILT module (atmosphere component).

Parameter	Definition	This study *(default)*
ampwir	Scaling coefficient for the longwave radiation scheme, excluding the equator area	1.0
ampeqir	Same, for the equator area between 15^oS and 15^oN	1.8
expir	Exponent for the longwave radiation scheme	0.4
relhmax	maximum relative humidity before saturation	0.83
hmoisr	reduction factor of mountain heights in order to tune the amount of water that is allowed to pass a topographic barrier	0.5
umoisr	reduction factor of 800 hPa winds used in advecting the moisture	0.6
rrdef1	Rossby radius of deformation layer 1 (200 - 500 hPa)	0.13
rrdef2	Rossby radius of deformation layer 2 (500 - 800 hPa)	0.07
cwdrag	drag coefficient to compute wind stress	$2.1 * 10^{-3}$
cdrag	same to compute sensible and latent heat fluxes	$1.4 * 10^{-3}$
uv10rfx	reduction of the wind speed between 800 hPa and 10 m	0.8
dragan	rotation of the wind vector in the boundary layer	15.0
alphd	albedo of snow	0.72
alphdi	albedo of bare ice	0.62
alphs	albedo of melting snow	0.53
albice	albedo of melting ice (general)	0.44
albin	albedo of melting ice (arctic)	0.44
cgren	increase in snow/ice albedo under cloudy conditions	0.04
corAN	reduction in precipitation over the North Atlantic	-0.085
corPN	reduction in precipitation over the North Pacific	1.0
corAS	reduction in precipitation over the South Atlantic	-0.085
corAC	reduction in precipitation over the Arctic	-0.25
mag_alpha	coefficient for the climate sensitivity	2.0 *(1.0)*
evfac	maximum evaporation factor over land	1.0

Table S1b : Main parameters of the CLIO module (ocean component).

Parameter	Definition	This study *(default)*
bering	Scaling factor for computing the Bering Strait throughflow	0.0 *(0.3)*
ai	Coefficient of isopycnal diffusion	300
aitd	Gent-McVilliams thickness diffusion coefficient	300
ahs	Horizontal diffusivity for scalars $[m^2 s^{-1}]$	100
ahu	Horizontal viscosity $[m^2 s^{-1}]$	10^5

The tables of parameter values allow comparison with previous work [1,2,3].

Table S1c : Main parameters of GRISLI (ice sheet model).

Parameter	Definition	This study
E_f	Flow enhancement factor for vertical shearing with a Glen viscosity	1.826
c_f	Basal drag parameter [yr.m^{-1}]	$3 * 10^{-4}$
λ	Longwave radiation coefficient for melt computation [W.m^{-2}.K^{-1}]	10
c_{rad}	Radiative parameter for melt computation [W.m^{-2}]	-40

These can be compared with parameters in [4,5].

S2. Information about the freshwater coupling

The continental ice melt fluxes are computed in GRISLI each year. These are distributed to the oceanic model over the following year. For the grounded ice sheet, surface melt is routed to the nearest oceanic grid cell following surface topography while the oceanic basal melt and the calving flux are transferred at the ocean surface where they occur. We take into account the local latent heat flux associated with the calving flux that corresponds to the melting of icebergs by the ocean, and the ocean temperatures are adjusted.

In the accelerated experiments, we do not maintain water conservation as we cannot conserve both total ice mass change and the rate of mass change. Indeed, in the accelerated experiments, for example with an acceleration factor of 10, the total mass change results from the melting of the ice sheet over 10 consecutive years. If we conserve this total mass change, the ocean model (CLIO) would receive a freshwater flux that is 10 times larger than the annual mean flux. While this approach is possible, it could have undesirable effects on oceanic circulation, such as an AMOC slowdown due to the large input of freshwater. Conversely, if we provide CLIO with the mean annual freshwater flux, we only account for one-tenth of the total mass change. Therefore, to obtain our initial conditions from the long spin up simulations, we conserve the total ice mass change and not the rate of mass change.

Below, INIT corresponds to the last 1500 years of the long spin-up simulation (no freshwater flux from the ice sheet to the ocean model) with asynchronous coupling described in section 2.2.1. CTRL is the continuation of the INIT simulation yet climate and ice sheets are annually coupled. Figure S2 shows both control simulations with and without freshwater flux as well as the perturbation experiment with multiplicative factor 100 (X100). It is clear that the inclusion of freshwater flux from the ice sheets to the ocean produces a global mean salinity decay when ice sheets volume is decreasing. In the CTRL experiments the discrepancies between with or without freshwater fluxes are small, with a mean difference of ± 0.0003 psu.

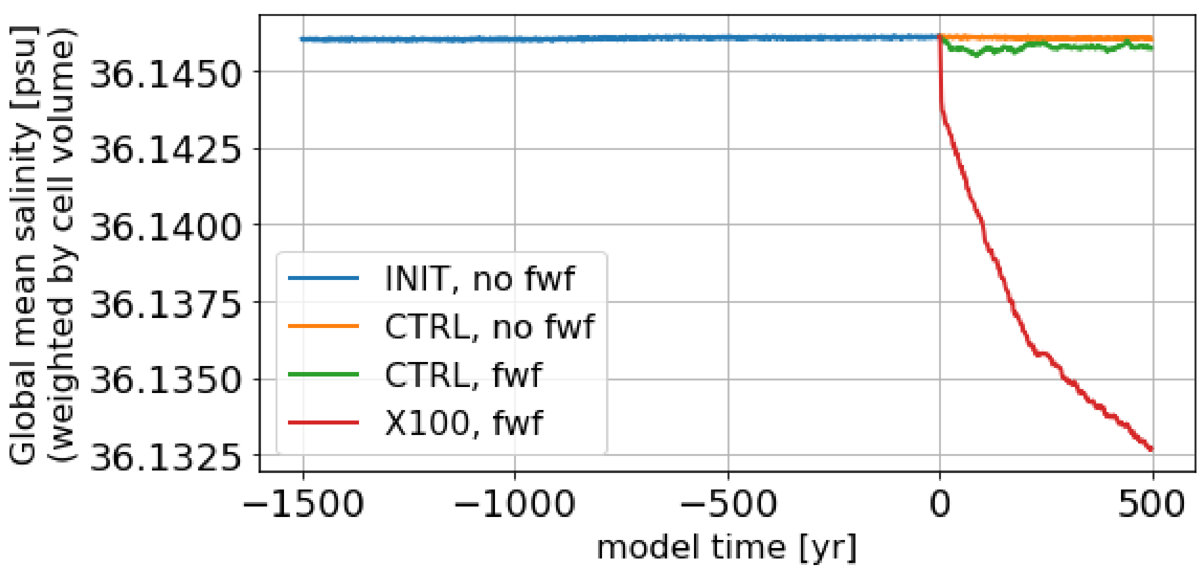

Figure S2. Freshwater contribution to total ocean mean salinity.
Global mean salinity in different experiments with and without freshwater flux from the ice sheet model to the ocean model.

S3. Accumulation anomalies during the perturbation

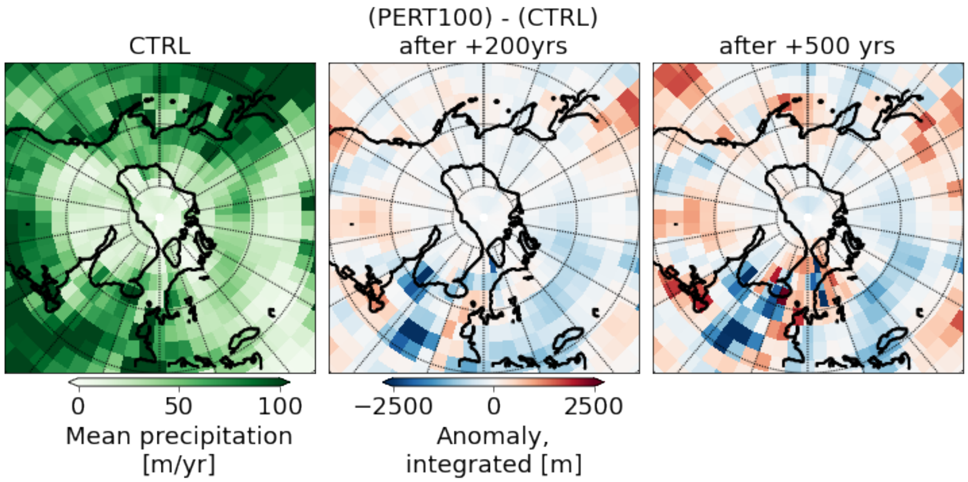

Figure S3. Precipitations response to the perturbation.
(left) Mean over the control simulation [m/yr] and integrated anomaly [m] (middle) after 200 years and (right) after 500 years, between perturbation experiment with factor 100 and the control simulation.

S4. Complements on Atlantic meridional circulation

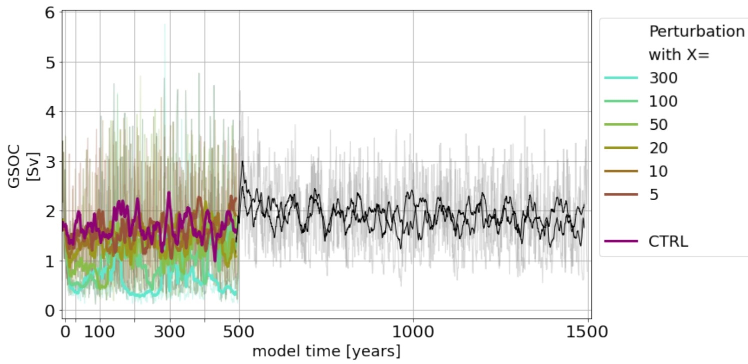

Figure S4. Times series of Greenland Sea overturning circulation [Sv]. Thin dark lines corresponds to the extension of the simulations with perturbation factors X=20 and 100, when the perturbation is halted.

Greenland Sea overturning circulation (GSOC) is computed as the maximum of the meridional stream function between 68 and 75^{o}N (excluding the Baffin Bay) below 500 meters depth (it encompasses the north of the Iceland Sea and the Norwegian Sea).

S5. Hydrography evolution of the Nordic Seas

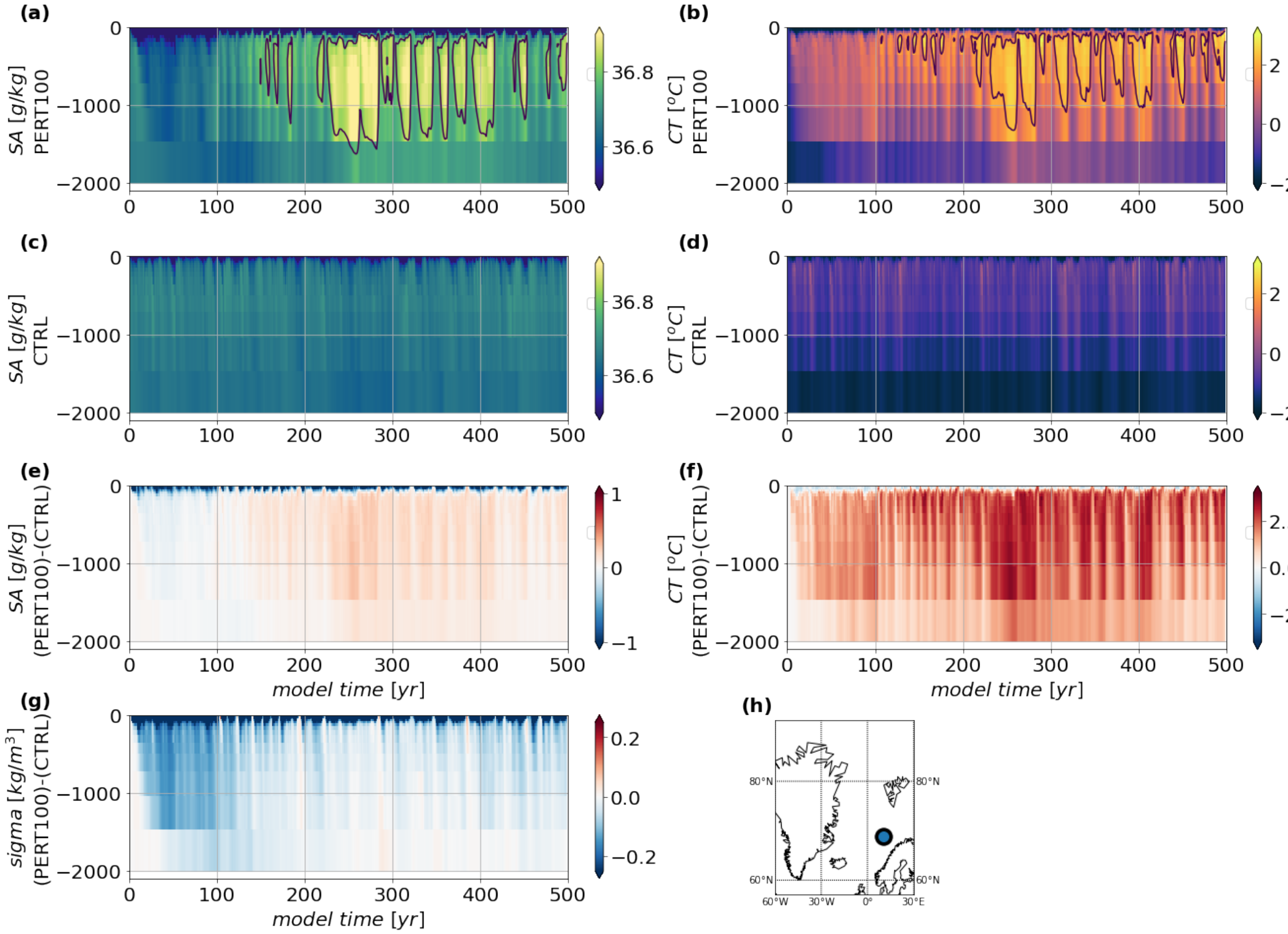

Figure S5. Hovmöller diagrams for one profile, at 71.5^o and 10^{o}E.
Absolute salinity [g/kg] (a) in the perturbation experiment with factor 100, (b) in the control experiment and (c) associated difference. (d)-(e)-(f) is the same for conservative temperature [^oC]. (g) is the density [kg/m^3] anomaly between the perturbation and the control. (h) Location of the profile. Black lines in (a) and (b) are 36.8 g/kg and 2 ^{o}C iso-contours.

S6. Convection evolution

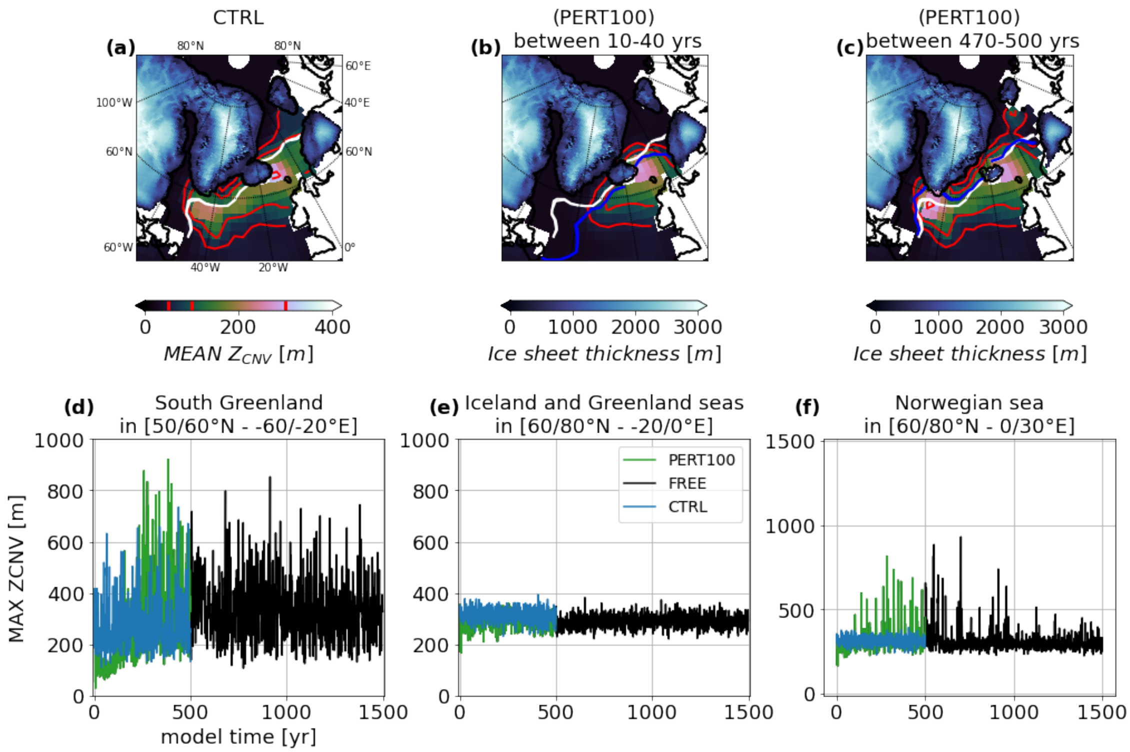

Figure S6.
Mean convection depth [m] (a) over the control simulation and in the perturbation experiment with factor 100 (b) averaged over 10-40 years and (c) over 400-450 years. White line (resp. dark blue) is the 30% sea-ice extent in the CTRL (resp. PERT100). Time series of annual maximum convection depth in three boxes : (d) south Greenland, (e) Iceland and Greenland seas and (f) Norwegian sea.

Here the convection depth, zcnv, is defined as the depth for which the Brunt-Väisälä frequency sign changes and becomes negative (unstratified environment) starting from the bottom.

S7. Ice sheet history in perturbation experiment with constant basal melt rates in the Baffin Bay

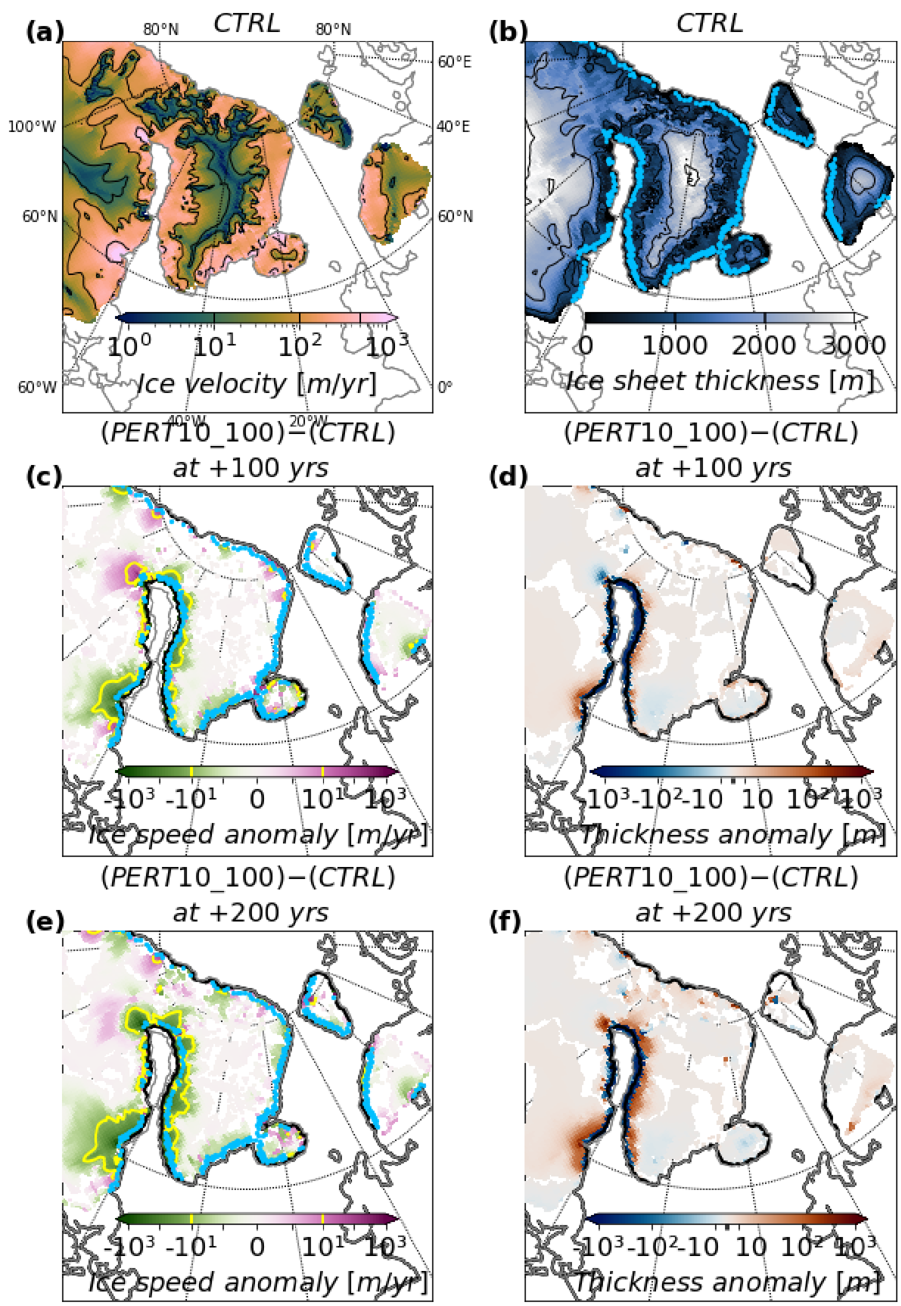

Figure S7. Ice sheet (a) velocity [m/yr] and (b) thickness [m] averaged over the control simulation. Sky blue contour indicates the position of the grounding line. PERT10_100 - CTRL anomalies of (c) thickness, (d) ice velocities after 100 years. (e) and (f) after 200 years. Only significant values to one standard deviation of the control are shown for (c)-(f).

PERT10_100 is the simulation with imposed constant oceanic basal melt rates of 10 m/yr in the Baffin Bay/Labrador Sea sector for 100 years.

S8. Pre-industrial bathymetry : Ice sheet initial condtions

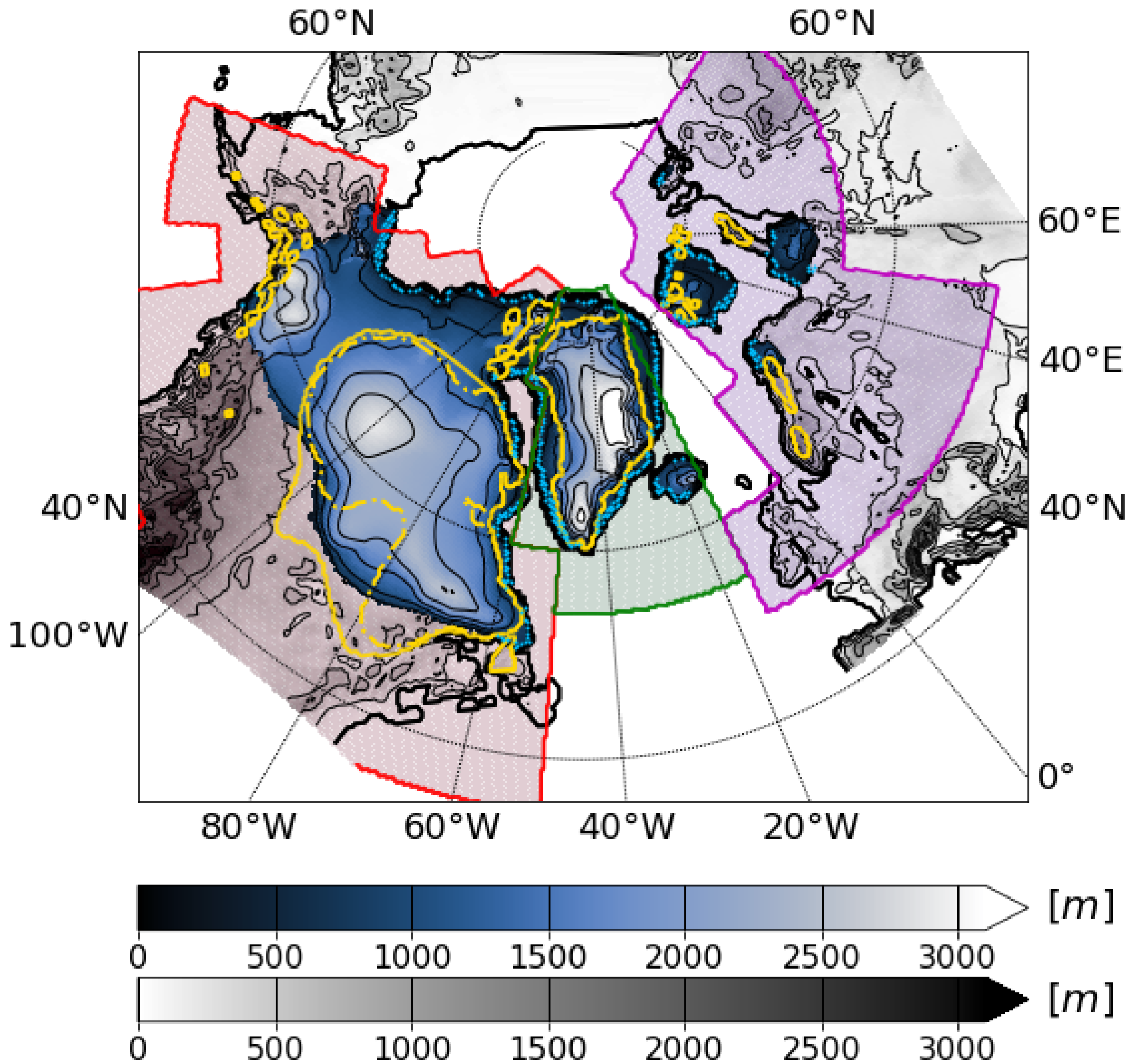

Figure S8. Equivalent of Figure 1 in the main text but with a Pre-industrial bathymetry.

S9. Pre-industrial bathymetry : Ice sheet history

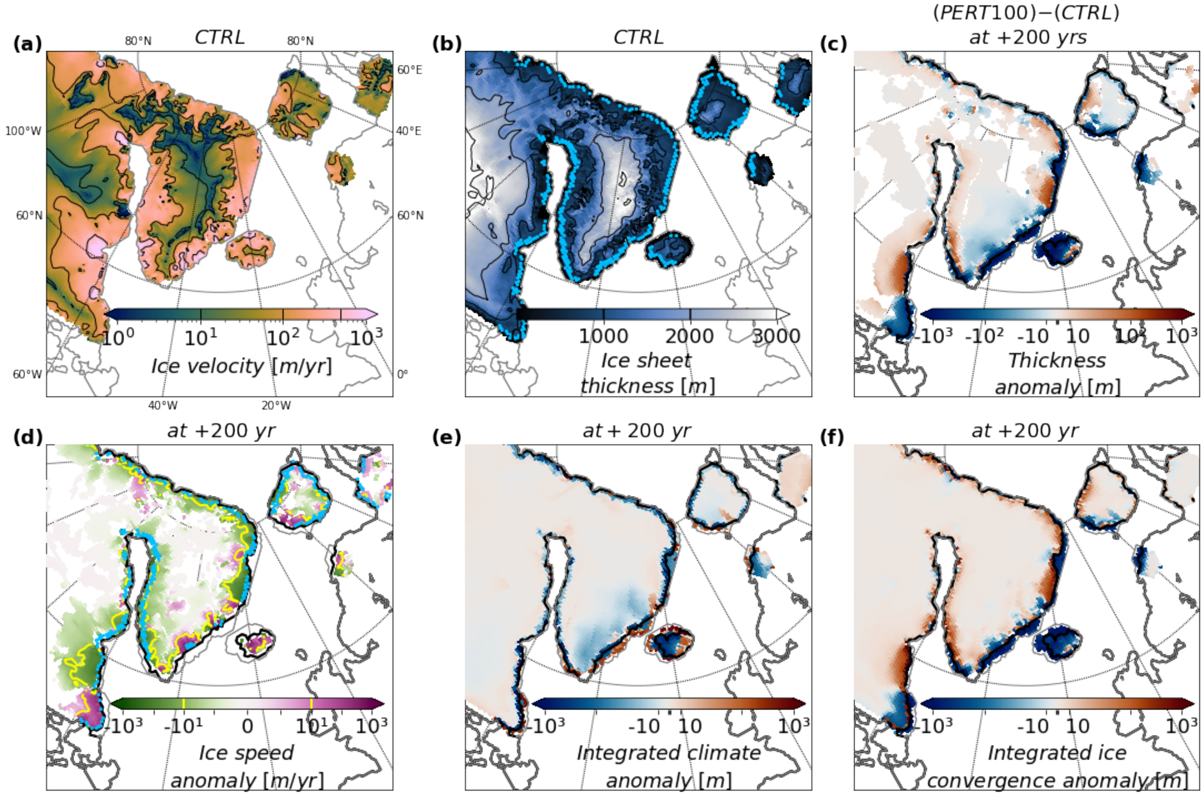

Figure S9. Equivalent of Figure 3 in the main text but with a Pre-Industrial bathymetry.

S10. Pre-industrial bathymetry : Surface hydrography

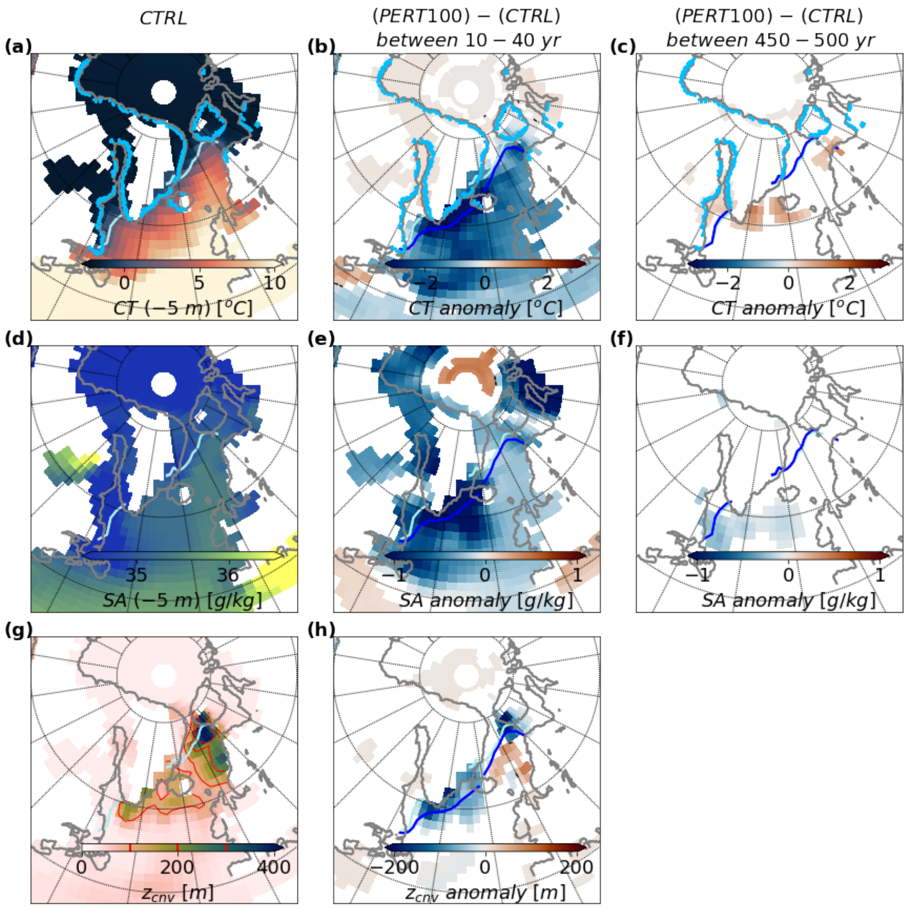

Figure S10. Equivalent of Figure 6 in the main text but with a Pre-Industrial bathymetry.

S11. Pre-industrial bathymetry : Sub-surface hydrography

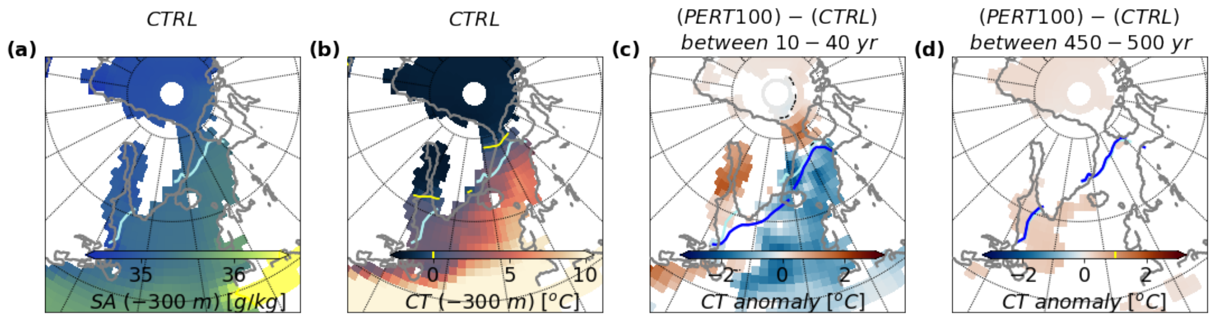

Figure S11. Equivalent of Figure 7 in the main text but with a Pre-Industrial bathymetry.

S12. Ice volume evolution

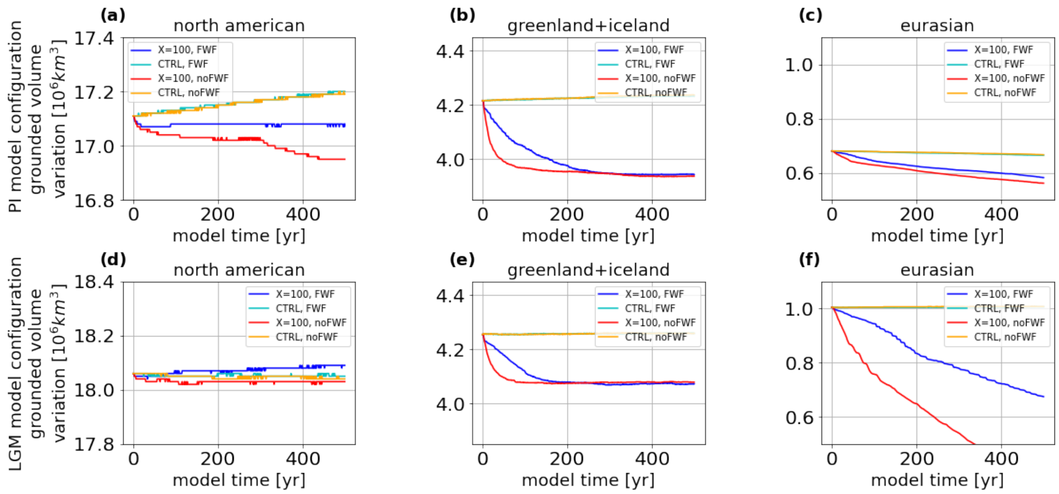

Figure S12. Continental ice volume response to oceanic perturbation (i.e. amplified OBM by a coefficient 100). Time series of grounded ice sheet volume [10^6 km^3] for the (a) North American, (b) Greenland and Iceland and (c) Eurasian ice sheets in experiments with X=100 with the PI model configuration. (e)-(f)-(g) Same for the LGM model configuration. Note that the same y-axis spacing is applied on the plots (0.6 10^6 km^3).

S13. Ocean temperatures evolution

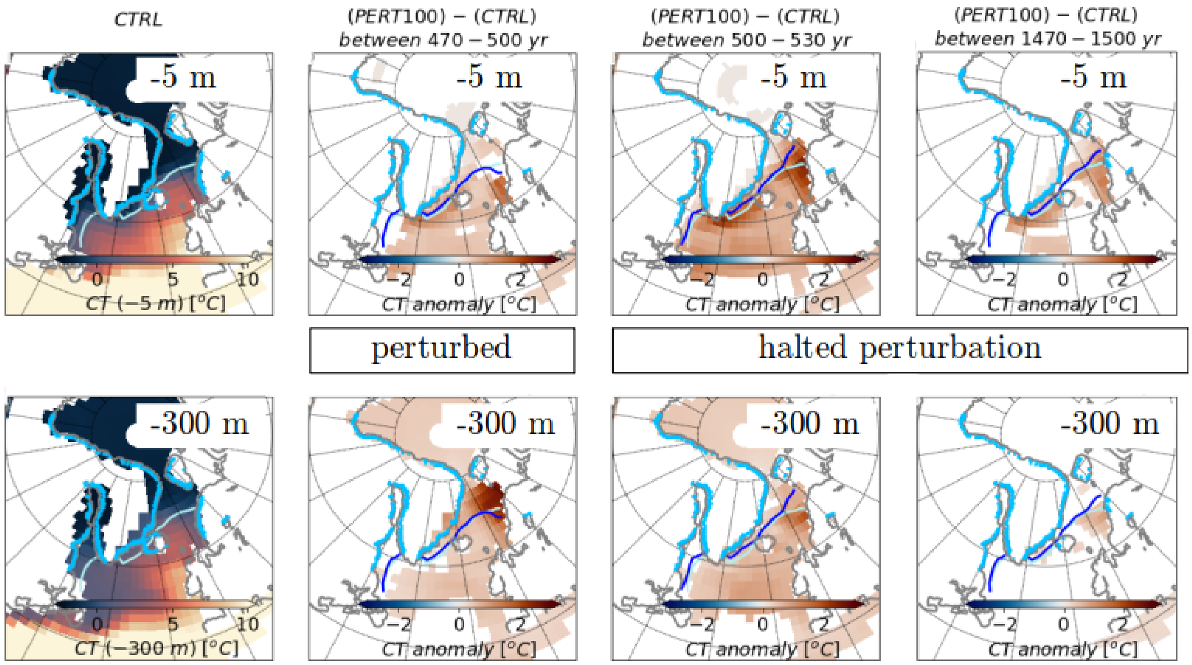

Figure S13. Conservative temperatures [^{o}C] at (top) 5 m depth horizon and (bottom) 300 m depth horizon in (from left to right) the control and differences between PERT100 and the control between 470-500 years, 500-530 years and 1470-1500 years. Dark blue is the sea-ice contour and turquoise the position of the grounding line.

Références

[1] Goosse, Hugues, et al. ”Description of the Earth system model of intermediate complexity LOVECLIM version 1.2.” Geoscientific Model Development 3.2 (2010) : 603-633.

[2] Shi, Yuhan, et al. ”How parameter specification of an Earth system model of intermediate complexity influences its climate simulations.” Progress in Earth and Planetary Science 6 (2019) : 1-18.

[3] Bahadory, Taimaz, and Lev Tarasov. ”LCice 1.0–a generalized Ice Sheet System Model coupler for LOVECLIM version 1.3 : description, sensitivities, and validation with the Glacial Systems Model (GSM version D2017. aug17).” Geoscientific Model Development 11.9 (2018) : 3883-3902.

[4] Quiquet, Aurélien, et al. ”The GRISLI ice sheet model (version 2.0) : calibration and validation for multi-millennial changes of the Antarctic ice sheet.” Geoscientific Model Development 11.12 (2018) : 5003-5025.

[5] Quiquet, Aurélien, et al. ”Climate and ice sheet evolutions from the last glacial maximum to the pre-industrial period with an ice-sheet–climate coupled model.” Climate of the Past 17.5 (2021) : 2179-2199.