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Last Glacial Maximum CO₂ and $\delta^{13}\text{C}$ successfully reconciled

N. Bouttes,¹ D. Paillard,¹ D. M. Roche,^{1,2} V. Brovkin,³ and L. Bopp¹

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[1] During the Last Glacial Maximum (LGM, ~21,000 years ago) the cold climate was strongly tied to low atmospheric CO₂ concentration (~190 ppm). Although it is generally assumed that this low CO₂ was due to an expansion of the oceanic carbon reservoir, simulating the glacial level has remained a challenge especially with the additional $\delta^{13}\text{C}$ constraint. Indeed the LGM carbon cycle was also characterized by a modern-like $\delta^{13}\text{C}$ in the atmosphere and a higher surface to deep Atlantic $\delta^{13}\text{C}$ gradient indicating probable changes in the thermohaline circulation. Here we show with a model of intermediate complexity, that adding three oceanic mechanisms: brine induced stratification, stratification-dependant diffusion and iron fertilization to the standard glacial simulation (which includes sea level drop, temperature change, carbonate compensation and terrestrial carbon release) decreases CO₂ down to the glacial value of ~190 ppm and simultaneously matches glacial atmospheric and oceanic $\delta^{13}\text{C}$ inferred from proxy data. LGM CO₂ and $\delta^{13}\text{C}$ can at last be successfully reconciled. **Citation:** Bouttes, N., D. Paillard, D. M. Roche, V. Brovkin, and L. Bopp (2011), Last Glacial Maximum CO₂ and $\delta^{13}\text{C}$ successfully reconciled, *Geophys. Res. Lett.*, 38, L02705, doi:10.1029/2010GL044499.

1. Introduction

[2] The Last Glacial Maximum (LGM, ~21,000 years ago) was characterized by a cold climate (−2 to −6°C in the surface Southern Ocean [MARGO Project Members, 2009]) associated with major northern hemisphere ice sheets covering large parts of Europe and North America [Peltier, 2004]. As it constitutes a different climate from the pre-industrial (PI) and is fairly well documented, it has been explored in many modeling studies and is now considered as a case study for coupled climate models used for anthropogenic climate change projections. These studies show that the low glacial atmospheric CO₂ (~190 ppm compared to 280 ppm during the pre-industrial) inferred from ice core data [Monnin *et al.*, 2001] plays a crucial role in explaining the cold climate [Jahn *et al.*, 2005]. Yet, although the Southern Ocean appears to be key in such changes [Fischer *et al.*, 2010; Sigman *et al.*, 2010], no complete explanation has been put forward that could both account for this low glacial CO₂ [Archer *et al.*, 2000; Sigman and Boyle, 2000] and the $\delta^{13}\text{C}$ values in the ocean and atmosphere [Brovkin *et al.*, 2007; Tagliabue *et al.*, 2009; Bouttes *et al.*, 2010].

Indeed the glacial oceanic $\delta^{13}\text{C}$ distribution was also changed [Duplessy *et al.*, 1988; Curry and Oppo, 2005], particularly with a higher surface (−2000 m to 0 m) to deep (−5000 m to −3000 m) gradient ($\Delta\delta^{13}\text{C}_{\text{ocean}}$ of ~1.4‰ in the Atlantic compared to ~0.6‰ in the modern ocean), while the $\delta^{13}\text{C}_{\text{atm}}$ level is close to the preindustrial one (~−6.45‰) [Lourantou *et al.*, 2010]. Only box models could account for such changes [Köhler *et al.*, 2005, 2010; Lourantou *et al.*, 2010]. Yet, because of their simplicity, some mechanisms like oceanic circulation changes were imposed and their dynamics could not be tested.

[3] Out of the three global carbon reservoirs (atmosphere, terrestrial biosphere and ocean), proxy data indicate that two were smaller during the LGM. Atmospheric CO₂ was lower [Monnin *et al.*, 2001] and the terrestrial vegetation was reduced by at least several hundred GtC [Bird *et al.*, 1994; Crowley, 1995]. Consequently, the ocean should contain the glacial excess of carbon. Modeling studies have shown that a greatly stratified glacial ocean with lower SSTs could get towards the glacial values for the carbon cycle [Toggweiler, 1999; Paillard and Parrenin, 2004; Brovkin *et al.*, 2007; Bouttes *et al.*, 2009; Tagliabue *et al.*, 2009; Bouttes *et al.*, 2010]. In particular, when deep oceanic stratification is reached through enhanced brine formation (saline water released by sea ice formation that can rapidly sink towards the deep ocean), simulations can simultaneously reduce atmospheric CO₂ and increase $\Delta\delta^{13}\text{C}_{\text{ocean}}$ in the Atlantic [Bouttes *et al.*, 2010].

[4] Other mechanisms have been studied such as carbonate compensation [Broecker and Peng, 1987; Brovkin *et al.*, 2007] or iron fertilization [Martin, 1990; Bopp *et al.*, 2003; Brovkin *et al.*, 2007; Tagliabue *et al.*, 2009]. The carbonate compensation mechanism acts as an amplifier of the ocean carbon uptake or loss. It tends to restore the initial oceanic [CO₃^{2−}] through changes in the sediment dissolution. Iron fertilization can take place in regions of High Nutrients Low Chlorophyll (HNLC) where the biological production is limited by iron (such as in the Southern Ocean). The supply of iron through dust transport and deposition during the LGM stimulates marine biology whose uptake of carbon increases. However, these mechanisms that alone can not account for the entire glacial carbon cycle values were not tested yet in conjunction with the brine mechanism.

[5] Here we show that we can finally reach simultaneously the glacial atmospheric CO₂ level, $\delta^{13}\text{C}_{\text{atm}}$ and $\Delta\delta^{13}\text{C}_{\text{ocean}}$ values with a combination of three main mechanisms when carbonate compensation is considered: brine induced stratification, stratification-dependant diffusion and iron fertilization.

2. Methods

[6] We use the CLIMBER-2 coupled intermediate complexity model [Petoukhov *et al.*, 2000] which is well suited to

¹Laboratoire des Sciences du Climat et de l'Environnement, IPSL/CEA-CNRS-UVSQ, Gif-sur-Yvette, France.

²Section Climate Change and Landscape Dynamics, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherlands.

³The Land in the Earth System, Max-Planck-Institute for Meteorology, Hamburg, Germany.

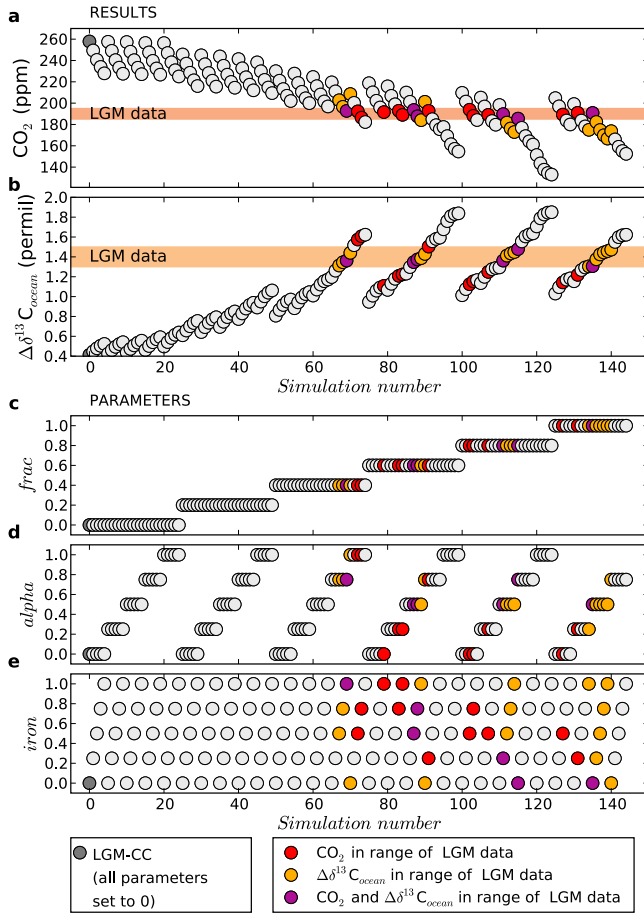


Figure 1. (a) Atmospheric CO₂ (ppm) and (b) Δδ¹³C_{ocean} (‰) (δ¹³C gradient in the Atlantic between the surface (0 to −2000 m) and the bottom (−3000 m to −5000 m)) for glacial simulations with brines, stratification-dependant diffusion and iron fertilization (carbonate compensation is included). The three varying parameters are: (c) *frac* (brine mechanism), (d) *alpha* (stratification-dependant diffusion) and (e) *iron* (iron fertilization). LGM-CC is the simulation with *frac* = *iron* = *alpha* = 0. Simulations that match the LGM data are highlighted with colors.

realize a large number of runs that are long enough to reach an equilibrium for the carbon cycle. Simulations were run for 50,000 years, but most of the CO₂ changes are reached by 10,000 years (less than 7 ppm change after 10,000 years). CLIMBER-2 includes a model of deep ocean carbonate sediments necessary to estimate the effect of carbonate compensation [Archer, 1991; Brovkin *et al.*, 2007]. The LGM conditions imposed are the glacial solar insolation [Berger, 1978], ice sheets [Peltier, 2004], and atmospheric CO₂ [Monnin *et al.*, 2001] for the radiative code (190 ppm, not used in the carbon cycle part of the model). To account for the ~120 m sea level fall, salinity and nutrient mean concentrations are increased by 3.3%. With these glacial conditions, despite the colder temperature and less intense thermohaline circulation, atmospheric CO₂ increases to 298 ppm (LGM simulation) mainly because of the reduced terrestrial biosphere (loss of 640 GtC compared to the pre-industrial). When carbonate compensation is included (LGM-CC) CO₂ decreases to 257 ppm as the carbonate

compensation mechanism amplifies the oceanic uptake of carbon, which was previously analyzed in more detail [Brovkin *et al.*, 2007]. Further to carbonate compensation, three mechanisms are tested: the brine mechanism, iron fertilization and stratification-dependant diffusivity.

[7] The brine mechanism is a simple parameterization of the deep sink linked to the release of very salty water (brines) during the formation of sea ice [Bouttes *et al.*, 2010]. In the standard version of CLIMBER-2, the flux of salt released into the ocean is diluted in the first oceanic cell which is quite big due to the coarse resolution. Yet, as brines are very dense because of the high salinity, they should rapidly sink to the deep ocean favored by the glacial conditions in the Southern Ocean. This brine sink has been parameterized in CLIMBER-2 [Bouttes *et al.*, 2010]. The relative importance of the brine mechanism is set by the parameter *frac*, which is the fraction of salt released by sea ice formation that sinks to the bottom of the ocean. The rest of the salt (1 − *frac*) is diluted in the corresponding surface oceanic cell. When *frac* = 0 no salt sinks to the abyss (standard simulation), whereas *frac* = 1 is the maximum effect when all the rejected salt sinks to the bottom of the ocean. This mechanism was shown to result in a net glacial CO₂ decrease with a maximum drop of 52 ppm and increased Atlantic Δδ¹³C_{ocean} (1.2‰) (LGM-brines).

[8] Iron fertilization is taken into account in the model by forcing biology to use a fraction (parameter *iron*) of the nutrients that would otherwise be left in the Atlantic and Indian sectors of the Sub-Antarctic surface ocean (30°S to 50°S) [Brovkin *et al.*, 2007]. The *iron* parameter represents the importance of iron fertilization. It can vary between 0 (no iron fertilization) and 1 (maximum iron fertilization, all nutrients in the area are consumed).

[9] Finally the stratification-dependant diffusivity relies on the parameterization of the vertical diffusion coefficient (*K_z*) according to the stratification. In the standard version of CLIMBER-2 the vertical diffusion coefficient profile is prescribed. Yet a more physical representation of the diffusion can play a great role for the ocean [Marzeion *et al.*, 2007] and potentially influence the carbon cycle [Bouttes *et al.*, 2009], as the more the ocean is stratified, the more *K_z* should be reduced. We thus introduce a physical parameterization of the vertical diffusion coefficient *K_z* depending on the vertical density gradient [Marzeion *et al.*, 2007] in the deep ocean (below 2000 m):

$$K_z = K_0 \left(\frac{N}{N_0} \right)^{-\alpha} \quad (1)$$

where α , K_0 and N_0 are parameters, and $N = \left(-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \right)^{\frac{1}{2}}$ is the local buoyancy frequency, with g the gravity acceleration, ρ_0 a reference density, and $\frac{\partial \rho}{\partial z}$ the vertical density gradient. The parameter α controls the sensitivity of the vertical diffusivity to changes in stratification. Its value depends on local conditions and is thus not experimentally constrained on a global scale. In the study we vary α between 0 ($K_z = K_0 = 1. \times 10^{-4} \text{ m}^2/\text{s}$) and 1.

[10] The importance of each of the three mechanisms is set by a parameter (*frac*, *iron* and α) between 0 (absence of mechanism) and 1 (maximum mechanism). We realize two ensembles of LGM simulations where the ocean, land and atmosphere carbon and δ¹³C reservoirs fully interact

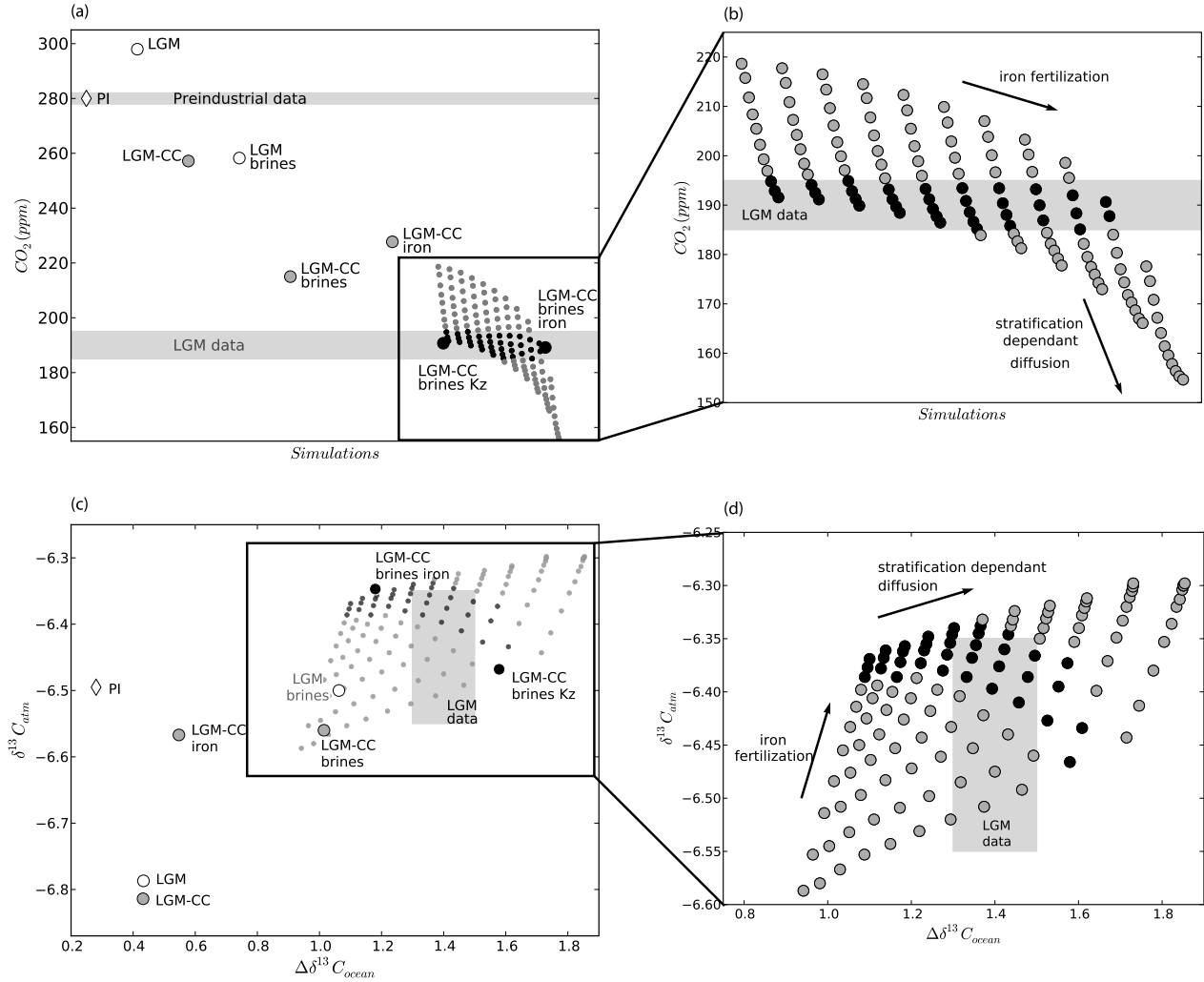


Figure 2. Atmospheric (a and b) CO₂ (ppm) and (c and d) $\delta^{13}\text{C}_{\text{atm}}$ vs $\Delta\delta^{13}\text{C}_{\text{ocean}}$ (‰) for LGM simulations with various mechanisms as compared to proxy data. Figures 2a and 2c: *LGM* (standard simulation) and *LGM brines* (with brines: $\text{frac} = 0.6$) are without carbonate compensation (CC). All the other simulations take CC into account. *LGM-CC* is the standard simulation with CC, *LGM-CC brines* with brines ($\text{frac} = 0.6$) and *LGM-CC iron* with the maximum iron fertilization ($\text{iron} = 1$). Two simulations reach the LGM data level: *LGM-CC brines K_z* with brines ($\text{frac} = 0.6$) and stratification-dependant diffusion ($\alpha = 0.9$), and *LGM-CC brines iron* with brines ($\text{frac} = 0.6$), and iron fertilization ($\text{iron} = 1$). Figures 2b and 2d: zoom for the ensemble of *LGM* simulations ($\text{frac} = 0.6$). The relative importance of iron fertilization (parameter iron between 0 and 1) and of the stratification-dependant diffusion (parameter α between 0 and 1) varies in the simulations. Simulations within the range of LGM data are in black. The preindustrial simulation (*PI*) is indicated with a diamond.

to assess the relative importance and role of each of the mechanisms in line with proxy data. In the first one (150 simulations) all parameters vary, which enables us to infer the range of possible values for frac (brines) when comparing the results with proxy data. With the second ensemble (120 simulations) the two other parameters only (iron and α) vary with better resolution, so that we narrow the range and find nine sets of parameters that match glacial proxy data. We then analyze them to understand the modeled CO₂ drawdown.

3. Results and Discussion

[11] As already studied [Brovkin et al., 2007], the *LGM-CC* simulation gives results that mismatch the data with CO₂ = 257 ppm, $\Delta\delta^{13}\text{C}_{\text{ocean}} = 0.43\text{‰}$ and $\delta^{13}\text{C}_{\text{atm}} = -6.8\text{‰}$

compared respectively to 190 ppm, 1.4‰ and -6.45‰ in the data. The addition of the sinking of brines, stratification-dependant diffusion and iron fertilization further decreases CO₂ and increases $\Delta\delta^{13}\text{C}_{\text{ocean}}$ (Figure 1). The sinking of brines creates a deep isolated oceanic carbon reservoir, mainly because of the stratification induced by the transport of salt as explored by Bouttes et al. [2010]. The interactive diffusion amplifies the brine mechanism effects. Because of the enhanced stratification the vertical diffusion coefficient is reduced down to $0.1 \times 10^{-4} \text{ m}^2/\text{s}$ in the deep (below 3000 m) Atlantic ocean. The vertical mixing is reduced which further isolates the deep water mass. The lower part of the meridional circulation is then less intense.

[12] The first ensemble shows that the frac parameter should lie between 0.4 and 1 to match the data. Yet $\text{frac} = 1$ is extreme and physically unrealistic as observations indi-

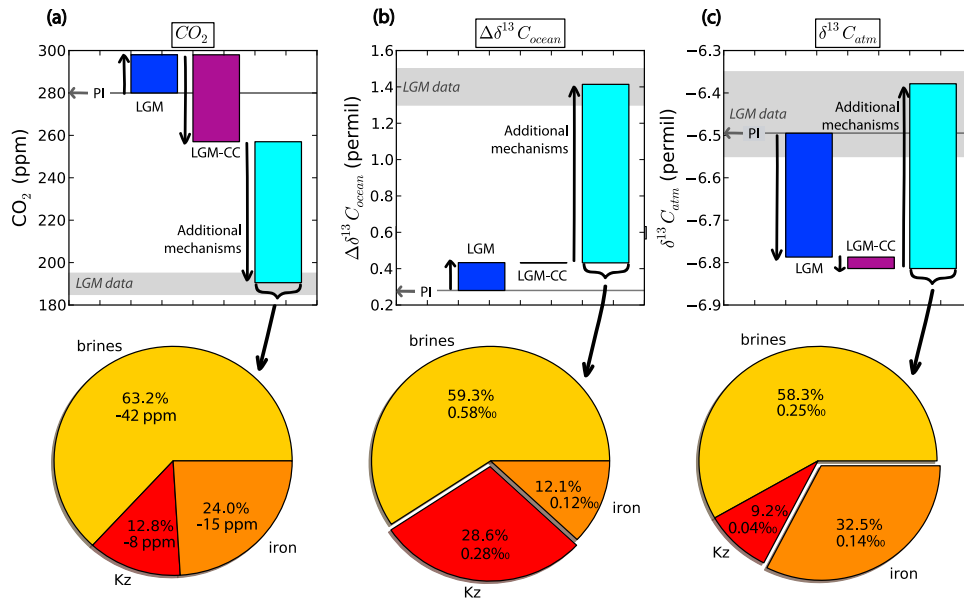


Figure 3. Change of (a) atmospheric CO₂, (b) Δδ¹³C_{ocean}, and (c) δ¹³C_{atm} for the control glacial simulation (*LGM*, from the preindustrial simulation *PI*), the glacial simulation with carbonate compensation (*LGM-CC*) and the glacial simulations with all considered mechanisms (mean of the nine simulations that agree best with the data). For the latter, the relative roles of the three additional mechanisms (brine induced stratification (*brines*), stratification-dependant diffusion (*K_z*) and iron fertilization (*iron*)) are given.

cate that only ~82% of the salt is released into the ocean during sea ice formation [Haarpaintner *et al.*, 2001]. Hence the *frac* range is more probably between 0.4 and 0.8. Such values are supported by modern observations such as measures in the Arctic fjords. Indeed, 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.

[13] The second ensemble thus focuses on cases with the median value from the inferred range of *frac* (*frac* = 0.6). We vary the parameters for iron fertilization (*iron*) and the stratification-dependant diffusion (*α*). In nine of these simulations the model simulates simultaneously the atmospheric CO₂ and δ¹³C in agreement with data (Figure 2). To disentangle the effects of these mechanisms we study their impacts when they are alone and in synergy.

[14] The glacial CO₂ level can be reached either with the brine mechanism and stratification-dependant diffusion or with the brine mechanism and iron fertilization. The addition of interactive diffusion to the brine mechanism (*LGM-CC brines K_z*) amplifies its effects. Because of the brine induced stratification, *K_z* is decreased and the vertical mixing reduced, which further decreases CO₂. Alternatively, iron fertilization associated to the brine mechanism also decreases CO₂ (*LGM-CC brines iron*). Yet the processes involved are different: the stratification-dependant diffusion amplifies the brine effect whereas the iron fertilization effect almost linearly adds to the brine one. However for Δδ¹³C_{ocean} the two simulations give results that disagree with the data, (respectively ~1.6‰ and ~1.2‰ compared to 1.4‰ in the data). As the data indicate that the “best” simulation should lie between the two considered ones, it clearly appears that both iron fertilization and the stratification-dependant diffusion have a role to play, as it is the

case for the nine simulations that match simultaneously the three data values.

[15] For these nine simulations that agree best with the data, we assess the relative role of the three additional mechanisms (brines, stratification-dependant diffusion and iron fertilization) in the CO₂ and δ¹³C changes (Figure 3) by successively adding them. The effect of brines alone (*LGM-CC brines*) is a ~42 ppm CO₂ decrease (to 215 ppm). If we add the stratification-dependant diffusion, the additional CO₂ drop is ~8 ppm (between 5 and 12 ppm). With iron fertilization the CO₂ decrease is ~15 ppm (between 10 and 21 ppm). It results that brines play a valuable role both for the CO₂ and δ¹³C modifications (around 60%). The other two mechanisms further decrease CO₂, the interactive diffusion appears important mostly for the Δδ¹³C_{ocean} and iron fertilization for δ¹³C_{atm}. In addition, our estimated effect for the iron-induced changes in CO₂ (10–20 ppm) lies well within previous estimates based on more complex ocean and biogeochemical models (10–25 ppm) [Bopp *et al.*, 2003; Tagliabue *et al.*, 2009]. The simulated Atlantic δ¹³C distribution is in better agreement with data with low values below 3000 m (between 0 and −0.8‰).

4. Conclusion

[16] In conclusion, after accounting for the carbonate compensation, brine mechanism, iron fertilization and stratification-dependant diffusion we can simultaneously reconcile the LGM CO₂ and δ¹³C. Indeed, not only can we simulate the low glacial CO₂ level of ~190 ppm, but the results are also consistent with the crucial proxy data for the carbon cycle that are δ¹³C in the atmosphere and ocean. The brine mechanism plays a major role in this additional change as it accounts for approximately 60% of it. Finally,

the mechanisms involved remain to be tested together in a fully coupled GCM as well as during transitions.

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L. Bopp, N. Bouttes, and D. Paillard, Laboratoire des Sciences du Climat et de l'Environnement, IPSL/CEA-CNRS-UVSQ, Orme des Merisiers, Gif-sur-Yvette, F-91191, France. (nathaelle.bouttes@lscce.ipsl.fr)

V. Brovkin, The Land in the Earth System, Max-Planck-Institute for Meteorology, Bundesstr. 55, Hamburg, D-20146, Germany.

D. M. Roche, Section Climate Change and Landscape Dynamics, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 Amsterdam, Netherlands.