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Climate
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Discussions

# *Interactive comment on* "Impact of brine-induced stratification on the glacial carbon cycle" *by* N. Bouttes et al.

**N. Bouttes et al.**

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We thank the reviewer for his very detailed comments and address the different points raised in the following.

## 1. Further details on the brine process

### (a) Sea ice production

*Brine is produced during sea ice formation. However, the paper does not describe the amount of sea ice production in the various scenarios. It seemed therefore to be necessary to describe briefly the way sea ice formation is contained in CLIMBER-2.*

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*This is necessary to set the brine process into context with the sea ice formation. As I understood LGM sea ice is mainly increased in winter time, while it is at LGM summer more or less similar to present day (Gersonde et al., 2005). Is this seasonality shown in the data also reproduced in sea ice in CLIMBER, and what does it mean for the brine rejection process?*

The sea ice formation is computed by a one layer thermodynamic sea ice model with a simple parameterization for horizontal ice transport (Brovkin et al., 2007). As pointed out by the reviewer, the data indicate that the LGM sea ice is mainly increased in the winter while similar to the present extent in summer (Gersonde et al., 2005). In CLIMBER-2 the sea ice extent increases both during winter and summer during the LGM (cf Figure 1). When the sinking of brines is taken into account (with frac=0.5 or frac=1) the seasonality is slightly enhanced in better agreement with proxy data. Yet this effect is not enough and sea ice formation needs to be better represented, a problem which is common to most models.

In the manuscript a paragraph has been addded to briefly remind how sea ice is computed in the model as described in (Brovkin et al., 2007): “The sinking of brines initially depends on the amount of salt rejected which is determined by the rate of sea ice formation. In CLIMBER-2, sea ice formation is computed by a one layer thermodynamic sea ice model with a simple parameterization for horizontal ice transport (Brovkin et al., 2007). The sea ice extent is increased in winter (Brovkin et al., 2007) in agreement with proxy data (Gersonde et al., 2005) although during summer sea ice extent is also increased contrary to the data which indicate a sea ice covered area similar to the modern one.”

**(b) Amount of brine rejection (volumetric fluxes)**

*The amount of brine rejection (volumetric fluxes) should be mentioned. Or does your* *approach mean, that only the ions are transported to the deep ocean without any water at all?*

In order to have a simple parameterization with only one free parameter ($frac$) no volume of water is transported by the sinking of brines, only the ions. This parameterization is coherent with the calculation of the surface flux done in the model, which considers salinity fluxes instead of water fluxes as done in rigid lid models. A more complex parameterization taking into account a transport of water has been tested and preliminary results indicate no major change.

**(c) Estimation of $frac$**
*Can you finally give an estimate on which value of frac (fraction of salt/brine transported to the deep ocean) you think is plausible? Are there any data on that or possibilities to measure it in the future?*

Observations indicate that only ∼82 % of the salt is released into the ocean during sea ice formation (Haarpaintner et al., 2001). Moreover, measures in the Arctic fjords indicate that out of the first rapid salt release of ∼82 % of the total salt flux, approximately 78% of the brine-enriched shelf water is released out of the fjord in the Norwegian Sea (Haarpaintner et al., 2001), i.e. ∼62 % of the salt flux rapidly released by sea ice formation. Hence a plausible value for $frac$ would be around 0.6. This seems to agree with the comparisons with salinity data that are in better agreement for frac∼0.5 in particular with respect to the glacial deep Southern salinity (Adkins et al., 2002; new figure 8 c).

In the manuscript we have added a discussion to include this plausible value and added the deep Southern ocean salinity in figure 8:

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"$frac$ values around 0.5 are the most plausible values as they are both supported by the comparisons of model results with data and modern observations. Indeed, comparisons between the modelled salinity and $\Delta\delta^{13}$C with data are in better agreement for $frac$ values around 0.5 (figure 8). Such a $frac$ value is also close to 0.62 which corresponds to the observed ~62 % of the salt flux rapidly released by sea ice formation that is released out of the fjord in the Norwegian Sea (Haarpaintner et al., 2001)."

**(d) Brines in the North Hemisphere**

*Surely, the change in sea ice formation (LGM versus present) was largest around Antarctica, but sea ice in the Northern Oceans was surely also enhanced at LGM (e.g. Pflaumann et al., 2003). What would be the effect of that on brine rejection in the Northern North Atlantic and thus on both ocean circulation and CO2?*

Because of the local topography, most brines rejected in the North and sinking to the bottom ocean would not be released southward into the Atlantic, but would be trapped in the Arctic. It would thus not have such an impact as the one released in the Southern Ocean. The sinking of brines in the north hemisphere has been tested in CLIMBER-2 and preliminary results show that it does not impact much atmospheric $CO_2$ (less than 5 ppm change for $frac$=0.5).

**(e) Time to gain steady**

*How long does it take for the model to gain steady state again, after brine rejection has changed the ocean circulation field due to density changes?*

It takes approximately 3000 years for the model to gain steady state again after the

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onset of the sinking of brines with respect to atmospheric $CO_2$. This information has been added to the manuscript: “In this case it takes approximately 3,000 years for the model to gain steady state again after the onset of the sinking of brines, as the ocean circulation has to adapt to the induced change of density distribution (Figure 1).”

**(f) $^{14}$C**

*What would the brine rejection process contribute to the explanation of glacial 14C (e.g. Broecker and Barker , 2007)? As I understood it, stratification is increased, but carbon from the surface (with high 14C) is also travelling fast to the deep ocean. This would counteract the need for the accumulation of 14C-depleted C in the abyss. This can be done this by stating how much DIC (in terms of mol/yr) is travelling via the brine rejection process to the deep ocean and you can set that into relation with the amount of C distributed to the deep ocean via other routes (export production and ocean circulation).*

The question of the impact on the $^{14}$C distribution has also been raised by the reviewer #2, hence we answer to both questions.

Reviewer #2: *I am surprised that radiocarbon (14C content of atmospheric CO2 and DIC) is not used in this study to complement the other tracers. This is a very classic tracer of oceanic ventilation, for which several measurements exist, both for the atmosphere and the ocean at different depths (eg. Galbraith et al., 2007; Skinner et al., 2010). It is very probably implemented in CLIMBER-2, and would really help constraining the peculiar ’decoupled’ circulation simulated here.*

The radiocarbon tracer is implemented in CLIMBER-2 and the model results for the modern climate compare relatively well with data (Key et al., 2004) (cf Figure 2).

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Because of the sinking of brines, stratification increases but surface water with high $^{14}$C is transported to the deep ocean. The prevailing effect is the stratification which leads to low values of $^{14}$C in the abyss which seems to be in agreement with the data (Robinson et al., 2005; Skinner et al., 2010). In the manuscript we have added two figures (Figures 11 and 12) showing the apparent ventilation age distribution and a discussion in the text:

“

Impact of brines and low diffusion on oceanic $\Delta^{14}$C

The oceanic distribution of $\Delta^{14}$C can be modified by both the change of circulation induced by the transport of salinity to the deep ocean and the direct effect of DI$^{14}$C transport during the sinking of brines. As for $\delta^{13}$C, these two processes have opposite effects on the $\Delta^{14}$C distribution: the change of circulation tends to increase the vertical gradient and lower $\delta^{14}$C in the deep ocean while the transport of DI$^{14}$C brings DIC with high $^{14}$C values from the surface to the bottom and increases the deep $\Delta^{14}$C. The change of circulation is the prevailing effect and the deep $\Delta^{14}$C values become very low (Figure 11 a, c and d). Yet only with very the very extreme and probably unrealistic $frac$ value ($frac$=1) can the circulation capture the increased deep-water ages present in the data.

The low diffusion enhances the vertical gradient as the deep ocean becomes even more isolated. The low data values can then be reached with lower $frac$ values. With very low diffusion profiles (Kz2 and 3, Figure 12), the deep water $\Delta^{14}$C become too low showing that the diffusion should be lowered but not as much.”

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## 2. Present presentation and discussion of results

### (a) Abstract references

*The abstract contains a lot of references to other papers. This is very unusual for CP and they should be deleted.*

The references in the abstract have been deleted.

### (b) Reduced Southern Ocean temperature

*Intro, p 683, l 2: reduced Southern Ocean temperature: in the surface or deep ocean?*

In the surface : it has been added in the manuscript : “in the Southern Ocean surface”.

### (c) Equations

*Throughout the text: Equations are not numbered, making it hard to refer to them.*

The equations are now numbered.

### (d) Eq d13C

*Eq d13C: “Rref” should read “$R_{ref}$”.*

“Rref” has been replaced by “$R_{ref}$”.

### (e) PDB

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*Intro, p 683, l 8: PDB. If you describe PDB, the carbon isotope standard, in such a detail it would also be good to give its value here.*

The absolute $^{13}$C/$^{12}$C ratio of the standard VPDB standard is 0.0112372. It has been added to the manuscript.

**(f) d13C data**

*Intro, p 363, l 12 and Fig 9: Data on LGM d13C: There are more data available than Curry and Oppo (2005), see for example the compilation given in Köhler and Bintanja (2008), Fig 5, which included the compilation of Bickert and Mackensen (2004).*

Following the reviewer's advice we have asked Peter Kohler for the data in Kohler in Bintanja (2008) and added them in figure 9. The additionnal data change slightly some of the quantitative results (the $\delta^{13}$C gradient in the Atlantic at the LGM is 1.2 ‰ instead of 1.4 ‰) but qualitatively the results are the same.

**(g)**

*Intro, p 364, l 4-6: "Moreover, it has remained especially difficult to simulate simultaneously the very negative 13C in the deep ocean inferred from marine sediment cores.". Please consider the very recent paper of Köhler et al. (2010a) in this statement, which connects atmospheric CO2 with deep ocean 13C. Throughout the introduction it is not mentioned, that one main effect of lower glacial terrestrial C storage is to reduce oceanic 13C. Although, reduced terrestrial C should lower both surface and deep ocean 13C and therefore not impact on the vertical gradient, the absolute value in 13C from sediments can not be understood without some thoughts on terrestrial carbon.*

We have added the reference to Kohler et al. (2010) and mentionned the role of the change of terrestrial biosphere on the glacial oceanic $^{13}$C:

“Moreover, it has remained especially difficult to correctly simulate simultaneously the very negative $\delta^{13}$C in the deep ocean inferred from marine sediment cores, although part of the change is due to the glacial reduced terrestrial biosphere which releases light $^{13}$C leading to a reduction of the global mean oceanic $\delta^{13}$C (Kohler et al., 2010).”

**(h) p 686 l 7**
*Methods, p 686, l 7: “Furthermore, like other GCMs, CLIMBER-2...”: CLIMBER is not a GCM, so it should read “Furthermore, like GCMs, CLIMBER-2...”*

“Furthermore, like other GCMs,” has been replaced by “Furthermore, like GCMs,”.

**(i) GHG other than CO$_2$**
*Methods, p 686, l 25: What about the radiative forcing of other GHG, such as CH4 and N2O? Are they considered here? If not why? Their radiative forcing at LGM adds up to -0.7 W m-2, which is about 25% of the total radiative forcing from GHG (e.g. Köhler et al., 2010b).*

CLIMBER-2 does not include the radiative forcing of other GHG such as N$_2$O and CH$_4$. In previous studies their effect was included by considering an “equivalent” CO$_2$ concentration that was 20 ppm lower in the radiative scheme (Brovkin et al., 2007). It yielded an “equivalent” CO$_2$ of 180 ppm for a “real” CO$_2$ of 200 ppm. In this study we only consider CO$_2$ as the ultimate goal is to use the same CO$_2$ that is calculated by the carbon cycle scheme for the radiative scheme. Ideally CLIMBER-2 should include the effect of CH$_4$ and N$_2$O. However to the first order the effect of CO$_2$ is prevailing and considering only its concentration should not change significatively the results. It would only decrease slightly more the atmospheric $CO_2$ by a few ppm because of the colder temperature effect.

### (j) Equation

*Methods, p 689, l 3, 8: Equation on Vbottom and Vsurface: If I make a check on the units of the equations, there seemed to be an error. Assuming* $V_{bottom}$ *in m3,* $\frac{dX_{bottom}}{dt}$ *in mmol m-3yr-1, frac is dimensionless, FX in mmol m-3yr-1 and area in m2 I get one unit of "[m]" more on the left hand side of the equation.*

$F_X$ is in $\mu$mol m$^{-2}$yr$^{-1}$ and not in $\mu$mol m$^{-3}$yr$^{-1}$.

### (k) description of the results

*Throughout the results: Nearly most of the time results are described as follows: "scenario X performs better than scenario Y with respect to variable Z as seen in Fig A". The values of the results are nearly never given in the text. This make the text very difficult to read. Please specify explicitly which values the different results achieve, so explain your figures in more details and take values out of them to be fed into the main text.*

To make it easier to follow the description of the figures we have added quantitative results throughout the text.

### (l) p 693 l 7-22 "$\delta^{12}$C

*Results, p 693, l 7-22: There is no such thing as "12C". This is according to your definition (Eq 1) zero. It needs to be rewritten to "12C".*

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There is indeed no $\delta^{12}$C. It has been replaced by $^{12}$C.

**(m) Results of Figure 3**

*Results, p 693, l 23-27: You varied "one variable at a time". There is certainly a nonlinearity component to this, meaning that the sum of the results from this "one variable at a time" scenarios is different from a scenario, in which all variable are active simultaneously. To my understanding this would mean the comparison of your Fig 2 and 3. Maybe this can be done by plotting the overall results (Fig 2) into Fig 3 for comparison and then the nonlinearly can be calculated.*

The description of the experiments can be misleading. In all simulations the transport of salinity is activated because it is the initial reason for the sinking of brines. In the "S transport" simulation only salinity is transported. Then in the "DIC+ALK transport" simulation salinity, DIC and ALK are transported, in "Nutrients transport" salinity and nutrients are transported. To compare with the simulation when all variables are transported we have added the result of the latter to figure 3 ("All"). If the variables were transported without salinity the changes would be much higher, which we have tested in CLIMBER-2. For example the transport of DIC and ALK then brings higher surface values to the deep ocean with a greater effect on $CO_2$. But because of the salinity transport the DIC and ALK concentrations in the surface are already lower so that the transport of DIC and ALK is less effective when salinity is also transported.

The caption of figure 3 and the text have been changed to make this clearer:

"To understand the reasons of the atmospheric $CO_2$ drawdown, we first assess which variable transport is a major contributor to these changes (Figure 3a). We explore the impact of the sinking of salinity alone, then we add either dissolved inorganic carbon

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(DIC) and alkalinity (ALK), nutrients (phosphate and nitrate) or dissolved organic carbon (DOC). The transport of salinity is activated in all simulations as it is the initial reason for the sinking of the brines.

First we consider only the transport of salinity to the deep ocean; the other variables do not sink with the brines. The salinity sink appears to be the main driver of the atmospheric $CO_2$ drawdown as it accounts for most of the entire brine induced drop (approximately 60 %, Figure 3a). The increased salinity of the bottom waters (Figure 2c) results in greater deep ocean density (Figure 1b). Hence the deep stratification is greater and the oceanic circulation modified (Figure 4). The upper part of the thermohaline circulation is slowed and the Glacial North Atlantic Deep Water (GNADW) becomes shallower. This leads to an increased efficiency of trapping of $CO_2$ released from the remineralization of organic matter, as the carbon enriched Antarctic Bottom Water (AABW) is less mixed with the surrounding waters and constitutes a greater volume of water. The deep carbon reservoir has thus expanded thanks to the density change induced by the salinity transport only.

The transport of dissolved inorganic carbon (DIC) and alkalinity (ALK) by brines also plays a role as it further decreases atmospheric $CO_2$ (Figure 3). The direct transport of DIC and ALK to the abyss helps building an increased deep oceanic carbon reservoir as carbon is brought to the deep ocean but can not escape because of the stratification set by the increased density. In the sensitivity experiments salinity, DIC and ALK are transported. If only DIC and ALK were transported the $CO_2$ change would be much greater, but with the salinity transport the DIC and ALK concentrations in the surface are already depleted so that the effect of transporting DIC and ALK is not as effective.”

**(n) Overall discussion**

*Overall discussion: The results of the study (how much glacial CO2 and 13C can be*

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*explained) should be discussed in the context of other recent studies on glacial CO2 and 13C, e.g. Brovkin et al. (2007); Tagliabue et al. (2009); Köhler et al. (2010a).*

We have added a discussion in the “Glacial-interglacial carbon cycle changes” section:

“Previous studies with simple box models showed that a reduced Southern ocean vertical mixing rate, which is imposed in the model, can reduce atmospheric $CO_2$ (Paillard and Parrenin, 2004; Kohler et al., 2005). It also decreases the deep Southern $\delta^{13}$C (Kohler et al., 2005). More complex models of intermediate complexity and general circulation showed that changes in the oceanic circulation impacts the $\delta^{13}$C distribution in the ocean. Reducing the strength of the meridional overturning circulation by adding fresh water fluxes to the North Atlantic tend to decrease the simulated $\delta^{13}$C of the deep ocean in line with data (Tagliabue et al., 2009). Alternatively, imposing a greater oceanic stratification by changing the vertical diffusion profile also increases the surface to deep oceanic $\delta^{13}$C in agreement with data (Bouttes et al., 2009). However in both cases the associated atmospheric $CO_2$ drawdown remains small compared to the glacial-interglacial change (less than 10 ppm compared to $\sim$90 ppm).

With the sinking of brines, the necessary change of circulation which leads to an increase of the oceanic vertical $\delta^{13}$C gradient is simulated with a more physical mechanism (no artificial fresh water flux is added). Moreover the $CO_2$ drawdown simulated is much more significant. With the maximum effect of the sinking of brines ($frac$=1 the $CO_2$ drawdown is 52 ppm. With less extreme values of $frac$ around 0.5, the $CO_2$ decrease is around 30 ppm, which can be further amplified by 5 to 15 ppm with vertical low diffusion. This $CO_2$ drop is important yet still not enough indicating the need for other processes.”

**(o) Reference Jahn et al.**

*References, p 698: The reference Jahn et al 2005 is given as Clim Past Discussion paper, but this is already published in CP as Jahn et al. (2005), so please update reference.*

The reference Jahn et al. has been updated.

**(p) Salinity in Figure 2**

*Fig 2: Is the salinity in Fig 2 c that of the whole ocean, or deep ocean or deep Atlantic? Please specify.*

The salinity is the one corresponding to the localisation of a core in the deep Southern Ocean (localisation: 50 degrees South, 6 degrees East and 3626 m depth) from (Adkins et al., 2002). It is the site where the highest glacial salinity has been measured. The localisation of the salinity has been added in the figure caption.

**(q) Figure 3b**

*Fig 3: It is not mentioned that Fig 3b is the d13C gradient in the Atlantic ocean. Please specify, if it is the whole ocean (not only Atlantic), then you need to explain more in the main text.*

It is the $\Delta\delta^{13}$C in the Atlantic. In the whole manuscript $\Delta\delta^{13}$C has been replaced by $\Delta\delta^{13}C_{atl}$ to make it clearer.

**(r) Figure 4: units of the color bar**

*Fig 4: Units of the color-bar are missing.*

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The units, which are in Sv, have been added to the figure.

**(s)**

*Fig 5: I do not understand the difference of Fig 5 to Fig 3. As you did some additional experiments to create Fig 5, they are not clearly motivated. Why is the contribution of S larger in Fig 5 than in Fig 3? Please expand?*

Figure 3 and 5 answer two different questions. The first one (figure 3) is: in the transport by the sinking of brines, what is the impact of each of the variables? In other terms, when only salt sinks, what is the effect on $CO_2$ and $\delta^{13}$C? Then if DIC and ALK are also transported, and nutrients? In the experiments, salinity is always transported as it is the basic element of the mechanism. Then either the salinity and DIC plus ALK is transported, or salinity and nutrients, or salinity and DOC.

In figure 5 all the variables are transported by the brine mechanism and we now want to know what change in the distribution of the ocean variables is reponsible for the change of $CO_2$ and $\delta^{13}$C. Indeed, the change of the distribution of DIC and ALK is impacted by both the sinking of salt which modifies the circulation and the sinking of DIC and ALK.

Hence the two figures give two different information. Figure 3 shows that the sinking of salt is the major process in altering $CO_2$ and $\delta^{13}$C. Figure 5 shows that the change of $CO_2$ and $\delta^{13}$C is mainly due to the change of DIC and ALK distribution in the ocean (which is different from the transport of DIC and ALK considered in figure 3, and is due to both the salinity and DIC+ALK transport).

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In the manuscript, to clarify it the paragraph p. 691 l. 6 has been replaced by the following:

"To understand the reasons of the atmospheric $CO_2$ drawdown, we first assess which variable transport is a major contributor to these changes (Figure 3). In the simulations considered, salinity (S) is always transported by the sinking of brines as it is the initial reason for the density change and the sinking of brines to the deep ocean. We explore the impact of the sinking of salinity alone, then salinity with dissolved inorganic carbon (DIC) and alkalinity (ALK), salinity with nutrients (phosphate and nitrate) and salinity with dissolved organic carbon (DOC). The distribution of DIC, ALK, nutrients and DOC is modified both directly by their transport to the deep ocean and indirectly because of the change of oceanic circulation due to the transport of salinity which modifies the density distribution."

The caption of figure 5 has also been modified:

"Mean global ocean surface $pCO_2$ decrease due to the brine mechanism as a function of the fraction of salt rejected by sea ice formation used for the brine mechanism (fraction of salt $frac$, $0 \leq frac \leq 1$). The $pCO_2$ is calculated from the chemical formulas of the surface ocean where the geochemical fields (salinity, temperature, DIC and ALK) are imposed and taken from the simulations with CLIMBER-2. In the $pCO_2$ calculations (except "All changes") all the geochemical fields are from the standard LGM run (LGM-std, $frac$=0) except for one variable. Hence the "S changes only" (red) is the $pCO_2$ change due to the contribution of the modification in the salinity (S) distribution only (the distribution of the other variables is the one from the standard simulation). Similarly, the "DIC + ALK changes only" (orange) corresponds to the contribution of the modification of dissolved inorganic carbon (DIC) and alkalinity (ALK) only. However, "All Changes" (purple) corresponds to the decrease due to the change of distribution of all oceanic variables."

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### (t) Figure 6: units

*Fig 6: Units of colour-bar is missing.*

The units ($\mu$mol/kg) have been added to the figure.

### (u) Figure 8: Atlantic $\delta^{13}$C

*Fig 8: It is not mentioned that Fig 8b is the d13C gradient in the Atlantic ocean. Please specify.*

It has been specified in the caption that it is the $\delta^{13}$C in the atlantic.

### (v) Figure 9

*Fig 9: I would like to see results from Kz1 and Kz2 here. From Fig 8b I would suggest that the best solution to bring the vertical gradient in Atlantic 13C in alignment with proxy data is to use Kz1 and frac between 0.4 and 1.0. Therefore the most likely results should be plotted here as well.*

The results with Kz1 and Kz2 have been added and figure 9 is now splitted in figures 9 (results with Kz0 and Kz1) and 10 (results with Kz2 and Kz3).

## References

Adkins, J. F., McIntyre, K., and Schrag, D. P.: The salinity, temperature, and $\delta^{18}$O of the glacial deep ocean, Science, 298, 1769–1773, 2002.

Brovkin, V., Ganopolski, A., Archer, D., and Rahmstorf, S.: Lowering of glacial atmospheric $CO_2$ in response to changes in oceanic circulation and marine biogeochemistry, Paleoceanography, 22, PA4202, doi:10.1029/2006PA001380, 2007.

Gersonde, R., Crosta, X., Abelmann, A., and et al.: Sea-surface temperature and sea lee distribution of the Southern Ocean at the EPILOG Last Glacial Maximum - A circum-Antarctic view based on siliceous microfossil records, Quat. Sci. Rev., 24, 869–896, 2005.

Haarpaintner, J., Gascard, J. C., and Haugan, P. M.: Ice production and brine formation in Storfjorden, Svalbard, J. Geophys. Res, 106, 14 001–14 013, 2001.

Key, R., Kozyr, A., Sabine, C., Lee, K., Wanninkhof, R., Bullister, J., Feely, R., Millero, F., Mordy, C., and Peng, T.-H.: A global ocean carbon climatology: Results from GLODAP, Global Biogeochem. Cycles, 18, GB4031, 2004.

Robinson, L. F., Adkins, J. F., Keigwin, L. D., Southon, J., Fernandez, D. P., Wang, S.-L., , and Scheirer, D. S.: Radiocarbon Variability in the Western North Atlantic During the Last Deglaciation, Science, 310, 1469–1473, doi:10.1126/science.1114832, 2005.

Skinner, L. C., Fallon, S., Waelbroeck, C., Michel, E., and Barker, S.: Ventilation of the Deep Southern Ocean and Deglacial $CO_2$ Rise, Science, 328 (5982), 1147–1151, doi:10.1126/science.1183627, 2010.

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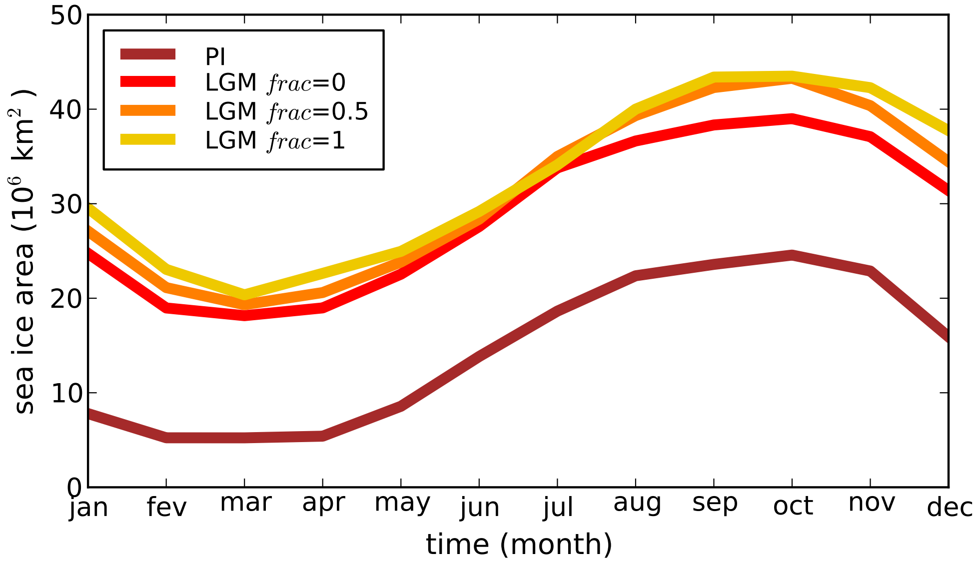

**Fig. 1.** Sea ice area around Antarctica in the simulations.

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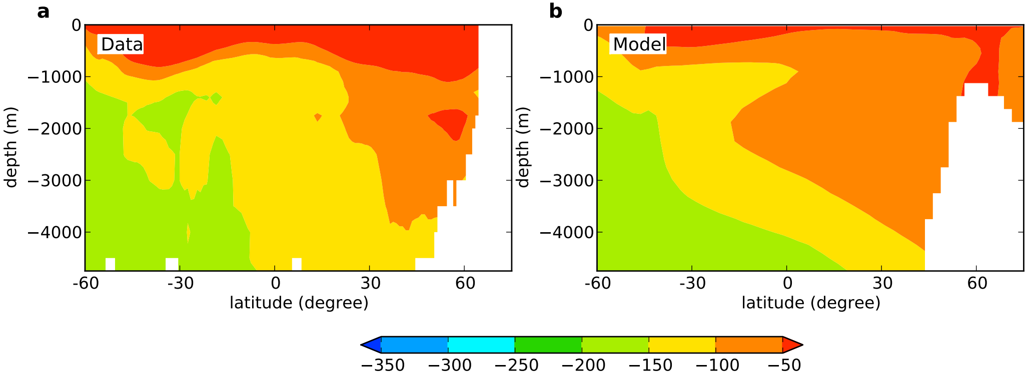

**Fig. 2.** Distribution of D14C (permil) in the modern Atlantic ocean from (a) data from Key et al., 2004 (GLODAP) and (b) model results.

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