Vol. 26(3):501-506 | Ocean and Polar Research | September 2004

Article

Implication of the Change in Overturning Circulation to the LGM CO_2 Budget

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Abstract : The observational proxy estimates suggest that the North Atlantic overturning stream function associated with the North Atlantic Deep Water (NADW) production and outflow was substantially weaker during the last glacial maximum (LGM) than that observed under present conditions. The impact of the changes in overturning circulation on the glacial carbon budget is investigated using a box model. The carbon box model reveals that the atmospheric CO_2 concentration is more sensitive to change in the overturning circulation of the North Atlantic than that of the Southern Ocean, especially when North Atlantic overturning becomes weaker. For example, when the strength of the North Atlantic overturning circulation is halved, the atmospheric CO_2 concentration is reduced by 50 ppm of that associated with the accumulation of CO_2 in the deep ocean. This result implies that a weaker North Atlantic overturning circulation may play an important role in the lowering of LGM atmospheric CO_2 concentration.

Key words : LGM CO_2, overturning circulation, numerical simulation, box model, NADW

1. Introduction

The atmospheric CO_2 concentration influences and is influenced by global climate change. The most recent glacial event, known as the last glacial maximum (LGM) 21,000 years ago was associated with a reduction in atmospheric CO_2 concentration, at least partially due to a change in the oceanic carbon system. Analyses of gas bubbles trapped in ice cores reveal that the atmospheric CO_2 concentration was about 80 ppm lower during the LGM than in the pre-industrial period (Barnola *et al.* 1987). Many theories and hypotheses have been proposed to explain this ice age CO_2 change, yet there is no consensus on the cause (see Broecker and Henderson 1998 for review). Nevertheless, there is a general agreement that a change in the ocean carbon system must have been responsible for at least some part of this glacial CO_2 change.

Reduced ocean temperatures during the LGM increase the solubility of CO_2 gas and contribute to the reduction in atmospheric CO_2. However, CO_2 reduction due to the colder ocean is in large part offset by the increase in salinity and by the reduction in terrestrial carbon storage. Other processes may also be responsible for the reduced CO_2 levels. One proposed mechanism is based on ocean chemistry change, but this process fails to either produce the magnitude of the atmospheric CO_2 change (Sigman and Boyle 2000) or match the CO_2 fluctuation timing, which is rather abrupt (Broecker and Henderson 1998). Another popular hypothesis is associated with the change in biological activity in the Southern Ocean. As revealed in box models (Knox and McElroy 1984; Sarmiento and Toggweiler 1984; Siegenthaler and Wenk 1984), the level of glacial CO_2 reduction (~80 ppm) could be readily obtained through only a slight increase in biological productivity in the Southern Ocean. This hypothesis, however, suffers from the lack of observational proxy evidence and is hard to justify for the LGM because, in the present Southern Ocean, the biological activity is limited by parameters other than the supply of nutrients (Sigman and Boyle 2000 and references therein). Alternatively, researchers have proposed that the change in deep ocean thermohaline circulation or ventilation in the Southern Ocean might play an important role in

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*Corresponding author. E-mail : seongjkim@kopri.re.kr lowering the LGM CO_2 (e.g., Toggweiler 1999; Francois *et al.* 1997).

In the present ocean, the thermohaline circulation is largely comprised of two distinct water masses: relatively warm and saline North Atlantic Deep Water (NADW) and relatively cold and fresh Antarctic Bottom Water (AABW) (Warren 1981; Killworth 1983). Formed in the Greenland, Iceland, and Norwegian (GIN) Seas and the Labrador Sea (Dickson and Brown 1994), NADW flows to the Southern Ocean and mixes with the lower part of Circumpolar Deep Water (LCDW). The formation of NADW ranges from 13 Sv to 15 Sv (Dickson and Brown 1994; Schmitz and McCartney 1993; Ganachaud and Wunsch 2000). The outflow of NADW tends to increase slightly to the south (e.g., ~17-20 Sv at 30°S) by entrainment of underlying water mass (Rintoul 1991). Flowing eastward along the Antarctic Circumpolar Current, warm, saline, and nutrient-poor LCDW spreads northward into the Indian and Pacific oceans. A fraction of LCDW also upwells slowly along the Antarctic continental margin and influences the formation of AABW (Whitworth *et al.* 1998).

AABW is formed in the Weddell Sea, Ross Sea, and along the Adelie Coast (Gill 1973; Foster and Carmack 1976; Rintoul 1998) and mixes with LCDW as it descends to the bottom and spreads northward, filling the abyssal basins of the Atlantic, Indian, and Pacific Oceans (Orsi *et al.* 1999). The observed estimates of the AABW formation ranges from 5 to 10 Sv (Orsi *et al.* 1999) although the uncertainty of these values is high in comparison to that of NADW. A portion of AABW and LCDW in the Indian-Pacific basins re-circulates to the south (Sloyan and Rintoul 2001) and ventilates at the south of the Antarctic Polar Front, forming the upper part of CDW (UCDW) with oxygen poor and nutrient rich characteristics (Sivers and Nowlin 1984). The rate of ventilation in the Southern Ocean is largely determined by the strength of the westerly winds over the ACC regime (Toggweiler and Samuels 1995).

Based on geological and geochemical proxy data, enormous efforts have been made to determine the nature of glacial thermohaline circulation changes. The preponderance of the proxy evidence suggests that the NADW formation was generally weaker and shallower during the LGM than at present (Table 1). In the North Atlantic, a large portion of NADW was replaced by water originating in the Southern Ocean with characteristics of substantially increased nutrient concentrations (Duplessy *et al.* 1980, 1988; Boyle and Keigwin 1982, 1987). Some numerical studies have also exhibited the reduction in the overturning circulation associated with NADW in the LGM (e.g., Fichefet *et al.* 1994; Weaver *et al.* 1998; Kim *et al.* 2003). In comparison to that of NADW, the observational proxy estimates of the glacial AABW formation and outflow are not consistent and the uncertainty is large. Nevertheless, there is some indication of a continuous glacial-age formation of AABW and enhancement of its outflow toward the Pacific basin (Hall *et al.* 2001).

This study hypothesizes that the change in the thermohaline circulation during the LGM might influence the global carbon budget. The objective of this study is to examine how the changes in oceanic thermohaline circulation impact the glacial/interglacial atmospheric pCO_2 variations using a box carbon model.

2. Box carbon model and method

The carbon model used in the current study is the seven-box model introduced by Toggweiler (1999) (hereafter T99). Fig. 1 depicts the structure of the box model where box **l** represents the low-latitude surface waters, box **n** the northern North Atlantic, box **m** the intermediate layer, box **a** the Atlantic deep ocean, box **d** the Indo-Pacific deep ocean, box **p** the Antarctic surface waters, and box **s** the sub-Antarctic surface waters. The long arrows depicted by *NA* represent the global conveyor (overturning) circulation, which is initiated in the North Atlantic and flows to the Atlantic and Indo-Pacific basins and eventually returns to

Table 1. Observed North Atlantic Deep Water production in the LGM.

Production	Method	References
Reduced	$\delta^{18}O$	Dupplessy *et al.* (1980)
	Cd/Ca and $\delta^{13}C$	Boyle and Keigwin (1982; 1987); Oppo and Horowitz (2000) Curry and Lohman (1982); Oppo and Fairbanks (1987);
	$\delta^{13}C$	Dupplessy *et al.* (1988); Curry *et al.* (1988); Sarnthein *et al.* (1994)
	Neodymium	Rutberg *et al.* (2000)
Slightly reduced	Cd/Ca	Boyle (1992); Oppo and Rosenthal (1994)
Similar to present	Pa/Th	Yu *et al.* (1996)

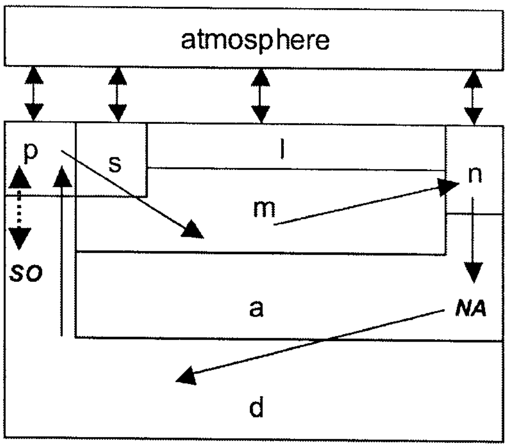

Fig. 1. Schematic diagram of the seven-box model adapted from Toggweiler (1999). The long arrows represent the overturning circulation originated in the North Atlantic and the thick dotted line indicates the southern high latitude mixing term associated with the formation and outflow of AABW.

the North Atlantic via the Southern Ocean as illustrated in section 1. The thick dotted line represents the southern high latitude mixing term associated with AABW production and outflow. In the box model, the *SO* together with the upwelling part of *NA* overturning represents the ventilation over the Southern Ocean.

Differences from the original seven-box model used in T99 include the volume of box **a**. In T99, box **a** was larger than box **d**, while in this study it becomes much smaller by about one third of box **d** and mimics the actual Atlantic Ocean. The southern high latitude sinking flux in the sub-Antarctic (**s**) box was a free-parameter in T99, varying from 0.075 to 7.5 moles C m yr^{-1}, but in this study, it was fixed at 1.5 moles C m^{-2} yr^{-1}. This is slightly larger than the polar (**p**) box of 1.0 moles C m^{-2} yr^{-1} but smaller than that of the **n** box (2.5 moles C m^{-2} yr^{-1}). Note that the observational uncertainties of these parameters are high. A more detailed description of the model is found in T99.

The sensitivity of the partial pressure of atmospheric pCO_2 to the change in overturning circulations originated in the North Atlantic and Southern Ocean is tested using the box model. In this study, the thermohaline or conveyor circulation is referred to as the overturning circulation. When the pCO_2 sensitivity associated with variations in production of the other water mass is estimated, the values of one or the other of the NADW and AABW productions are fixed at 20 Sv and 25 Sv, respectively. The values of the NADW and AABW productions are from recent observed estimates, though their uncertainties are relatively large.

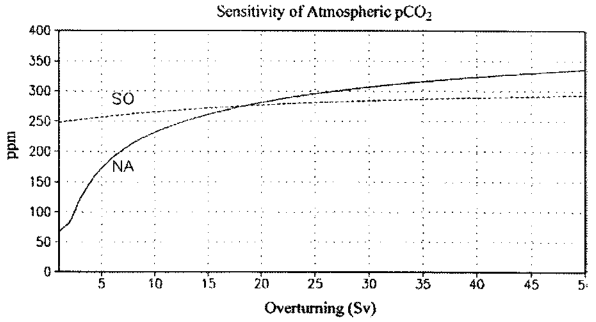

Fig. 2. Sensitivity of atmospheric partial pressure of CO_2 to changes in overturning circulation in the North Atlantic (solid) and the Southern Ocean (dotted).

3. Results

As described in section 1, paleoclimate proxy estimates reveal that during the LGM, the North Atlantic overturning circulation was markedly reduced and presumably the role of the Southern Ocean overturning was enhanced. The sensitivity of the partial pressure of atmospheric pCO_2 to the change in overturning circulations originated in the North Atlantic and Southern Ocean is displayed in Fig. 2.

In both cases, atmospheric pCO_2 increases with the strength of the overturning circulation. In response to changes in Southern Ocean overturning between 0 to 50 Sv, the pCO_2 varies from 250 ppm to about 290 ppm. Much larger pCO_2 changes from 70 ppm to 330 ppm are found in response to similar change in North Atlantic overturning, especially when the NA overturning circulation becomes weaker than in present conditions (~20 Sv). The sensitivity of atmospheric pCO_2 appears to be larger than that of the Southern Ocean due to changes in the North Atlantic overturning circulation. This result suggests that the weaker North Atlantic overturning in the LGM, broadly supported by the observed proxy evidence, brings about a significant decrease in atmospheric pCO_2.

In order to investigate the impact of the reduced North Atlantic overturning circulation on the pCO_2 concentration as well as other properties (e.g., Phosphate, Oxygen, and $\delta^{13}C$, etc.), a sensitivity experiment with NADW productions reduced by 50% is performed. Fig. 3 compares the results of CO_2, PO_4, O_2, and $\delta^{13}C$ concentrations between current circulation levels and those of the reduced North Atlantic overturning levels. The modern solution features the North Atlantic overturning specified at 20 Sv. This value roughly matches observational estimates. In the reduced case, the strength of the North Atlantic overturning is reduced to 10 Sv. It is notable that, in the current structure

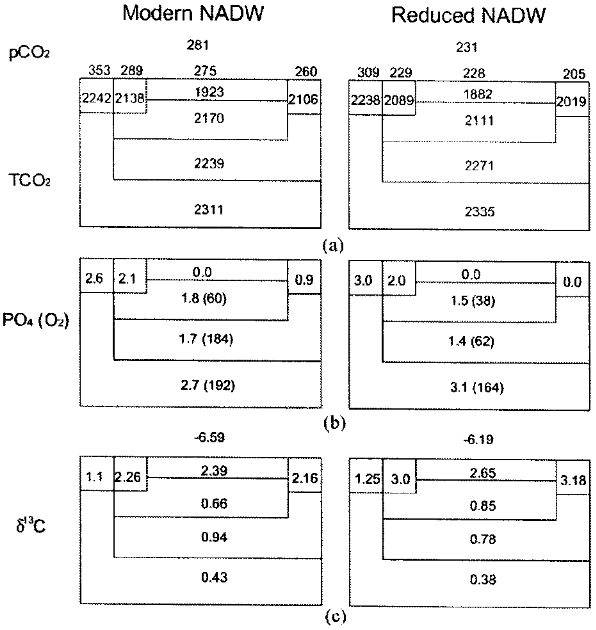

Fig. 3. Results of the seven-box model for (a) CO_2, (b) PO_4 and O_2, and (c) $\delta^{13}C$ for the modern North Atlantic overturning circulation (20 Sv) and reduced circulation to half the modern value. Units are μmoles kg^{-1} for CO_2, PO_4, and O_2 and per mil for $\delta^{13}C$.

of the box model, the Southern Ocean ventilation depends on both the strength of the North Atlantic and Southern Ocean overturning circulation. Thus, the reduction in North Atlantic overturning leads to a reduction in ventilation in the Southern Ocean. This may not necessarily be the case for the real ocean where the Southern Ocean ventilation is largely determined by the strength of westerly wind stress. For both cases in Fig. 3, the overturning in the Southern Ocean is fixed at 25 Sv and there is no change in biological productivity.

With the 50% reduction in North Atlantic overturning, the atmospheric CO_2 concentration drops by 50 ppm. This value is larger than that observed in previous studies. For example, using the Hamburg Ocean Carbon Cycle Model, Heinze *et al.* (1991) obtained a reduction in pCO_2 by ~25 ppm in response to the decrease in ocean ventilation. Using a five-box carbon cycle model, Schulz *et al.* (2001) applied a significant reduction in North Atlantic circulation and obtained ~35 ppm reduction in the atmospheric pCO_2 level. The reduction in pCO_2 in this study is associated with a reduction of CO_2 in the upper boxes, while CO_2 in the Atlantic and deep boxes increases by 20-30 μmoles kg^{-1}. This response is in part, but not solely, due to the reduced Southern Ocean ventilation associated with weaker North Atlantic overturning.

In addition to the atmospheric CO_2 concentration, the oxygen content and nutrient concentrations are prognostic variables in the box model and the way they are solved in the model is illustrated in T99 in detail. The nutrient concentration, which is represented by PO_4 concentration in the current set up of the box model, decreases slightly, except in boxes **d** and **p** where it increases slightly. The oxygen decreases overall as would be expected with the reduced overturning, especially in box **a**. Nevertheless, boxes **a** and **d** are fairly well oxygenated in the reduced NADW case and this is consistent with observed glacial estimates (Broecker and Peng 1982). The simulated atmospheric $\delta^{13}C$ increases by 0.4 per mil as a result of the halving of the North Atlantic overturning. This result is in contrast to observed estimates, which suggest it was more negative by 0.3-0.7 per mil during the LGM (Leubenberger *et al.* 1992; Marino *et al.* 1992). Other mechanisms such as the change in ocean temperature and terrestrial biosphere effects are required to explain this discrepancy. For example, Curry *et al.* (1988) suggested that a terrestrial biosphere effect may produce about a 0.35 per mil reduction in atmospheric $\delta^{13}C$ (see also T99 for a more detailed description). The $\delta^{13}C$ in the deep box decreases slightly, but the magnitude of the change is less than that suggested by observational proxy (~–0.5 per mil from Boyle 1992).

4. Summary and conclusion

The seven-box model introduced by Toggweiler (1999) is adopted to examine the implications of change in overturning circulation for the LGM carbon budget. The atmospheric pCO_2 level varies more dramatically than that of the Southern Ocean due to changes in North Atlantic overturning circulation. This is particularly the case when the North Atlantic overturning circulation becomes weaker, implying a significant role for weaker NADW in the lowering of atmospheric CO_2 concentrations. For example, when the North Atlantic overturning circulation weakens to 50%, the atmospheric pCO_2 level drops by 50 ppm. This is associated with changes in oceanic CO_2 concentrations, which are reduced at surface boxes, while tending to accumulate in the deep boxes. This is in part due to the reduction in ventilation in the Southern Ocean. Other supplementary mechanisms such as changes in solubility, ocean chemistry, and Antarctic sea ice cover (Stephens and Keeling 2000) also partially explain the LGM CO_2 changes.

In conclusion, the weaker and shallower North Atlantic overturning circulation during the LGM possibly plays an important role in the lowering of atmospheric CO_2.

Acknowledgements

Valuable comments from Duke colleagues, especially Paul Baker, Thomas Crowley, Bruce Corliss, Gary Dwyer, and Jesse Kenyon and two anonymous reviewers are appreciated. This study was supported by Studies of the Arctic and Antarctic Environmental Monitoring and Characteristics (PP04108, PP04102) of Korea Polar Research Institute.

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Received Jun. 24, 2004
Accepted Aug. 13, 2004