We thank the editor L. Menviel for the time she spent processing our manuscript. Below is the response to her comments.

In addition, all reviewers raised the issue of the processes leading to the significant loss of carbon at 125 ka, and I feel these processes need to be appropriately highlighted in your revised version.

Response: We have added few statement accordingly.

Revision in abstract: "The biological pump is mainly driven by changes in interior ocean ventilation timescales, but the processes controlling the changes in ocean DIC disequilibrium remain difficult to assess and seem more regionally affected. While the Atlantic bottom water disequilibrium is affected by the sea-ice induced SSW/NSW organization, the upper layer changes remain unexplained. Due to its large size, the Pacific accounts for the largest DIC-loss, approximately 57% of the global decrease. This is largely associated with better ventilation of the interior Pacific water mass."

Enhanced Southern Ocean ventilation (is AABW stronger in your simulation?) as is seen in Fig.3 and in Fig.2 of AC3 would lead to a carbon loss from the deep ocean (and particularly the Pacific) (see for example Menviel et al. 2014 (Paleo), or Menviel et al., 2015 (gbc)).

Response: Our simulations show clearly that under warmer climate (125ka) the interior ocean is better ventilated than under colder climate state (115ka). The mechanisms leading to this changes in ventilation rate seems however complex and our model outputs does not allow us to identify it as purely coming from the changes in AABW, but rather in changes of water pathways. Nevertheless, reduction in ventilation we simulate are consistent with previous studies (Menviel et al. 2014, 2015).

Revision in Sect. 5: "We find that the global ocean carbon budget decreases during the warm (125ka) period by 314.1 PgC and are related mainly to better ventilation in the interior ocean. The Pacific Ocean has the largest reduction and accounts for 57% of the global DIC loss. The response of the Pacific ventilation in a warmer climate shown in this study is consistent with previous studies (Menviel et al., 2014, 2015)."

This loss is probably enhanced by the constant atmospheric CO2 forcing and the higher SST.

Response: It is true. While higher atmospheric CO_2 concentration lead to an oceanic uptake, higher SSTs pushes the Ocean toward outgassing. Both of these processes are included in the computation of DIC^{sat}. However in our study, this component seems to be more sensitive to changes in preformed ALK as mentioned in Sect. 2.3. Therefore, higher preformed ALK lead to higher DIC and vice versa.

References:

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outgassing CO$_2$ during Heinrich events, Paleoceanography, 29, 58-70, 2014. http://doi.org/10.1002/2013PA002542

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Ocean carbon inventory under warmer climate – the case of the ~~LIG~~Last Interglacial

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Abstract. During the Last Interglacial period (LIG), the transition from 125ka to 115ka provides a case study for assessing the response of the carbon system to different levels of high-latitude warmth. Elucidating the mechanisms responsible for interglacial changes in the ocean carbon inventory provides constraints on natural carbon sources and sinks and their climate ~~sensitivy~~ sensitivity which are essential for assessing potential future changes. However, the mechanisms leading to modifications of the ocean's carbon budget during this period remain poorly documented and not well understood. Using a state-of-the-art Earth System model, we analyze the changes in oceanic carbon dynamics by comparing two quasi equilibrium states: the early, warm Eemian (125ka) versus the cooler, late Eemian (115ka). We find ~~a considerable weaker~~ considerably reduced ocean dissolved inorganic carbon (DIC; -314.1 Pg C) storage under the warm climate state in 125ka as compared to 115ka, mainly attributed to changes in the biological pump and ocean DIC disequilibrium components. The biological pump is mainly driven by changes in interior ocean ventilation timescales, but the processes controlling the changes in ocean DIC disequilibrium remain difficult to assess and seem more regionally affected. While the Atlantic bottom water disequilibrium is affected by the sea-ice induced SSW/NSW organization, the upper layer changes remain unexplained. Due to its large size, the Pacific accounts for the largest DIC-loss, approximately 57% of the global decrease. This is largely associated with better ventilation of the interior Pacific water mass. However, the largest simulated DIC differences per unit-volume are found in the southern sourced waters of the Atlantic. Our study shows that the deep water geometry and ventilation in the South Atlantic is altered between the two climate states where warmer climatic conditions cause southern sourced waters to retreat southward and northern sourced waters to ~~extend~~ extent further south. This process is mainly responsible for the simulated DIC reduction by restricting the ~~extend~~ extent of DIC rich southern sourced water, thereby reducing the storage of biological remineralized carbon at depth.

1 Introduction

The Last interglacial (LIG, or Eemian) is composed of a warm onset around 125ka before present (BP) characterized by warmer temperature in the high latitudes relative to the present and a progressive cooling toward 115ka when the last glaciation was initiated (Otto-Bliesner et al., 2006; Masson-Delmotte et al., 2010). Evidence from land, ice, and ocean records identify the former as the period with the most intense global warming during the last 200,000 years (Turney and Jones, 2010; Dorthedahl-

Jensen et al., 2013; Capron et al., 2014) mainly due by changes in the orbital configurations. If ~~the~~ anthropogenic greenhouse gas emissions continue unabated, a climatically anomalously warm state is expected to occur in the near future with a warming that may be equivalent to the high-latitude reconstructed temperature for the LIG (Otto-Bliesner et al., 2013) by the end of this century. ~~For this, the~~ The changes in the ~~the~~ warm Eemian period may ~~be considered as~~ therefore be considered an analog for a future warmer climate.

~~A few studies have examined~~ Few model based studies examine the carbon cycle dynamics ~~from~~ for the LIG period with a particular focus on ~~(1)~~ the ability of models to simulate the transient changes in atmospheric CO_2 concentration, which ~~remained~~ remains relatively stable around 270-280 ppm without displaying any trends ~~and (2)~~ (Lourantou et al., 2010; Schneider et al., 201? Most of these studies provide a better understanding of the land carbon budget ~~(Lourantou et al., 2010; Schneider et al., 2013; Brovkin et al.~~ ~~Schurgers et al. (2006) used a General Circulation Model (GCM) coupled with a dynamic global vegetation model (DGVM) and a marine biogeochemistry model (HAMOCC3) to analyze the global carbon dynamics. Their simulated trend in atmospheric CO_2 concentration diverges from that recorded in the ice core data and shows a constant increase for the 128-113ka period. This was mainly attributed to the simulated decrease in the terrestrial carbon storage of 350 PgC. Brovkin et al. (2016) used three different Earth system Model of Intermediate Complexities (EMIC; Bern3D-LPJ, CLIMBA and GENIE). The computationally efficient EMIC models explicitly simulate interactions between all Earth system components but in a more parametrized form, allowing for long-term transient simulations. However, they have limitations in assessing climate change processes at regional scale. Thereby Brovkin et al. (2016) analyzed and compared the carbon cycle dynamics during the Holocene and the Eemian by applying the same set of forcings to these two periods. They could qualitatively explain carbon dynamics during the Holocene but as with Schurgers et al. (2006) , their simulated atmospheric CO_2 diverges after 121ka from that of the data. They suggested that the forcings~~ (particularly highlighting the importance of temperature changes on the land vegetation and slow processes of CO_2 change such as peatland carbon dynamics and CaCO$_3$ shallow water accumulation ~~and natural terrestrial carbon changes) were rather unrealistic to apply for the Eemian period and the absence of permafrost module could lead to an inability of the model to properly respond to cooling. Kleinen et al. (2016) simulated~~ (Schurgers et al., 2006; Kleinen et al., 2016; Brovkin et al., 2016) . Although they are numerous studies that have analyzed the role of the ocean carbon cycle in regulating the atmospheric CO_2 ~~within the range of the ice core data as compiled by ? using the EMIC CLIMBER2-LPJ, which includes shallow water coral CaCO$_3$ sedimentation and peatland dynamics. In their experiment, the ocean acts as a source of CO_2 to the atmosphere, with outgassing rates that range from 0.35 PgC yr^{-1} in 126ka to 0.17 PgC yr^{-1} in 116ka. This outgassing is mainly attributed to the strong CaCO$_3$ coral formations during the first half of the period , induced by sea level rise, which counterbalances the weathering and peatland fluxes~~, especially for the interglacial-glacial transition period (Ridgwell, 2001; Sigman and Boyle, 2000; Menviel to the authors' knowledge, there is no study that investigate in details changes in marine carbon and nutrient cycling during the Eemian period of the LIG (125ka – 115ka).

~~While the above studies provide a better understanding of land carbon budgets, the mechanisms leading to changes of the ocean 's~~ With respect to changes in large-scale ocean circulation, reconstructions indicate that deep Atlantic circulation patterns and water mass geometries likely change over this interval, with a persistent mid-depth Atlantic ventilation of northern sourced waters (McManus et al., 2002; Mokeddem et al., 2014) , while southern sourced waters expanded at depth toward

115ka (Govin et al., 2009) . In addition to large-scale circulation changes, temperature-induced changes in carbon solubility pumps and biological production are expected to alter the ocean carbon budget, ~~and more generally marine carbon and nutrient cycling, during the Eemian period remain poorly documented and not well understood~~in particular in the interior ocean. Other changes such as sea-ice extent and ocean ventilation could also affect ocean carbon sequestration rate during the LIG. Elucidating the mechanisms responsible for changes in the ocean carbon distribution and inventory is of interest as it provides past constraints and context for evaluating the response of natural carbon sources and sinks to future climate change. This study aims to fill this knowledge gap by analyzing and comparing, in terms of ocean carbon dynamic, two opposite states of the LIG: the early and warm Eemian onset (125ka) versus the cooler and late Eemian (115ka). Using a state-of-the-art Earth System model, our study addresses the regional differences in the ocean carbon storage and the underlying mechanisms.

The paper is organized as follows: in Section 2, we describe the model, the experiment design, as well as the terms and metrics used to quantify the differences in carbon dynamics during the two periods. Section 3 presents the results of the model simulations, while discussions and comparison with previous studies are presented in Section 4. Finally, the study is summarized in Section 5.

2 Method

2.1 Model description

The present study uses output of an updated version of the Norwegian Earth System model (NorESM1-ME), which has been recently developed to efficiently perform multi-millenial and ensemble simulations (Bentsen et al., 2013; Luo et al., 2018). This model includes an isopycnal-coordinate ocean general circulation model based on the Miami Isopycnic Coordinate Ocean Model (MICOM, Bleck et al., 1992) and a biogeochemical ocean module adapted from the Hamburg Oceanic Carbon Cycle (HAMOCC5) model (Maier-Reimer, 1993; Maier-Reimer et al., 2005; Tjiputra et al., 2013). The inorganic seawater carbon chemistry in HAMOCC5 includes prognostic partial pressure of CO_2 (pCO_2) according to the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) protocols. The pCO_2 is computed as a function of temperature, salinity, dissolved inorganic carbon (DIC), total alkalinity (TALK) and pressure. This adapted version of HAMOCC5 does not include prognostic weathering fluxes, but employs a 12-layers sediment model following Heinze et al. (1999), which is particularly relevant for long-term transient simulations. The horizontal resolution of the land and atmospheric components is approximately $2°$, while the ocean and ice components have higher resolutions of approximately $1°$. In the vertical, the ocean model adopts 53 isopycnal layers.

The land component in NorESM (CLM4, Community Land Model version 4) is based on version 4 of the CLM family (Lawrence et al., 2012a). The land surface is sub-gridded into three sub-gridded entities: land units, columns and plant functional types (PFTs). These sub-gridded cells are used to represent large-scale patterns of the landscape, variability in the soil and snow state variables, and the exchanges between land surface and atmosphere, respectively. Each of the sub-grid entities has its own prognostic variables, is independent and experiences the same atmospheric forcing. Each cell is averaged and weighted with its fractional area.

The marine ecosystem is based on a Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model that includes dissolved organic carbon (DOC). The inorganic nutrients consist of three macronutrients (phosphate, nitrate and silicate) and one micronutrient (dissolved iron). A constant Redfield ratio is adopted in the model as $P : C : N : \triangle O_2 = 1 : 122 : 16 : -172$. The phytoplankton growth rate is expressed as function of temperature, light (Smith, 1936; Eppley, 1972), phosphate, nitrate and dissolved iron availability, and its loss is regulated by an exudation and mortality rate, in addition to zooplankton grazing. The penetration of light decreases with depth following an exponential function, which responds to a gradual extinction factor formulated as a function of water depth and chlorophyll concentration (Maier-Reimer et al., 2005). The model ~~prescribed~~ prescribes a global constant vertical sinking speed of particles produced in the euphotic zone (~~>~~above 100 m depth). The particulate organic carbon (POC), which comprises dead phytoplankton and zooplankton, sinks through the water column with a speed of 5 m day^{-1} and is remineralized at a constant rate of 0.02 day^{-1} when oxygen is available. Other particles such as opal shells and particulate inorganic carbon (PIC) sink at a speed of 60 and 30 m day^{-1}, respectively. Particulates that reach the sea floor without being remineralized interact chemically with the sediment pore water via bioturbation and vertical ~~advection~~mixing and advection within the sediment layers. In the model, the air-sea gas exchange of CO_2 and O_2 only occurs between the ocean surface and the atmosphere in ice-free regions and is computed according to the following three components (Wanninkhof, 1992): the gas solubility in seawater, which is computed as a function of surface salinity and temperature according to Weiss (1970, 1974); the gas transfer velocity, which is proportional to the square of the surface wind speed and is computed as a function of the Schmidt number; and finally the air-sea gradient of gas partial pressures. To better elucidate various biogeochemical processes on the carbon cycle, the model is updated to also include preformed O_2, TALK and PO_4 tracers in the biogeochemical module. At surface, these preformed tracers are set to their non-preformed value and are advected passively by the ocean circulation in the interior without any other sources and sinks. Finally, in order to provide information of the water mass ages since its last contact with the atmopshere, an idealized age tracer is implemented and simulated in the NorESM model. Hence, the age tracer is set to zero for all water masses at the ocean surface and subsequently transported and mixed passively with circulation in the ocean interior and integrated with the model time step. This tracer is also used to estimate the the ventilation rate of different interior water masses.

2.2 Experiment setup

Two equilibrium experiments are performed over the Eemian, one near the onset (warmer than today; 125ka) and one at the end (colder; 115ka) of the Last Interglacial. Both experimental configurations follow the standard protocols of the third phase of the Paleoclimate Modelling Intercomparison Project (PMIP3; $URL = https : //pmip3.lsce.ipsl.fr/$), with a fixed vegetation coverage from the pre-industrial boundary conditions. The only differences with the pre-industrial configurations are the orbital parameters and the greenhouse gases concentrations (CO_2, CH_4, N_2O). For the experiment at 125ka (115ka), the atmospheric CO_2, CH_4 and N_2O levels are prescribed to be 276 ppmv (273 ppmv), 640 ppb (472 ppb) and 263 ppb (251 ppb), respectively. The two experiments are branched off from 1000 years of spin up with a pre-industrial set up and forced with their respective interglacial boundary conditions for 4000 simulation years.

In the last 50 years of Eemian forcing simulations the ocean is close to equilibrium. Only small drifts remain, mainly in the Pacific basin where the equilibrium is still not fully established. Therefore, the global ocean DIC and TALK slightly decrease in 125ka (115ka) experiment by approximately -0.15 ~~Pg C~~ PgC yr^{-1} (-0.06 ~~Pg C~~ PgC yr^{-1}) and -0.01 Pmol yr^{-1} (-0.01 Pmol yr^{-1}), respectively. However, these drifts are small compared to the absolute ocean budget in DIC (37391 and 37705 ~~Pg C~~ PgC) and TALK (3291 and 3303 Pmol) for the experiment 125ka and 115ka, respectively. The differences in pCO$_2$ and TALK budget are small between the two experiment. Such changes would affect the DIC budget of about 32 PgC. The CO$_2$ flux is relatively constant and depicts the ocean as a weak source to the atmosphere with an outgassing of 0.12 ± 0.06 in 115ka and 0.15 ± 0.06 Pg C.yr^{-1} in 125ka. In addition, the difference in sedimentation rates between the two experiments ($\approx 6.10^{-4}$ PgC) appears to be negligible compared to the difference in DIC budget.

2.3 DIC decomposition

In order to analyze the oceanic carbon cycle, ~~the~~ dissolved inorganic carbon (DIC) is decomposed into ~~three DIC~~ its preformed and biological components (Eq. (1)), ~~of saturated, biological and disequilibrium components~~ following Bernadello et al. (2014):

$$DIC^{tot} = DIC^{sat pre} + DIC^{bio} + DIC^{dis} \tag{1}$$

The preformed component of DIC (DIC^{pre}) comprises satured and disequilibrium parts (Eq. (2)).

$$DIC^{pre} = DIC^{sat} + DIC^{dis}, \tag{2}$$

where the DIC at saturation (DIC^{sat}) describes the DIC concentration when the water parcel is in full equilibrium with the atmospheric CO$_2$ when it is last in contact at surface. ~~This variable is computed~~ In our model it seems to mainly refer to changes in preformed ALK. However, we compute this variable offline with the inorganic carbon chemistry program CO2SYS developed in Matlab (van Heuven et al., 2011) ~~using~~ computation including other parameters such as the model output of preformed alkalinity ($TALK^{pre}$), preformed phosphate (PO_4^{pre}), surface silicate, salinity and temperature. In addition, the atmospheric CO$_2$ concentration from each experiment is used. To complete the CO2SYS input, we applied the dissociation constants K1 and K2 introduced by Mehrbach et al. (1973) and refitted by Dickson and Millero (1987). The disequilibrium part of DIC (DIC^{dis}) measures the disequilibrium state of the surface water with respect to the atmosphere. This parameter is computed from the DIC^{tot} (output) to which the biological and satured DIC components (DIC^{bio} and DIC^{sat}) are subtracted. Therefore, all components are included in its calculation. A negative DIC^{dis} occurs when the water parcel sinks into the ocean interior before a full equilibration with the atmosphere is obtained, which lead to an undersaturation of the water parcel. This undersaturation can also be reinforced by biological CO$_2$ consumption at the surface, which tends to increase the time scale needed for the water parcel to equilibrate. On the contrary, a positive DIC^{dis} translates into a supersaturation. This latter occurs when deep waters, which contains high concentration of DIC because of remineralization processes, upwell or mix vertically with the surface waters (Follows and Williams, 2004) . Both, DIC^{dis} and DIC^{sat} are transported by ocean circulation into the interior ocean.

The biological component of DIC comprises (1) the interior remineralization of organic matter (expressed in carbon), which is produced in the euphotic layer via photosynthesis (also referred to as soft-tissue pump) and (2) the remineralization of planktonic calcium carbonate shells (expressed in carbon; calcium carbonate pump). These two remineralization components are added to form the biological component of DIC, as shown in Eq. (2).

3).

$$DIC^{bio} = DIC^{soft} + DIC^{carb}. \tag{3}$$

The remineralization of soft tissues (hereafter DIC^{soft}) contributes via phosphate (PO_4)-remineralization through a carbon phosphorus stoichiometric ratio $r_{C:P} = 122$. This component is calculated from the difference between the total and the preformed PO_4 according to

$$DIC^{soft} = r_{C:P}(PO_4^{tot} - PO_4^{pre}). \tag{4}$$

The carbonate pump contributes through the dissolution of $CaCO_3$ hard shells, calculated as difference between the total and the preformed alkalinity and PO_4 following

$$DIC^{carb} = 0.5[TALK^{tot} - TALK^{pre} + r_{N:P}(PO_4^{tot} - PO_4^{pre})], \tag{5}$$

where $r_{N:P} = 16$ is the Redfield ratio adopted by the model and the phosphate term accounts for the alkalinity changes owing to the soft-tissue pump.

Finally, the disequilibrium component of DIC (DIC^{dis}) measures the disequilibrium state of the surface water with respect to the atmosphere. This parameter is computed from the difference between the DIC^{tot} (output) and the other DIC components previously mentioned in Eq. (1). A negative DIC^{dis} occurs when the water parcel sinks into the ocean interior before a full equilibration with the atmosphere is obtained, which lead to an undersaturation of the water parcel. This undersaturation can also be reinforced by biological CO_2 consumption at the surface, which tends to increase the time scale needed for the water parcel to equilibrate. On the contrary, a positive DIC^{dis} translates into a supersaturation. This latter occurs when deep waters, which contains high concentration of DIC because of remineralization processes, upwell or mix vertically with the surface waters (Follows and Williams, 2004) . Both, DIC^{dis} and DIC^{sat} are transported by ocean circulation into the interior ocean.

In our analysis, we mostly show differences between the warmer 125ka and the colder 115ka experiments. We therefore use the delta notations $\triangle DIC^{tot}$, $\triangle DIC^{sat}$, $\triangle DIC^{soft}$, $\triangle DIC^{carb}$ and $\triangle DIC^{dis}$ to refer changes between the warmer and the colder periods.

2.4 Water mass analysis

In order to identify water mass sources, we apply the 'PO' tracer as defined by Broecker (1974). It is computed using phosphate and oxygen fields following

$$PO = O_2 + r_{O:P} \underline{* PO} \times PO_4 \qquad (6)$$

where $r_{O:P} = 172$ is the phosphorus to oxygen stoichiometric ratio used in the model. This tracer is presumed to be nearly constant for a specific water mass. It is based on the principle that phosphate is released, while oxygen is used during remineralization, and vice versa during biological production. The distinction of water masses using PO is useful for contrasting water masses with very different surface PO values. Here, we mainly use PO to identify northern- and southern-sourced water masses (NSW and SSW) in the deep ocean below 1000 m depth characterized by low and high PO values, respectively.

3 Results

~~We will first describe~~ Section 3.1 describes the sea surface temperature and sea ice changes while changes in water mass properties are discussed in Sect. 3.2. The near surface changes that particularly influence the biological pump ~~. The second section addresses the differences in water mass properties. Finally, we describe and summarize the overall changes in the global and~~ is addressed in Sect. 3.3 and global to regional oceanic DIC storage ~~. Each analysis have been~~ changes are presented in Sect 3.4. The analysis is performed over the average of the last 50 years of the simulations. In addition, ~~we divided~~ the global ocean is divided into three main basins~~(:~~ Atlantic, Indian and Pacific~~)~~.

3.1 ~~Near surface productivity~~ **Sea Surface Temperature and Sea-ice**

~~Simulated~~ Our model simulates a global and annual increase of sea surface temperature (SST~~) during the~~ ; +0.27°C) in 125ka ~~experiment were warmer globally, but the changes varied spatially and seasonaly, affecting both the ventilation and the nutrient supply at the surface. Warmer (cooler) SSTs lead to a more (less) stratified and lower (higher) nutrient concentration in~~ relative to 115ka experiment. This warming is mainly simulated in the high latitudes (Fig. 1a-d) where higher SSTs are simulated throughout the year in the Southern Ocean, south of Greenland, the ~~surface ocean, due to a weakening (strengthening) of the mixing process. In the Atlantic, cooler SSTs are simulated during boreal winter and spring ($\triangle SST < 0$, Fig. 1a-b) , which allow for more upwelled nutrients to the surface~~ Norwegian sea and the northern part of the Pacific Ocean. This persistent warming in 125ka induces the sea ice to melt (Fig. 1, green and purple lines). This impacts directly the mixed layer depth (MLD) by leaving new areas free from sea-ice allowing for air-sea exchanges (Fig. ~~2a)via an increasing of~~ 1, black lines in the Southern Ocean). In the Labrador Sea the mixed layer depth ~~. This higher concentration of nutrients increases the biological production (Fig. 2b) under more favorable warmer blooming season in summer~~ in 125ka ~~($\triangle SST > 0$, Fig. 1c).~~

~~In the Atlantic section of the Southern Ocean (SO), colder SSTs throughout the year are simulated during 125ka~~ is deeper of more than 100m than in 115ka. This is due to higher salinity simulated in this region in 125ka. At lower latitudes, the SSTs

7

vary more spatially and seasonally. For example, in some parts of the Atlantic Ocean (North Atlantic drift, Equatorial and some sections of the ~~subantarctic ($45°S$ latitude band) corresponding to southern sourced intermediate water formation region in the model (Fig. 1). This high nutrient water mass~~ Subantarctic near $45°S$ band) cooler SSTs are simulated over several seasons ($\triangle SST < 0$, Fig. 1a-b). While the North Atlantic drift depicts cooler SSTs during boreal winter and spring (Fig. ~~2a)sinks and reemerges along the Equator leading to an increased biological and hence export production in this region~~ 1a-b), colder SSTs last until the boreal summer in the Equatorial region of the Atlantic Ocean (Fig. ~~2b). A similar 'ocean tunnel' connects the high and low latitude Pacific but results in the opposite sign of change. Herethe SO is simulated as having warmer SSTs throughout the entire year (Fig. 1a-d). This leads to lower nutrient concentration in~~ 1a-c). The $45°S$ latitude band remains cooler over the four seasons. Here, the MLD seems to be more controlled by changes in salinity instead of temperature distribution.

We note that relative to the preindustrial, based on proxy (Hoffman et al., 2017) , our model simulates consistent spatial feature of annual SST anomalies at 125ka~~(Fig. 2a) negatively affecting the biological productivity in the equatorial upwelling regions where these waters return to the surface (Fig. 2b) . Thus, the simulations reveal that changes in southern hemisphere thermocline ventilation regions modulate basin scale productivity and export production even within an interglacial period with modest changes in external forcing. This result is broadly consistent with previous studies suggesting that the upper limb of the biogeochemical divide is critical for setting biological export production and is sensitive to climate changes (Sarmiento et al., 2004; Marinov et al., 2006; Moore et al. , 2018). Despite latitudinally homogeneous forcing we find a basinally heterogeneous response in both subantarctic ventilation and in low latitude productivity which is similar to, albeit more extreme than, the basin specific response simulated for future warming and stratification (Moore et al. , 2018).~~ It simulates (i) strongest warming in the high latitude, specifically in parts of the Southern Ocean, (ii) weak cooling in the low latitude, (iii) cooler SST in most of Indian Ocean, and (iv) warmer north-east Pacific, among others. Nevertheless, the amplitude of SST warming and cooling at specific sites tend to be weaker in our model. This feature appears to be common in other global models and could be attributed to their low spatial resolutions (Hoffman et al., 2017) .

~~There are no significant changes in the biological activity in the Indian Ocean . However, a weak decrease in phosphate availability is simulated (Fig. 2a) , probably induced by warmer SSTs during the boreal fall season leading to less nutrient upwelling to the surface . Here the carbon export is slightly weaker~~

3.2 Water mass properties

In order to analyze the water mass properties, it is useful to examine the changes in the overturning circulation. Figure 2 shows the global overturning stream function in the Southern Ocean for both experiments. The Antarctic circumpolar current is simulated stronger and deeper in 125ka compared to 115ka (Fig. 2). This strengthening is mainly occurring in the Pacific section of the Southern Ocean (near $50°S$), suggesting an increase of the ventilation rate of the intermediate waters formed in this region. The Atlantic section of the Southern Ocean remains weakly modified. Indeed, using the same model simulations as the present study, Luo et al. (2018 , supplementary information Fig. S8) show that the surface wind speed in the east and west southern Atlantic are relatively similar in 125ka and ~~more particularly around $40°S$ and the Arabian sea where the waters upwell.~~

8

~~In additionto variation in ventilation rates, these changes in surface physical and biological activities could also have implications on the exchanges of carbon between near-surface and interior water masses, and therefore the interior carbon budget. In the next section, ventilation changes~~ 115ka. In addition, they also show that the simulated AMOC in 125ka ~~are compared to~~ is as vigorous as in 115ka but deepen by about 300m depth. This suggests that the mid-depth and bottom water in the North Atlantic Ocean should be better ventilated in 125ka than in 115ka~~by analyzing the simulated water mass properties~~.

3.3 ~~Water mass properties~~

~~The analysis of~~ This changes in the overturning circulation affect the water mass age tracer. Analyzing this parameter allows us to examine the interior ocean ventilation rate. A reduction in water mass age translates to a stronger ventilation rate ~~age~~ and vice versa for an increase in age. The differences in water mass age between 125ka and 115ka are presented in Fig. 3 depicting the zonally averaged sections for each ocean basin. The water mass ages in the Atlantic and the Indian Oceans show similar patterns with mean older water masses in the upper layers at 125ka (roughly $+100$ years), and younger water masses below 1000 m depth (by as much as 500 years younger). This is consistent with a deeper and slightly deeper AMOC in 125ka as shown in Luo et al. (2018) . The Southern Ocean (south of $50°S$) contains younger water masses throughout the entire water column in both basins at 125ka, ~~suggesting~~ translating a stronger ventilation rate. ~~However, this does not stem from temperature changes since the SST in the SO is rather warmer in 125ka (Fig 1). Instead, this~~ This is likely due to changes in the SSW to NSW distribution. Figure 4 ~~shows~~ show that there is a clear distinction between interior water mass structure in the Atlantic ~~between 125ka and~~ basin between 115ka (Fig. 4a) and 125ka (Fig. 4c). It shows that below 2000m depth the SSW retreats further southward in 125ka relative to 115ka in the Atlantic basin. This confinement in SSW is induced by the change in the Antarctic sea-ice cover (Fig 1). Such processes have been introduced by Ferrari et al. (2014). ~~In addition, using the same model simulations as the present study,Luo et al. (2018) show in the supplementary information Fig. S8 that the surface wind speed in the east and west southern Atlantic are relatively similar in 125ka and 115ka, translating a relative unchanged Antarctic circumpolar current between the two periods which can therefore not explain the SSW retreat.~~ However, the model also simulates a modification in SSW density (-0.2 kg m^{-3} in 125ka compare to 115ka, Fig ~~4~~4a,c). This reduction in water density is mainly driven by the input of low salinity fresh water from the melting of the Antarctic sea-ice and may have an additional impact on determining the Atlantic distributions of NSW and SSW. As a net result, the water mass becomes younger in the SO because of sea-ice retreat and the influx of meltwater, which in turn induces a southward retraction of SSW and southward incursion of more ~~and younger NSW.~~ NSW. At the near surface ($\approx 800m$ depth) the SSW seems to enter further north in the Atlantic basin in 125ka (Fig. 4c) relative to 115ka (Fig. 4a).

While such large redistributions of northern and southern origin deep waters only occurs in the Atlantic, these changes also influence water properties in the Indian Ocean due to the 'downstream' advection of younger deep water into the interior during the warmest period (~~Fig~~125ka - Fig. 3b). In addition to simple advection of younger water northward in the Indian basin, the residence time ~~(turnover rate) of Indian~~ of Indian Ocean's deep water must also decrease ~~(increase)~~ since the ventilation ages decrease northward at depth. By contrast, in the Pacific Ocean, the zonally averaged bottom water mass ages are simulated to be older in 125ka (Fig. 3c). However, this basin can be divided between the western and eastern side. While the western

9

side is also influenced by the younger water masses created in the Atlantic Ocean, the eastern side waters of the basin are simulated to be older in 125ka by as much as 300 years~~older. This~~. These older water masses are created in the Pacific SO and ~~are predominantly affected by the strong increase in SST, increasing therefore the stratification. In the northern hemisphere the younger waters are due to to cooler SST~~ may be affected by a flattening of the isopycnals south of $60°S$ in 125ka (Fig. 4d, gray lines). This flattening of the isopycnals is influenced by both sea-ice melting and higher SSTs, and suggests stronger stratification and weaker subduction rate. At the Pacific near surface, the SSW also seems to be slightly poleward shifted in 125ka compared to 115ka (Fig. 3b,d), hence more water coming from the subtropical gyre would affect the Pacific SO. Finally, the Pacific intermediate waters are simulated as younger in 125ka when compared to 115ka (Fig. ~~1)~~3c), which is consistent with the strengthening of upper cell of the overturning circulation previously mentioned for this region.

The southern sourced waters are particularly affected in terms of geometry distribution. We therefore ~~divided~~ divide the changes from these SSW into the three basins. Table 1 summarizes the changes occurring below 1000 m depth in the SSW in terms of volume, DIC and water mass age for each basin and reveals the Atlantic as the most affected area under warmer climate conditions. The relative difference in all those three characteristics ($\triangle V_{SSW}$, $\triangle Age_{SSW}$ and $\triangle DIC_{SSW}$) between 125ka and 115ka are the greatest in the Atlantic (-37% , -262 years and -0.92 g C m^{-3}). This demonstrates that the ventilation mechanism in the Atlantic sector of the SO is likely to be more sensitive (than in other basins) to climate change.

~~They are significantly different and basin specific responses of~~ In response to the different forcings between 125ka and 115ka, significant changes are simulated in deep water ventilation rates and water mass distribution ~~to uniform changesin forcing~~in the three basins. While the responses in the Atlantic and Indian Oceans have some similarity (better deep water ventilation), the Atlantic basin seems to be the most sensitive and simulates also water mass geometry changes. However, the ventilation rate in the Pacific Ocean depicts an opposite sign of change than the Atlantic and Indian Oceans. In the next section we discuss ~~the global and regional carbon budget differences~~ how these modification impact the near surface productivity in our model.

3.3 Near surface productivity

Figure 5 shows the differences in carbon export production (EPC) and phosphate (PO4) at the surface of the ocean between 125ka and 115ka~~periods associated to these responses~~. When comparing 125ka to 115ka experiments, our model simulates two major features characterized by (i) an increase in EPC in the equatorial region of the Atlantic Ocean (Fig. 5a, turquoise rectangle) and (ii) a reduction in EPC of similar magnitude in the equatorial region of the Pacific Ocean (Fig. 5a, purple rectangle). Although there are changes in surface wind speeds in the Equatorial regions of Atlantic and Pacific basins, they do not explain the simulated changes in export production. In the Atlantic Ocean, the Subantarctic water (45°S latitude band) corresponds in the model to the southern sourced intermediate water formation. This water mass sinks and reemerges along the Equator (Fig. 5, turquoise rectangles). This pattern expected from models and modern observations shows that the intermediate and mode waters formed in the high southern latitudes feed the subtropical thermocline and act as a predominant source of nutrients important for sustaining low-latitude biological productivity (Gu and Philander, 1997; Sarmiento et al., 2004b) . We acknowledge that there is uncertainty in the complex pathways of the subantarctic water masses toward the Equator simulated

in the model. Nevertheless, due to higher preformed and remineralized phosphate in the subantarctic water sinking region, more PO_4 is advected through this 'ocean tunnel' to the equator and therefore leads to an increase in EPC (Fig. 5a, turquoise rectangle). A similar 'ocean tunnel' (Fig. 5, purple rectangle) connects the high and low latitude in the Pacific Ocean but results in the opposite sign of change. Here, as pointed out in Sect. 3.2, more subtropical waters seems to enter the Pacific Southern Ocean in 125ka than in 115ka. These waters are depleted in phosphate compared to southern sourced waters. As a result, less phosphate is subducted toward the equatorial Pacific Ocean (Fig. 5b, purple rectangle) leading to a reduction in the EPC near the equatorial upwelling (Fig. 5a, purple rectangle).

4   ~~Global and regional carbon budgets~~

There are no significant changes in the biological activity in the Indian Ocean or the remaining of the Southern Ocean. Only a weaker carbon export in 125ka relative to 115ka is simulated around $40°$S and the Arabian sea where subantarctic waters upwell again.

Thus, the simulations reveal that changes in Southern Hemisphere thermocline ventilation regions modulate basin scale productivity and export production even within an interglacial period with modest changes in external forcing. This result is broadly consistent with previous studies suggesting that the upper limb of the biogeochemical divide is critical for setting biological export production and is sensitive to climate changes (Sarmiento et al., 2004a; Marinov et al., 2006; Moore et al., 2018). Despite zonally homogeneous forcing we find a basinally heterogeneous response in both Subantarctic ventilation and in low latitude productivity which is similar to, albeit more extreme than, the basin specific response simulated for future warming and stratification (Moore et al., 2018).

These changes in surface physical and biological activities could also have implications on the exchanges of carbon between near-surface and interior water masses, and therefore the interior carbon budget. In the next section, ventilation changes in 125ka are compared to 115ka by analyzing the simulated water mass properties.

3.1   **Global and regional carbon budgets**

Figure ~~5~~ 6 shows the difference in the carbon inventory vertical profiles between 125ka and 115ka as simulated by our model. The changes in DIC^{tot}, DIC^{sat}, DIC^{soft}, DIC^{carb} and DIC^{dis} are averaged over a 500 m depth interval. The global amount of DIC^{tot} is -314.1 PgC in the ocean under the warmer condition (Fig. ~~5a~~6a, gray $\triangle DIC^{tot}$). Since the atmospheric CO_2 is kept constant in each experiment, this carbon loss in 125ka compared to 115ka is implicitly assumed to be balanced out by the changes in the land carbon reservoir. Here, the Atlantic Ocean accounts for 15% (-49.1 PgC) of that global decrease, while the Indian and the Pacific basins contribute to 28% (-87.2 PgC) and 57% (-179.0 PgC), respectively. Only in the near-surface layers the model simulates a positive $\triangle DIC^{tot}$, which translates to higher surface DIC concentration at 125ka relative to 115ka. Most of the ocean interior has lower DIC concentration at 125ka with the strongest difference in $\triangle DIC^{tot}$ simulated between $2000-3000$ m depths for each basin (Fig. ~~5b-d~~6b-d). The soft-tissue pump and the disequilibrium effect are the main contributors for the ~~weaker~~ reduced carbon inventory depicted at 125ka at global scale (Fig. ~~5a~~6a, green and purple bars) -

each accounting for a third of the total -314.1 PgC decrease. Similarly, $\triangle DIC^{tot}$ in the Atlantic basin is also predominantly controlled by the biological pump, i.e. the soft-tissue plus carbonate pump throughout the entire water column with a decrease at depth and an increase in the near-surface (Fig. ~~5b~~6b). Except for the upper ocean, the contribution from saturation component related to temperature and salinity change is generally negligible.

The $\triangle DIC^{tot}$ of the Indian basin ~~resembles that of the Atlantic at depth, where~~ also depicts a strong reduction in 125ka relative to 115ka. Here the soft-tissue and ~~disequilibrium~~ saturation components simulate the strongest decrease (Fig. ~~5c~~6c, green and ~~purple~~ blue bars). ~~However, the saturation component depicts persistent negative $\triangle DIC$ below 1000 m depth, thereby accounting for the second most important component of the decrease throughout the water column.~~ In addition, near-surface changes in $\triangle DIC^{tot}$ are controlled by the changes in $\triangle DIC^{sat}$. Similarly, the near-surface layer of the Pacific Ocean is also controlled by the changes in saturation component (Fig. ~~5d~~6d), simulating a ~~strong~~ positive difference of about $+18$ PgC. Changes in the deeper layers are mainly attributed to the disequilibrium effect and the soft-tissue pump accounting for a decrease of -83.6 PgC and -44.0 PgC in 125ka relative to 115ka, respectively. However, the saturation component ~~has also~~ also has a considerable influence on the carbon storage with persistent negative $\triangle DIC^{sat}$ throughout the water column.

In order to address the regional changes, we analyze the differences in each DIC components further by calculating the zonally averaged values in each basin. Figures ~~6, 7and~~, 8 and 9 depict these differences for the Atlantic, Indian and Pacific basins, respectively. As shown in Fig. ~~5a~~6a, the carbon inventory of the Atlantic is reduced mainly below 1500 m depth. Here the ~~southern hemisphere~~ Southern Hemisphere is the most affected region, which depicts the strongest differences in $\triangle DIC^{tot}$ (Fig. ~~6a~~7a, blue shades). This pattern corresponds well to the changes in soft-tissue pump (Fig. ~~6b~~7b). Near the surface, ~~the~~ higher carbon export ~~mentioned in Sect. 3.1.~~ (Fig. 5a) increases the remineralization of organic matter leading to higher DIC concentration in 125ka. At depth, the ~~changes in SSW and NSW lead to a decrease in younger water masses, hence~~ slightly deeper AMOC in 125ka (compared to 115ka), leads to better ventilated mid-depth to bottom waters in the Northern Hemisphere leading to less remineralized organic matter by reducing the water mass age. This is reflected by the negative $\triangle DIC^{soft}$ and $\triangle DIC^{carb}$, translating to a less effective soft-tissue and carbonate pump in 125ka. Positive ~~change~~ changes in $\triangle DIC^{tot}$ ~~also arises~~ in near surface waters and bottom water at $20°N$ also arise from the soft-tissue and carbonate signal due to the increase of the alkalinity (not shown here) and slightly older water masses along the African coast. The bottom waters in the ~~southern hemisphere~~ Southern Hemisphere are mainly controlled by a stronger disequilibrium effect, i.e. negative change in comparison to 115ka. ~~The latter~~ This change in disequilibrium is due to the sea-ice induced retreat of the SSW and the inflow of more NSW between $50°S$ and the Equator in 125ka. The NSW water mass, formed in the North Atlantic, is generally more subject to biological production during its near surface northward transport before sinking into the interior than the SSW (Duteil et al., 2012). The biological production consumes DIC during photosynthesis and pushes the water mass further out of the equilibrium with the atmospheric CO_2, inducing $\triangle DIC^{dis}$ to be more negative. The negative values of $\triangle DIC^{dis}$ are conserved when the water parcel flows southward into the deep ocean. For this reason, the regions that are no longer influenced by SSW in 125ka depict a negative $\triangle DIC^{dis}$ (Fig. ~~6d~~7d). However, the upper layers of the ~~north Atlantic are~~ Atlantic Ocean are mostly simulated with higher DIC^{dis} (positive $\triangle DIC^{dis}$~~) due to weaker ventilation induced by stronger SSTs in the Labrador and Nordic sea~~; or less disequilibrium in 125ka). This could be induced by more SSW (less

disequilibrated than NSW) entering further north the Atlantic basin at the near surface as suggests Fig. 4c. Finally, the loss of carbon in the Southern Ocean is shown to be mainly attributed to a decrease of the saturation component in 125ka. This decrease is mainly attributed to lower ~~salinity and~~ TALK^{pre} (not shown here) possibly provoked by the melting of the sea-ice.

The DIC storage in the Indian Ocean generally shows a decrease in 125ka with the strongest changes occurring at depth north of $30°S$ (Fig. ~~7a~~8a, dark blue shade). ~~Only~~ Positive $\triangle DIC^{tot}$ are nevertheless simulated in the region that may correspond to the AAIW ~~the simulated $\triangle DIC^{tot}$ are positive~~ (Fig. ~~7a~~8a, red shade). Similar to the Atlantic basin, the pattern of the soft-tissue pump changes corresponds to the $\triangle DIC^{tot}$ pattern throughout most of the Indian ~~basin~~Ocean. This decrease in biological remineralization is in agreement with the water mass age changes seen in Sect. 3.2 (Fig. 3b): younger water masses account for less biologically-induced DIC content. However, the bottom and the surface waters show opposite signs in the $\triangle DIC^{tot}$, which suggests that other processes are acting in these regions. The differences in the carbonate pump remain small and roughly follow the pattern of the soft-tissue pump (Fig. ~~7c~~8c). Changes in the bottom water ~~DIC^{soft}~~$\triangle DIC^{tot}$ can be attributed primarily ~~related~~ to the difference in the disequilibrium effect ~~due to~~ which is probably affected by larger influence of NSW in 125ka relative to 115ka as described for the Atlantic basin, and to a slight reduction in the saturation component. In addition, the disequilibrium component might also be influenced by stronger carbon export in the Southern Ocean (~~Fig. 2b)and to a slight decrease in the saturation component~~as the positive $\triangle DIC^{soft}$ and Fig. 5a suggest). The strong positive $\triangle DIC^{dis}$ simulated at near-surface along the Indian coast is well in agreement with ~~the~~ lower SSTs (Fig. 1a-c) allowing more DIC to be absorbed in 125ka and a strong reduction in ~~primary productivity. However, this is not shown in the soft-tissue pump because of the cooler SSTs described previously, increasing the ventilation and the DIC supply from DIC-rich deep waters~~carbon export production (Fig. 5a). Finally the negative $\triangle DIC^{sat}$ depicted in the top layers in the north of the Indian Ocean is mainly attributed to a change in water mass origin from 115ka to 125ka. During 115ka the SSW upwells from the deep ocean into the Arabian sea. By contrast, at 125ka, the waters coming from the Indonesian region mix with SSW. These Indonesian throughflow water masses initially coming from the Pacific Ocean are affected by strong precipitation in the Indonesian basin, which reduces the ALK at the surface and therefore DIC^{sat}.

The Pacific basin shows the strongest DIC^{tot} decrease in the ~~northern hemisphere~~Northern Hemisphere, mainly due to the reduction in soft-tissue pump (Fig. ~~8b~~9b). This ~~lower organic remineralization arises from an increase of the ventilation~~ decrease in biogenic carbon is induced by better ventilated water mass around $30°N$ ~~and a potential increase of the upwelling generating younger water masses~~ (Fig. 3c~~. This is in good agreement with the increased carbon export production (Fig. 2b), inducing positive $\triangle DIC^{tot}$ near the surface, and with the cooler SST depicted in Fig. 1. The~~), which may come from the increase of the overturning circulation in the upper cell of the Pacific Ocean. On the opposite, the DIC inventory of the ~~southern hemisphere~~ high latitude Southern Hemisphere bottom and near-surface waters is larger in 125ka relative to 115ka. This is ~~also mainly due~~ attributed to the changes in soft-tissue pump, which is more effective in 125ka ~~both~~ due to longer residence time of the water masses (Fig. 3c)~~and increased biological export production during the Austral spring. The older water masses also suggest that the formation of bottom water in the South Pacific is slower in 125ka, mainly attributed to the warmer SSTs as mentioned in Sect 3.1. (Fig. 1)~~. The carbonate pump has a relatively low impact on the total $\triangle DIC$ inventory in the Pacific basin but follows the same pattern than the changes in the organic carbon remineralization. The disequilibrium

13

effect accounts for the strongest decrease of DIC throughout the basin as seen by the negative $\triangle DIC^{dis}$ in almost all regions (Fig. ~~8d). It can be attributed to the higher biological productivity and export~~ 9d). However, the bottom waters seems to be the most affected and become more undersaturated in 125ka relative to 115ka. This may be influenced by the slowing down of the subduction process in the Southern Ocean~~. This SSW mainly composes the Pacific interior ocean~~, induced by the flattening of the isopycnals. The possible higher carbon export production in the SO south of $60°S$ (Fig. 5a) may also pushes the water mass further out of equilibrium. Finally, the saturation component is controlling the changes occurring in the near-surface waters (Fig. ~~8e~~9e). Lower saturations are attributed to higher export of calcium carbonate south of $60°S$, which lower the alkalinity at the surface and thereby the buffering capacity. On the other hand, the calcium carbonate formation decreases north of $60°S$, resulting in a higher alkalinity and buffering capacity.

4   Discussion

The ocean plays an important role in storing carbon and, thus, in the long term regulation of atmospheric CO_2 levels. The processes involved in regulating the ocean carbon inventory are likely to change under warmer future conditions. In this study, we simulate two equilibrium states of the penultimate interglacial period using a state-of-the-art Earth System Model and make a first attempt at quantifying the biogeochemical and physical processes responsible for carbon storage changes caused by different (interglacial) orbital configurations and background climates. Significant decreases ~~of~~ in the ocean carbon storage capacity are found under a warmer climate. ~~Most~~ More than 48% of this decrease is induced by the reduction of the biological pump. This decrease is found to be mainly driven by the shorter residence time of interior deep water masses ~~.~~ ~~Additionally, spatial modifications in ventilation structure are shown to be also responsible for this carbon change, by impacting the biological pump and hence the remineralization process~~arising from changes in Southern Ocean sea-ice extent that influence the NSW/SSW water mass geometry, in addition to changes in overturning circulation in the Atlantic (deeper but almost equally vigorous) and Pacific basins (stronger upper cell).

Using the available proxy reconstructions during the LIG period allows us to assess the validity of important features in our model results. We assess the validity of the simulated 115ka to 125ka water mass geometry change using LIG proxy reconstructions of bottom water $\delta^{13}C$, a water mass tracer strongly but inversely related to carbon and PO_4 contents (Eide et al., 2017). Similar to our results, expanded SSW in the late compared to early LIG ~~has been previously been~~ is inferred from such reconstructions ~~(Govin et al., 2009) . Records of~~ to explain bottom water δ^{13}C decreases in different regions proximal to the Southern Ocean (Ninnemann and Charles, 2002; Govin et al., 2009) . Bottom water δ^{13}C reconstructions indicate less influence of ~~(high-δ^{13}C)~~ NSW in the deep South Atlantic at 115ka ~~(lower δ^{13}C)~~ than at 125ka ~~(higher δ^{13}C) while mid-depth North Atlantic NSW influence (high δ^{13}C) remained largely unchanged (Fig. 9). This pattern of δ^{13}C in the deep South Atlantic (Site 1089, ~4.6 km water depth) diverging from the~~ (Ninnemann et al., 1999; Govin et al., 2009) . In addition, persistent (millennial-scale) mid-depth ~~North Atlantic (Site 983 and JPC8, ~2 km water depth) indicates relatively greater SSW influence in the abyssal South Atlantic at ~115ka, while $\delta^{13}C$ intermediate between these two indicates an mixture of SSW and NSW shallower in the South Atlantic (Site 1090 and MD07-3077, ~3.8 km) (Fig. 9). This ~115ka to ~125ka water mass~~

14

geometry change inferred from reconstructions is strikingly similar to our model results, suggesting that in the colder (NSW ventilation extending from the LIG and into the subsequent glacial inception is also suggested based on proxy reconstructions (Mokeddem et al., 2014; McManus et al., 2002) and is consistent with model simulations (Born et al., 2011; Wang et al., 2002). In our study, even though the AMOC is simulated slightly stronger and deeper in 125ka, vigorous AMOC persists during 115ka) climate NSW ventilationpersisted while SSW expanded northward in the abyss on millennial timescales (Fig. 4). ventilating the North Atlantic mid-depth. We also note that our model may not properly represent North Atlantic overflows due to its sparse resolution. This can further add uncertainties to North Atlantic water ventilation.

Also consistent with our results, ice core proxies indicate that Southern Ocean sea ice extent was is greater at 115ka than at 125ka (Wolff et al., 2006; Röthlisberger et al., 2008), while our model reproduces the volumetric SSW expansion in response to this increase in Southern Ocean sea ice extent as suggested for glacial climates (e.g. Ferrari et al. (2014)). Our model results (Fig. 4) suggest similar sea ice (Fig. 1) and SSW expansions (Fig. 4a), albeit muted compared to glacial changes, occurred in response to LIG orbital configuration changes and without continental ice sheet growth (not included in the model), indicating a relatively tight coupling between Antarctic climate, sea ice, and the deep Atlantic water mass geometry changes influencing ocean carbon storage.

The changes in ocean carbon storage simulated by our model are significant and demonstrates that warm (interglacial) ocean carbon content changes with climate forcing. While atmospheric CO_2 is fixed in our model preventing a direct assessment of ocean carbon changes on atmospheric CO_2, the decrease in deep carbon storage and shoaling of the DIC pool during the warm 125Ka interval is generally consistent with higher atmospheric CO_2 levels at this time. A sense of the scale of the changes our model simulations can be gained through comparison to previous modelling efforts where atmospheric CO_2 was not fixedOur estimated changes in ocean carbon budget is in the range of previous modeling effort studies that also suggest weaker ocean carbon storage during the beginning of the LIG (125ka) relative to the glacial inception (115ka). Brovkin et al. (2016) also simulated simulates a decrease in DIC^{tot} under warmer Eemian conditions using simpler EMIC models, but at slightly weaker decrease amplitude than in our study. In their study, the contribution of the ocean to the change in atmospheric CO_2 concentration ranged ranges from 11 to 41 ppm between 126ka and 115ka translating a difference of DIC storage capacity of about 22 to 82 PgC – four times smaller than our finding. Their simulated change in atmospheric CO_2 after 121ka was is in the opposite direction (increasing) than that of the atmospheric trend observed in ice core data. Hence, assuming their vegetation model is correct, this suggests that to keep the atmospheric CO_2 level within the observed range, the ocean needed needs to take up more carbon at the end of the LIG to counteract terrestrial reservoir changes. In other words, the difference in ocean carbon storage they simulated should be larger, in accordance with our study. Thus, both studies suggest that ocean carbon storage must have been the dominant factor driving changes in atmospheric CO2 CO_2 concentrations during the LIG.

Another study by Schurgers et al. (2006) obtained obtains a difference in atmospheric CO_2 concentration and terrestrial carbon storage of about 40 PgC and 350 PgC, respectively, between the onset and end of the LIG. This potentially translates to a 310 PgC of difference in weaker ocean carbon storage of 310 PgC at the onset compared to the late LIG, which corresponds well in absolute magnitude to with our findings of -314.1 Pg C314.1 PgC decrease in 125ka. However, the changes in their simulated atmospheric CO_2 concentration in the atmosphere that they simulated steadily increasessteadily increases over this

period, which potentially points toward more carbon needing to be stored in land or ocean toward the end of the LIG. ~~Finally, these carbon dynamic focused studies demonstrate a weakening in the capacity of the ocean to store carbon in the beginning of the Eemian period under warmer climate conditions, which is supported by our study.~~

Concerning the modification in the upper ocean productivity under warmer climatic conditions, our model study shows a heterogeneous response in phosphate availability and carbon export production especially between the Atlantic and Pacific basins. Moore et al. (2018) also highlight such biogeochemical divide response for future projections under warmer climatic conditions. This implies that future anthropogenic CO_2 forcings may have a similar impact on the biogeochemical divide with that of past forcings. Therefore, reconstructing and understanding the large scale productivity responses to past climate forcing are critical for assessing both global and regional sensitivity of the ocean carbon dynamic to climate change.

There are limitations to our study. Factors that could influence ocean carbon storage including sea level, riverine input of nutrients, and atmospheric dust loading ~~, which~~ are all set to preindustrial levels in our simulations, but may ~~have been~~ be different in the LIG. Global sea level, for example, may ~~have been~~ be as much as 6-9 m above present (Kopp et al., 2009). In addition, our model does not include weathering fluxes, which might influence the carbon budget on such longtime scale. Further, we compare two quasi-equilibrated states, which is unrealistic and ignores transient forcings and shorter-term variability. This may explain differences between our model results and some proxy reconstructions. For example, proxy reconstructions suggest that both NSW and SSW ventilation may have varied considerable near 125ka (Galaasen et al., 2014; Hayes et al., 2014). The changes suggested by these studies include reductions of NSW and expansions of SSW similar to our modeled 115-125ka equilibrium difference, but then occurring as short-lived (centennial-scale) transient events associated with freshwater input episodes during the final phase of northern deglaciation (Galaasen et al., 2014). Our quasi-equilibrated model simulations for 115ka and 125ka, also lack ice sheet and the corresponding freshwater input variability, and do not address such shorter-term changes that could affect the ocean carbon inventory (Stocker and Schmittner, 1997). However, short-lived changes would likely have less impact on the ocean carbon inventory than the longer-term (millennial-scale) changes we address, the latter allowing all carbon system components and ocean dynamics to adjust. Thus, we still expect our model simulations to provide insight into baseline changes and redistribution of ocean DIC forced by the different LIG orbital configurations, supported by the important role of deep Atlantic water mass geometry changes coupled with its similarity to the long-term (millennial-scale) evolution inferred from proxy reconstructions (Fig. ~~4; Fig. 9~~3).

5   Conclusions

~~The ongoing global~~ Ongoing anthropogenic warming raises questions about the oceanic carbon sink and its efficiency under a warmer climate condition. In this study, we use ~~a~~ the fully-coupled NorESM model to simulate two quasi-equilibrium states of the Last Interglacial: one period is globally colder (115ka) and one is globally warmer (125ka) than today. We focus on the differences ~~that occurred~~ in ocean carbon cycle that occur in 125ka in comparison to 115ka, specifically the differences at global and basin scales. ~~Thereby, to our knowledge, it is the first attempt in elucidating~~ We provide a detailed description of

the biogeochemical and physical processes that are responsible for the ocean carbon inventory changes under warmer climate conditions during the LIG at the temporal and spatial scales discussed here.

We ~~found~~ find that the global ocean carbon budget decreases during the warm ~~period (-314.1 PgC)~~ (125ka) period by 314.1 PgC and are related mainly to better ventilation in the interior ocean. The Pacific Ocean has the largest reduction and accounts for 57% of the global DIC loss~~, while the~~. The response of the Pacific ventilation in a warmer climate shown in this study is consistent with previous studies (Menviel et al., 2014, 2015). The Indian and Atlantic basins account for 28% and 15%, respectively. ~~However, these~~ These quantities mostly reflect basin volumes. The southern-sourced waters (SSW) are revealed to play an instrumental role for the DIC changes in the interior below 1000 m depth. In these waters, the Atlantic is highlighted to be the region where the strongest DIC loss occur per unit volume and is characterized by a stronger ventilation and a DIC^{tot} decrease of about 37% compared to its respective value in 115ka.

The reduced DIC budget in 125ka occurs mostly in the interior ocean, while there is a weak increase in the top 1000 to 1500 m depths. Two factors contribute mainly to the drop in the DIC budget in the interior ocean are (1) a weaker biological component from both the soft-tissue and the carbonate pumps that dominates at the depth between 1000 to 3000 m, and (2) a stronger disequilibrium effect (i.e. more negative) of DIC in the bottom waters. ~~The latter is predominantly affected by changes in biological production at the surface. Stronger biological production during warmer period pushes the surface water out of equilibrium with the atmospheric CO$_2$ and vice versa during the colder period. These modifications in biological productivity are, however, heterogeneous between basins~~However, the processes affecting the disequilibrium component can arise from different factors such as changes in the physical pump, overturning circulation or biological pump. No general process could be attributed to its variation which seems to be regionally affected. While the ~~Atlantic accounts for more biological production~~ SSW seem to become more undersaturated in 125ka, the ~~Pacific productivity decreases~~NSW seem to be more saturated. Further experiments with for instance fixed biological productivity or overturning circulation could help to identify the sensitivity of this component to such factors, but remain too expensive to perform with our model.

The weakening of the biological component at depth is driven by younger water masses simulated in the interior ocean. This decrease in residence time of the water masses is provoked by the strong SST modifications that affect the ventilation in 125ka as compared to 115ka. Higher SST, especially in the high latitudes, induces strong summer sea-ice retreat in the Atlantic sector of the Southern Ocean and stratification in the Pacific Ocean. In the Atlantic basin, this results in a more southerly confined SSW and southward expansion of NSW in the deep ocean. These water masses are advected by the Antarctic circumpolar current into the Indian and the ~~eastern Pacific. The~~ western Pacific basins. The eastern Pacific Ocean is influenced by water masses coming from the Pacific sector of the Southern Ocean, with a warmer SST that hinders the ventilation and increases the residence time of the interior water masses on the eastern side of the basin.

Concerning the modification in the upper ocean productivity under warmer climatic conditions, our model study reveals clear yet heterogeneous changes in phosphate availability and carbon export production especially between the Atlantic and Pacific basins. Such inter basinal response in the biogeochemical divide is also highlighted by Moore et al. (2018) for future projections under warmer climatic conditions. This implies that changes in the biogeochemical divide could somewhat be similarly impacted from past and future anthropogenic CO_2 forcings although the basin specific responses suggest that it may

not be *a priori* simple to predict the pattern or sign of the response of large scale productivity to a given common forcing. Given the economic importance of basin scale productivity and the sensitivity found in past and future similations, reconstructing and understanding the pattern and validating the sign and (model) response of large scale productivity to climate forcing is therefore critical for assessing not only the sign but also the sensitivity of global productivity to climate change.

The remaining uncertainties include, among others, the use of pre-industrial states for some boundary conditions and the absence of fresh water input, which could modify the spatial response particularly during the early interglacial period which might include the final episodes of continental deglaciation. This is due to the lack of knowledge on such forcing during past climate. Additional model based studies using different Earth system model would be useful to confirm the robustness of our finding and further improve our understanding of the carbon dynamics and the feedback in the ocean under warmer climate. Finally, our model based study suggests that past warm periods experienced considerable carbon cycle and ocean DIC changes, linked to the response of the interior-ocean ventilation and biological productivity to high-latitude warming and interglacial background climate differences. It also suggests that the Atlantic part of the Southern Ocean, which is shown to be a sensitive past climate change, could provide an indicator of future large-scale circulation changes. Close monitoring of the region could be critical in addressing carbon climate feedback in a future warmer climate.

6

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Table 1. Difference in southern ~~sources~~ sourced water ($\triangle_{SSW}$) in the global ocean and for each basin. Row 1 shows the volume (V_{SSW}) according to our $PO \geq 0.57$ mol O m^{-3} criteria. Row 2 and 3 summarizes the DIC and water mass age mean value for the two period of study. The changes relative to 115ka are given as a percentage in parenthesis.

	Global	Atlantic	Indian	Pacific
$\triangle V_{SSW}$ [$10^6 km^3$]	-3.43 (1%)	-18.91 (37%)	+9.76 (8%)	+5.72 (1%)
$\triangle DIC_{SSW}$ [gCm^{-3}]	-0.34 (1.2%)	-0.92 (3.3%)	-0.61 (2.1%)	-0.36 (1.2%)
$\triangle Age_{SSW}$ [years]	-108 (9.3%)	-262 (78.2%)	-152 (29.0%)	-39 (3.0%)
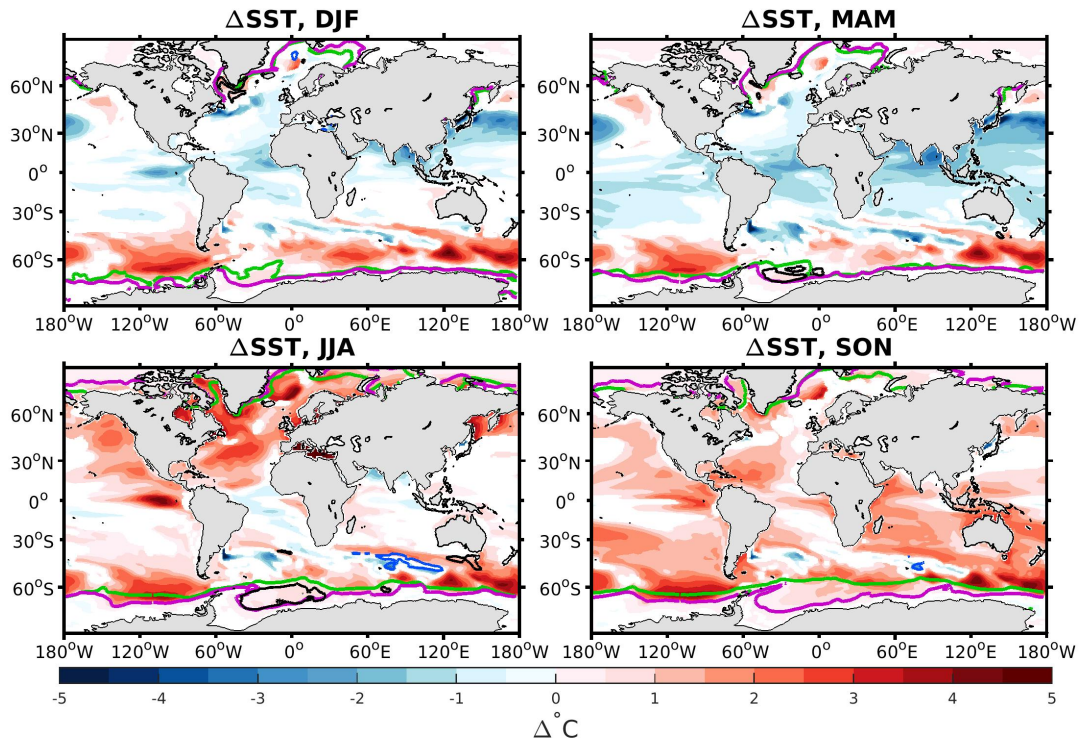
Figure 1. Difference in Sea Surface Temperature ($\triangle SST$) between 125ka and 115ka. Only significant differences (i.e., with absolute value ~~less~~ greater than the interannual standard deviation over the last 50 years in both 125ka and 115ka) are shown. The green and purple lines correspond to 50% sea ice extent in 115ka and 125ka, respectively. The black (blue) thick lines depict regions affected by a deepening (shallowing) of the mixed layer depth (with difference superior of 100m depth) in 125ka compared to 115ka.
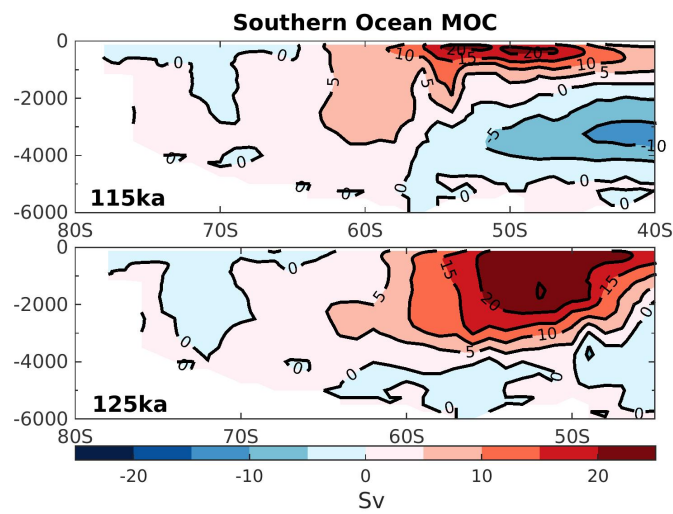
Figure 2. ~~Difference~~ Southern Ocean global overturning stream function in Sverdrup (~~a~~Sv) ~~phosphate at~~ for the ~~surface~~ experiment at 115ka ($\triangle PO_4$top panel) and 125ka (~~b) export production of carbon at 100 m depth ($\triangle EPC$bottom panel)~~between 125ka and 115ka~~. ~~When the absolute value of the difference is below the standard deviation over the last 50 years in 125ka~~ Red colors represent water masses moving clockwise and ~~115ka, the value returns a NaN~~reverse for blue colors.
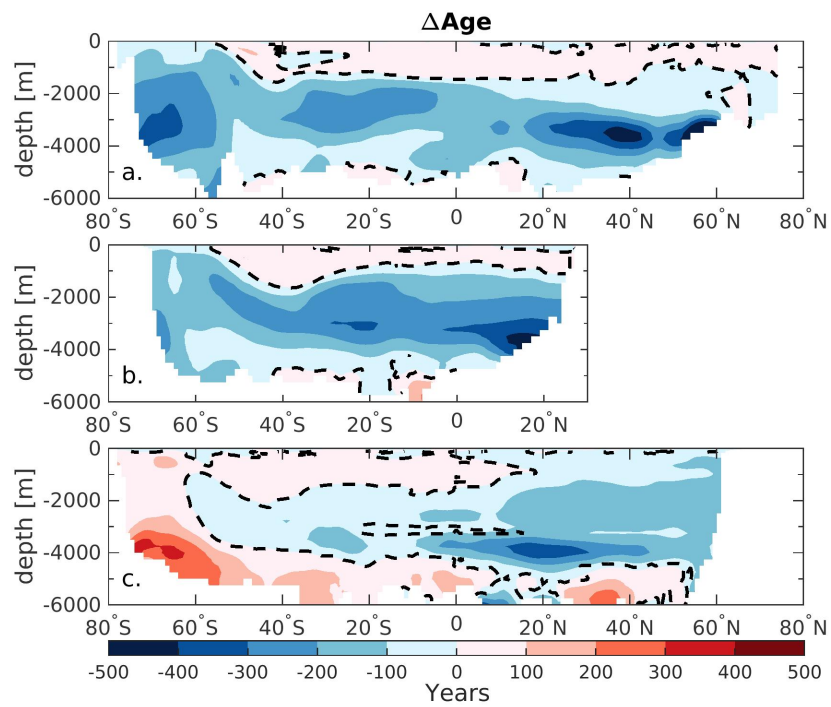
Figure 3. Zonally averaged section of the difference in water mass age ($\triangle Age$) between 125ka and 115ka in (a) the Atlantic Ocean, (b) the Indian Ocean and (c) the Pacific ~~basins~~Ocean. The dashed-lines display $\triangle Age = 0$.
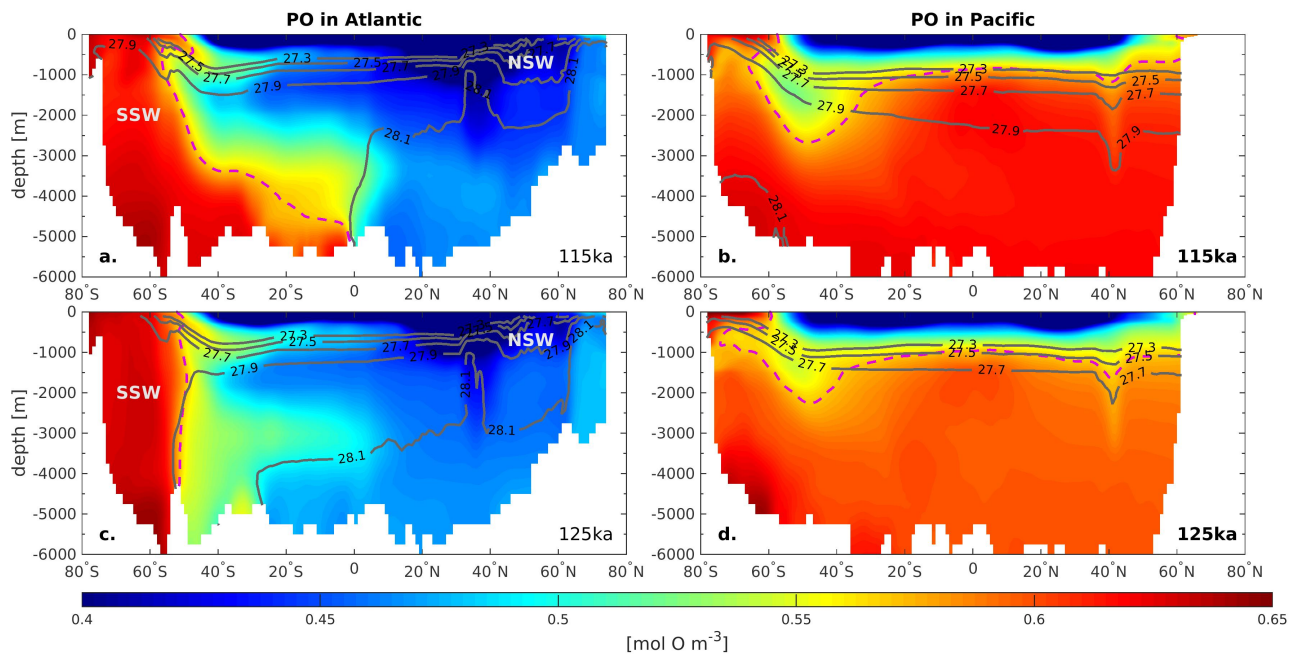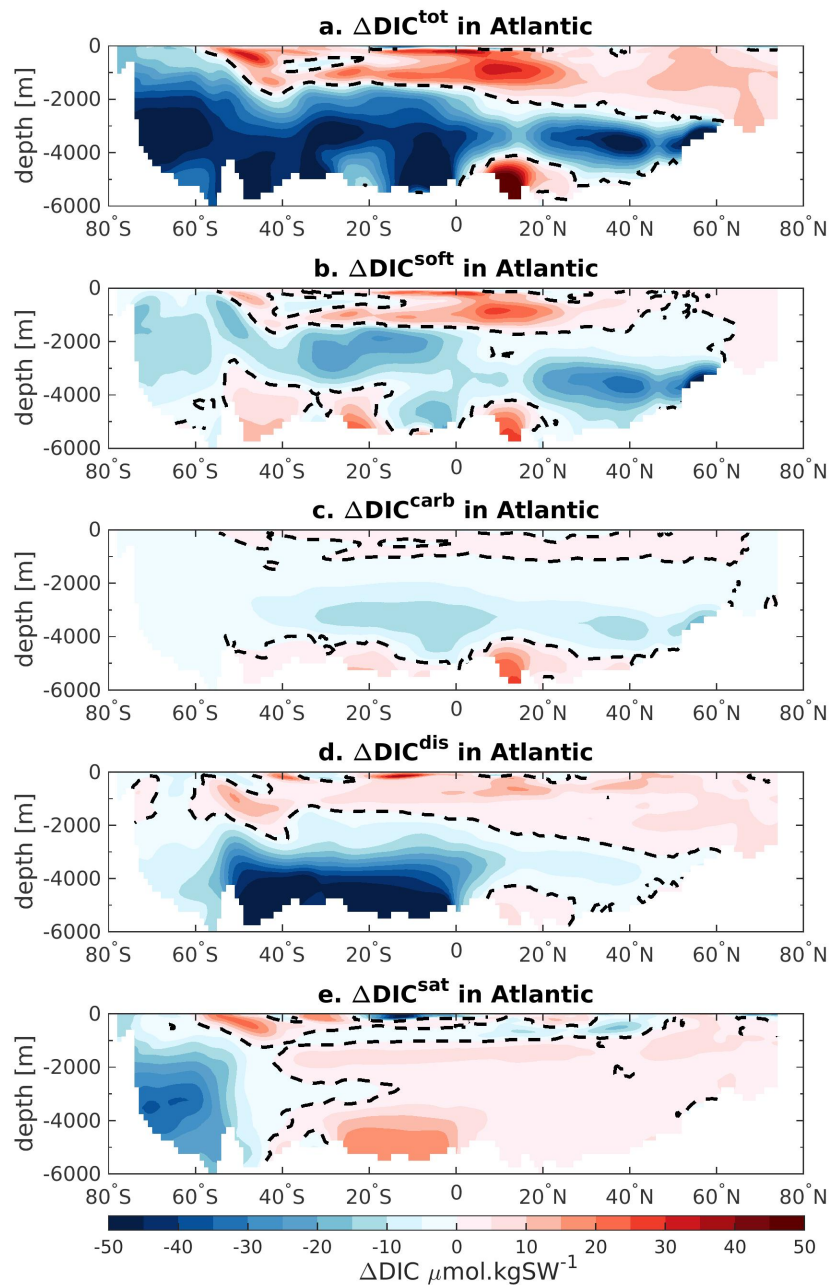
Figure 4. ~~Atlantic zonally~~ Zonally averaged section of PO as defined by Broecker (1974) in (a,c) the Atlantic Ocean in 115ka and 125ka, respectively, and (b,d) the Pacific Ocean in 115ka and 125ka, respectively. The light ~~gray~~ purple dashed-lines delimit the water influenced by the SSW from NSW. The ~~white rectangles represent the sea ice extend during each period and the~~ dark gray solid-lines depict the neutral density [in kg m^{-3}].
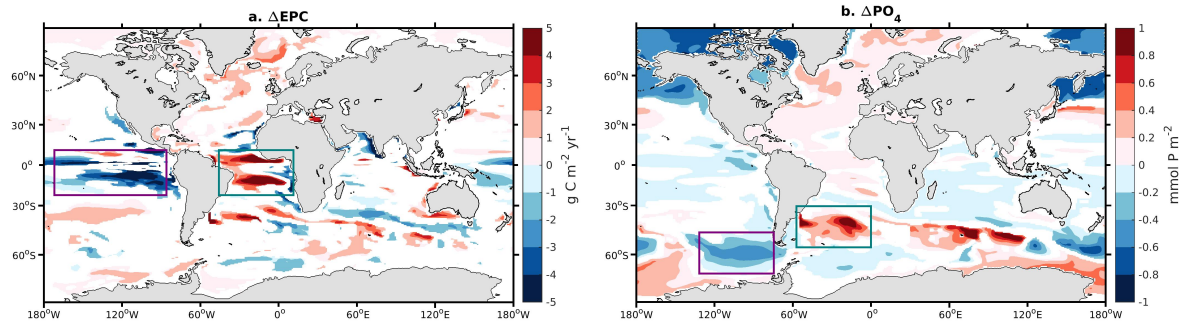
Figure 5. Difference in (a) export production of carbon at 100 m depth ($\triangle EPC$) and (b) phosphate at the surface ($\triangle PO_4$) between 125ka and 115ka. When the absolute value of the difference is below the standard deviation over the last 50 years in 125ka and 115ka, the value returns a NaN. Purple and turquoise rectangles highlight the two 'ocean tunnels' linking the sinking/upwelling regions of southern sourced intermediate waters in our model.
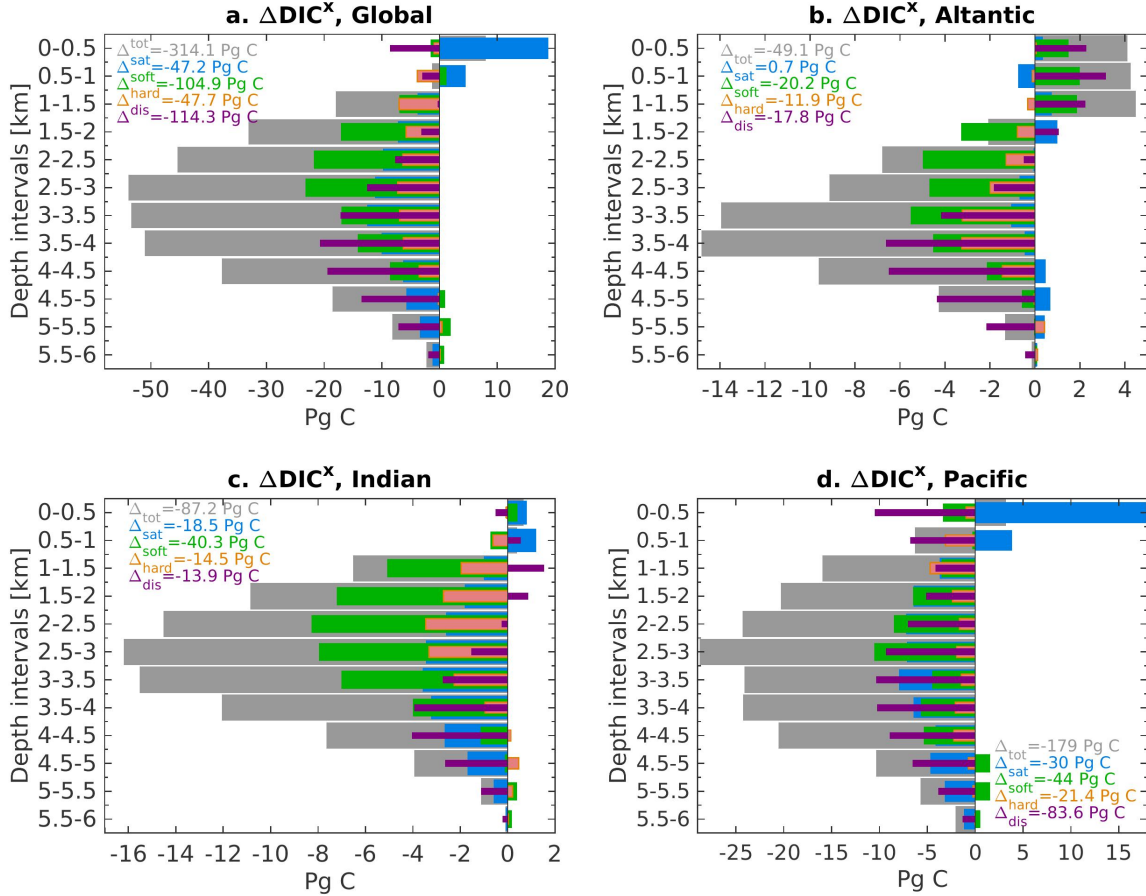
Figure 6. DIC differences between 125ka and 115ka ($\triangle DIC^x$) in (a) Global Ocean, (b) Atlantic, (c) Indian and (d) Pacific basins. The $\triangle DIC^x$ is averaged over a 500 m depth interval where 'x' refers to the different components of the DIC. The DIC^{tot} is represented by the gray bars and is decomposed into its 4 components $\triangle DIC^{sat}$ (blue), $\triangle DIC^{soft}$ (green), $\triangle DIC^{carb}$ (orange) and $\triangle DIC^{dis}$ (purple). The sum throughout the water column of each components is given by the legend.
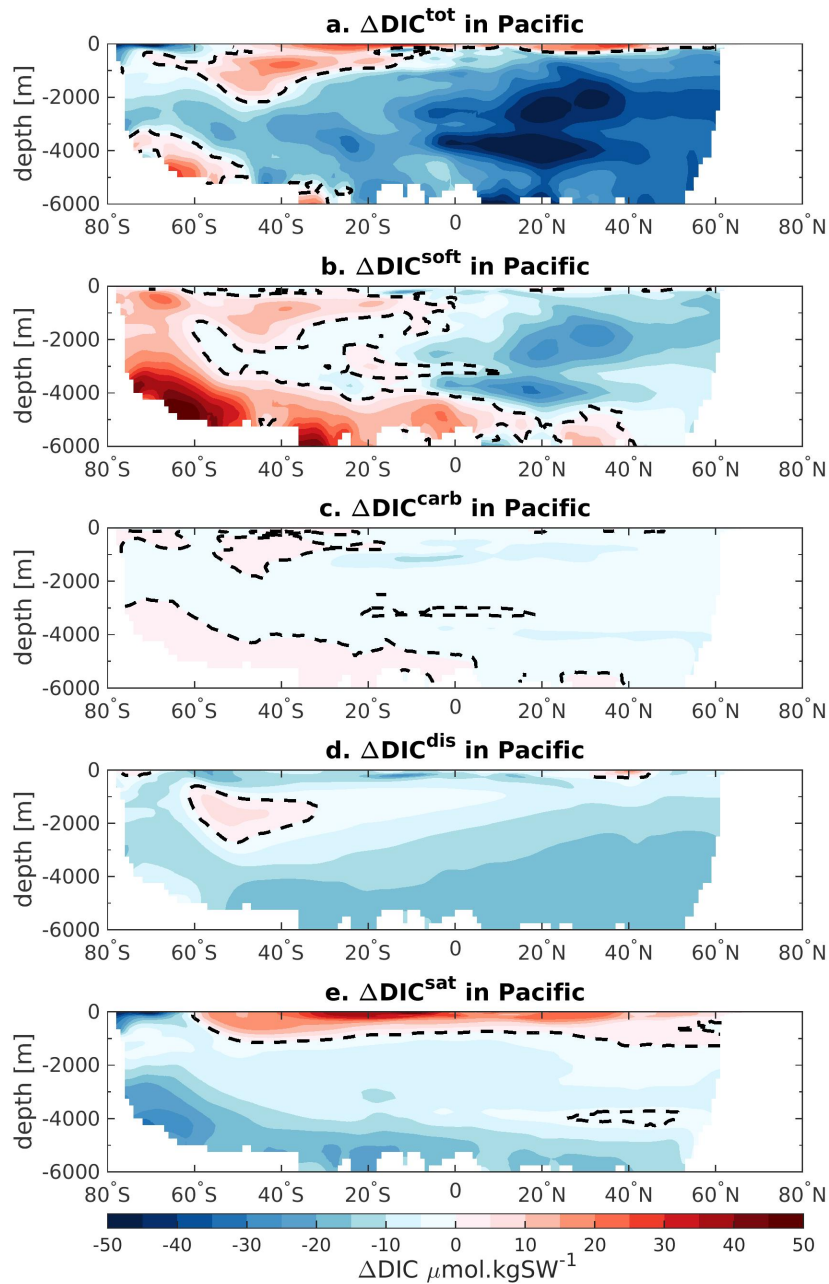
28

Figure 7. Atlantic zonally averaged section of the difference in (a) $\triangle DIC^{tot}$, (b) $\triangle DIC^{soft}$, (c) $\triangle DIC^{carb}$, (d) $\triangle DIC^{dis}$ and (e) $\triangle DIC^{sat}$ between 125ka and 115ka. The black dashed-lines represent the zero values.
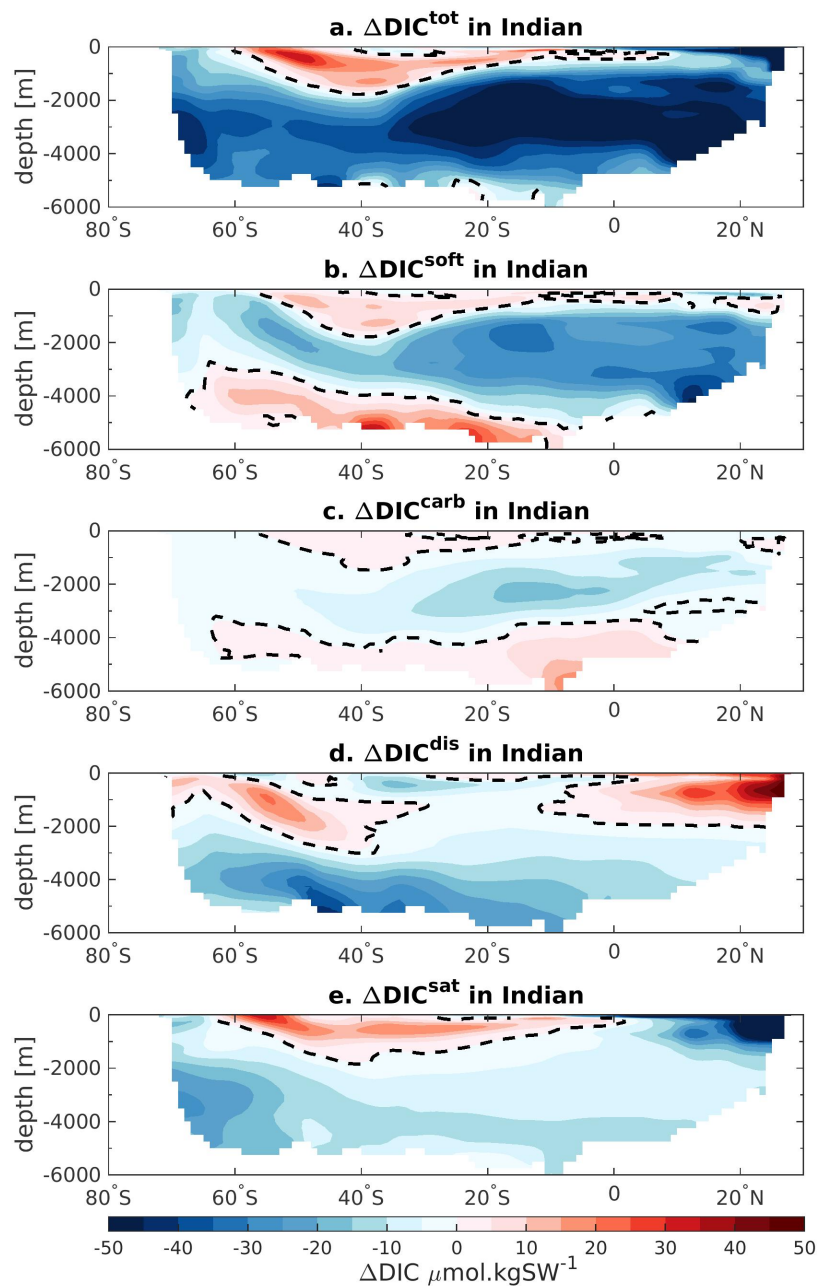
Figure 8. Same as Fig. ~~6~~ 7 for the Indian Ocean.

Figure 9. (a) LIG reconstructions of bottom water $\delta^{13}C$ based on epibenthic foraminifera Cibicidoides wuellerstorfi (five-point running means) from core sites Ocean Drilling Program (ODP) Site 983 (light blue; **?**), JPC8 (dark blue; **?**), MD07-3077 (dark gray; **?**), ODP Site 1090 (light gray; **?**), and ODP Site 1089 (red; Ninnemann et al. (1999)) plotted versus age (ka) where yellow bands denote the modeled 115ka and 125ka windows. VPDB, Vienna Pee Dee Belemnite Same as Fig. (b) The core locations (Site 983: 60°24′N, 23°38′W, 1984 m depth; JPC8: 61°00′N, 25°00′W, 1917 m depth; MD07-3077: 44°09′S, 14°13′W, 3770 m depth; Site 1090: 42°54′S, 8°54′E; Site 1089: 40°55′S, 9°54′E, 4624 m depth) projected on 7 for the preindustrial $\delta^{13}C$ of DIC (Eide et al., 2017) plotted using Pacific Ocean Data View