

Southern control of interhemispheric synergy on marine carbon sequestration during glacial cycles

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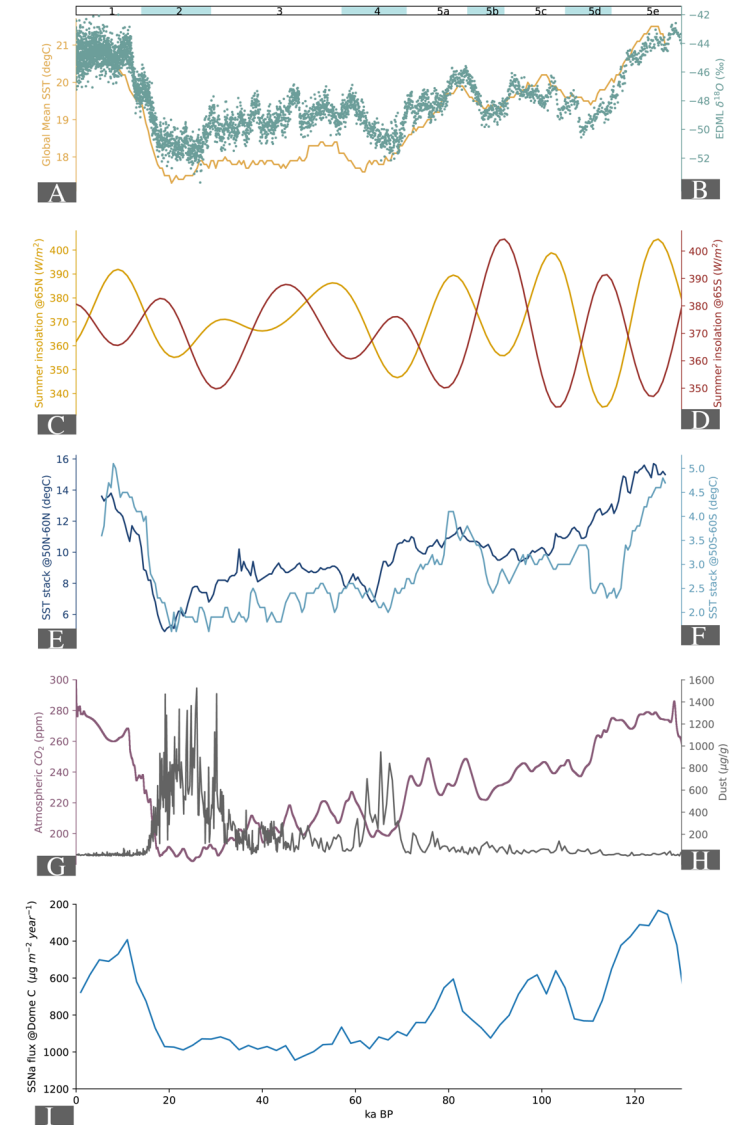
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Background

1. Glacial atmospheric $p\text{CO}_2$ ($p\text{CO}_2^{atm}$) decreases by ~ 90 ppm and showed 2 main stages (glacial inception, glacial maxima).
2. Processes in the Southern Ocean (SO) have been suggested to be at the heart (including deep-stratification, sea ice “barrier effect”, and iron fertilization), while the North Atlantic (NA) is recently proposed to be critical via the enhanced solubility pump during glacial periods as well. However, in a full course of glacial cycles, **the individual and synergic roles** of these two regions remain enigmatic.
3. The effects of a specific process may vary due to different background climate conditions.

Target

- ✓ To figure out **the individual and synergic roles** of SO- and NA-related processes in a full course of glacial cycles based on model results



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Model description __ MITgcm-REcoM2

1. for detailed model description, please refer to the following studies:

Hauck, J. et al. Seasonally different carbon flux changes in the Southern Ocean in response to the southern annular mode. *Global Biogeochem. Cycles* 27, 1236–1245 (2013).

Hauck, J. & Völker, C. Rising atmospheric CO₂ leads to large impact of biology on Southern Ocean CO₂ uptake via changes of the Revelle factor. *Geophys. Res. Lett.* 42, 1459–1464 (2015).

Ye, Y. & Völker, C. On the Role of Dust-Deposited Lithogenic Particles for Iron Cycling in the Tropical and Subtropical Atlantic. *Global Biogeochem. Cycles* 31, 1543–1558 (2017).

2. an interactive pCO_2^{atm} box is implemented to REcoM2 to ensure the total carbon in the air-sea carbon cycle is conservative in all runs.
3. In *_nice runs, sea ice was formed in the same way as in the corresponding simulations without _nice but the sea ice cover does not prevent gas exchange.

Experimental design

IG_ctl: the interglacial control run based on pre-industrial physics and present-day biogeochemistry;

IG_Gso: SO cooling to the glacial state

IG_Gna: NA cooling to the glacial state

IG_Gns: SO & NA cooling to the glacial state

IG_Gd: applying the glacial SO dust deposition to IG_ctl

IG_Gnsd: applying the glacial SO dust deposition to IG_Gns

G_ctl: the glacial (maximum) control run

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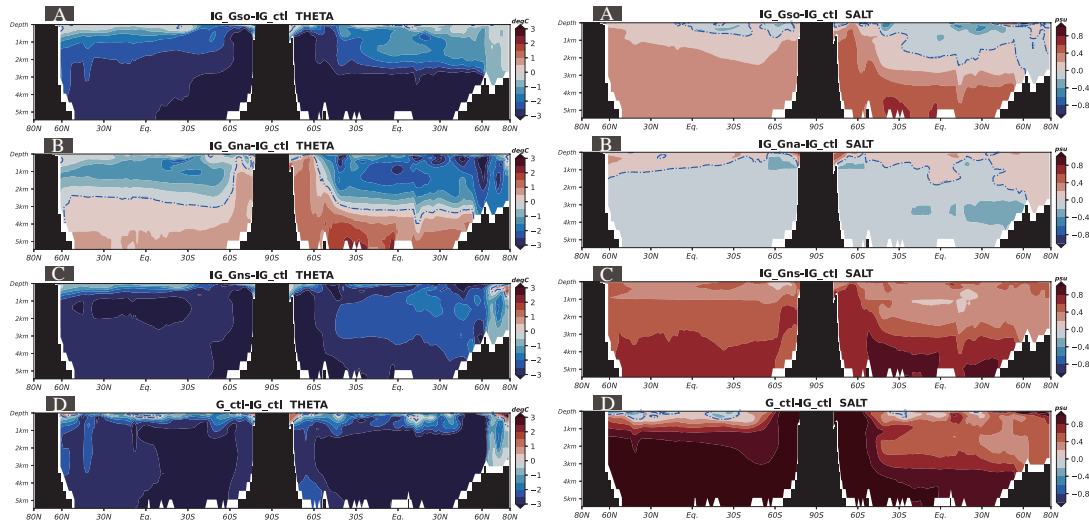


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Distinct pCO_2^{atm} responses to SO/NA surface cooling

- 1. pCO_2^{atm} in IG_Gso shows a considerable decrease of 21.97 ppm comparing to IG_ctl, whereas a slight increase of 5.56 ppm is obtained in IG_Gna. Notably, pCO_2^{atm} draw-down of 26.55 ppm in IG_Gns is not simply the sum of IG_Gso and IG_Gna (-21.97+5.56=-16.41ppm), but significantly larger, indicating a synergetic interplay of processes in SO and NA in carbon sequestration.
- 2. In IG_Gso, cooling the SO facilitates the establishment of deep stratification and efficiently lowers the exposure time of the SO surface water (exposure time in IG_ctl, IG_Gso, IG_Gns, G_ctl is 315, 76, 58, and 26 days), suppressing CO₂ outgassing. In IG_Gna, drastic cooling of the NA leads to break-down of the deep stratification and hence the deep carbon leakage.
- 3. the SO-determined stratification would hinder the diapycnal mixing between the two overturning cells, such that excess carbon from the enhanced NA solubility pump can be stored in the ocean.

Exp.name	SO		NA		$p\text{CO}_2^{atm}$ (ppm)	diff. (ppm)	Use (_nice)
	dust	SST	dust	SST			
diff.: difference with respect to IG_ctl							
Use(_nice).: difference with respect to original setup							
IG_ctl	IG	IG	IG	IG	276.70	–	-1.42
IG_Gso	IG	G	IG	IG	254.73	-21.97	-1.98
IG_Gna	IG	IG	IG	G	282.26	+5.56	-1.64
IG_Gns	IG	G	IG	G	250.15	-26.55	+2.38
IG_Gd	G	IG	IG	IG	263.77	-12.93	–
IG_Gnsd	G	G	IG	G	235.56	-41.14	–
G_ctl	G	G	G	G	223.65	-53.05	+5.63



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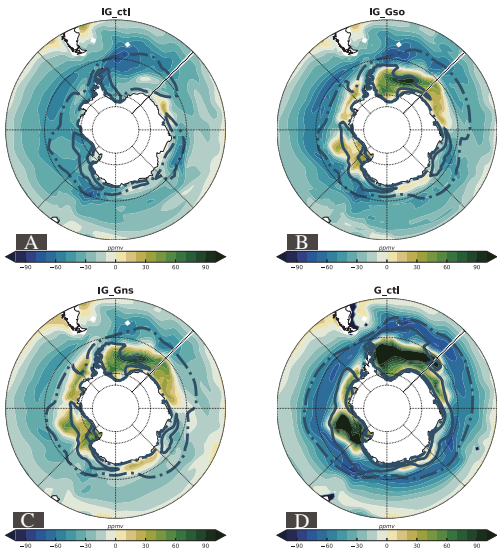


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Climate-dependent roles of the SO sea ice barrier effects

- Under the full glacial condition (G_nice vs. G_ctl), the barrier effect lowers pCO_2^{atm} by 5.63 ppm, Under the interglacial condition (IG_nice vs. IG_ctl), the barrier effect slightly reduces the ocean uptake of CO₂ by 1.42 ppm. Similar pCO_2^{atm} changes are obtained in comparing the SO/NA cooling experiments (IG_Gso/IG_Gsonice, IG_Gna/IG_Gnalice). Only if both the SO and the NA are cooled to the glacial state and pCO_2^{atm} is sufficiently low (IG_Gns vs. IG_Gnsnice) would the barrier effect act to lower pCO_2^{atm} by 2.38 ppm.
- Not only the extension of sea ice cover plays a role, but also the tendency of potential carbon exchange beneath the ice cover to CO₂ uptake or outgassing, which can be seen in the sea surface-air pCO₂ difference.

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contours: annual-mean sea ice concentration of 0.9(solid) and 0.15(dashed)

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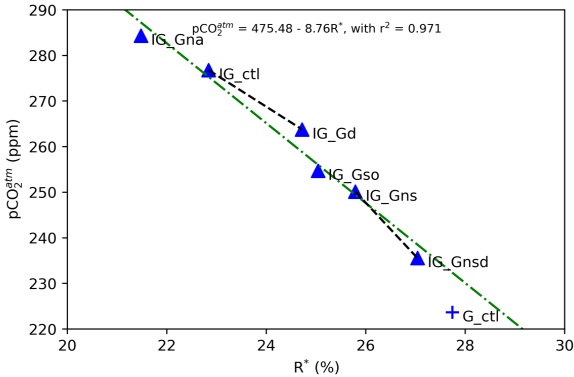
Iron fertilization and southern contribution to global export production

- Applying the glacial (LGM) SO dust deposition map to the inter-glacial condition (IG_Gd) results in a pCO_2^{atm} draw-down of 12.93 ppm. Together with the cooling of SO/NA, pCO_2^{atm} in IG_Gnsd decreases by 41.14 ppm compared to IG_ctl and by 14.59 ppm compared to the run without glacial iron fertilization (IG_Gns).
- We found a clear negative relationship between R^* = $\frac{EP(SO)}{EP(Global)} \times 100\%$ and pCO_2^{atm} : $pCO_2^{atm} = 475.48 - 8.76 \times R^*$, with $r^2 = 0.971$
- Among the well aligned R^* vs pCO_2^{atm} pairs, the slope between IG_ctl/IG_Gd is clearly less steep than that between IG_Gns/IG_Gnsd, indicating that pCO_2^{atm} is more sensitive to R^* variation under cold conditions.

Exp.name	SO		NA		$p\text{CO}_2^{atm}$ (ppm)	diff. (ppm)	Use (_nice)
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IG_Gnsd	G	G	IG	G	235.56	-41.14	–
G_ctl	G	G	G	G	223.65	-53.05	+5.63

Exp.name	EP(Global)	EP(SO)	$\frac{EP(SO)}{EP(Global)} \times 100\%$	pCO_2^{atm}
IG_ctl	6.05	1.38	22.84%	276.70
IG_Gso	6.31	1.58	25.04%	254.73
IG_Gna	6.56	1.41	21.48%	284.36
IG_Gns	6.32	1.63	25.79%	250.15
IG_Gd	6.21	1.53	24.72%	263.77
IG_Gnsd	6.69	1.81	27.04%	235.56
G_ctl	4.63	1.28	27.74%	223.65

EP was calculated in $PgCyr^{-1}$, where $1PgC = 1 \times 10^{15}gC$.



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Southern control of the stepwise glacial pCO_2^{atm} draw-down

1. At the end of glacial inceptions (IG_Gso), cooling in SO contributes to a larger portion of CO_2 draw-down than cooling in NA, by shortening the surface water exposure time and facilitating deep carbon trapping, while the early sea ice expansion tends to weaken the carbon uptake (IG_ctlnice).
2. The efficiency of surface carbon storage in the North Atlantic depends on the volume of Antarctic bottom water (IG_Gna) and reaches its maximum when the glacial stratification is well developed during glacial maxima (IG_Gns).
3. SO cooling and sea ice expansion strongly promote the formation of AABW and the full development of glacial stratification (IG_Gns, G_ctl). Increased dust deposition during the glacial maxima (IG_Gnsd, G_ctl) raises the contribution of the SO in the global biological carbon pump. Moreover, the maximally expanded sea ice suppresses local carbon leakage (IG_Gnsdnice, G_nice).

