Quaternary International xxx (2017) 1–10

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Sensitivity of southern hemisphere westerly wind to boundary conditions for the last glacial maximum

Seong-Joong Kim*, Sang-Yoon Jun, Baek-Min Kim

Korea Polar Research Institute, KORDI, PO Box 32, Incheon, 406-840, South Korea

A R T I C L E I N F O

Article history:
Received 28 October 2016
Received in revised form
21 March 2017
Accepted 3 April 2017
Available online xxx

Keywords:
Southern hemisphere
Last glacial maximum
Westerly winds
Surface temperature
CMIP5

A B S T R A C T

The southern hemisphere (SH) westerly wind change in the LGM is critical in understanding the glacial-interglacial carbon cycle since its strength and position influence the upwelling of the carbon rich deep water to the surface. To examine the change in SH westerly wind in the LGM, we adopted CAM5 atmosphere general circulation model (GCM) and performed LGM simulation with sensitivity experiments by specifying the LGM sea ice in the Southern Ocean (SO), ice sheet over Antarctica, and tropical pacific sea surface temperature. The SH westerly response to LGM boundary conditions in the CAM5 was compared with those from CMIP5 LGM simulations. In the CAM5 LGM simulation, the SH westerly wind substantially increases between 40°S and 65°S, while the zonal-mean zonal wind decreases at latitudes higher than 65°S. The position of the SH maximum westerly wind moves poleward by about 8° in the LGM simulation. Sensitivity experiments suggest that the increase in SH westerly winds is mainly due to the increase in sea ice in the SO that accounts for 60% of total wind change. In the CMIP5-PMIP3 LGM experiments, most of the models show the slight increase and poleward shift of the SH westerly wind as in the CAM5 experiment. The increased and poleward shifted westerly wind in the LGM obtained in the current model result is consistent with previous model results and some lines of proxy evidence, though opposite model responses and proxy evidence exist for the SH westerly wind change.

1. Introduction

The atmosphere carbon dioxide concentration (CO_2) has increased continuously since the industrialization and it is expected to increase in the future. The glacial-interglacial climate fluctuation is linked to cyclic changes in orbital parameters of the Earth, but the energy budget from the change in orbital parameters is not enough to account for the magnitude of the glacial-interglacial climate change. The change in atmospheric CO_2 modulated the glacial-interglacial climate change by feedback mechanism (Kim et al., 1998; Sigman and Boyle, 2000; Ahn and Brook, 2008). During the Last Glacial Maximum (LGM), occurred about 21,000 years before present (ka BP), the atmospheric CO_2 was lower than at present by about 80 ppmv. While the naturally varied atmospheric CO_2 amount (about 80 ppmv) from interglacial to glacial time is smaller than the artificially increased atmosphere CO_2 after industrialization (about 100 ppmv), the cause of the glacial reduction of atmospheric CO_2 remains controversial.

There have been numerous hypotheses to account for the magnitude of glacial CO_2 reduction including biological and chemical pumps, but toward present, hypotheses based on the Southern Ocean (SO) barrier has become more popular (Sigman and Boyle, 2000; Toggweiler et al., 2006; Toggweiler and Russell, 2008; Toggweiler, 2009; Anderson et al., 2009). The reason behind the importance of the SO in the glacial CO_2 budget is associated with the upwelling rate of carbon rich water from the deep ocean to the surface that could play as a source or sink of atmospheric CO_2 (Toggweiler et al., 2006). In the SO, air-sea CO_2 flux can be modulated by the strength of the vertical mixing, that influences the upwelling of dissolved inorganic carbon to the surface. The oceanic eddy activity also plays an important role in modulating the air-sea CO_2 flux by shallowing or thickening of the mixed layer depths (Song et al., 2016).

The strength of upwelling is determined by the position and strength of the westerly wind. During the LGM, the temperature reduction in the SO is much larger than the tropics, where temperature changed little. This stronger equator-pole temperature gradient should give a stronger zonal winds and consequent stronger ocean circulation and ventilation (old deep ocean water is replaced by newly produced water in the polar oceans). However,

---

* Corresponding author.
E-mail address: seongjkim@kopri.re.kr (S.-J. Kim).

http://dx.doi.org/10.1016/j.quaint.2017.04.001

Please cite this article in press as: Kim, S.-J., et al., Sensitivity of southern hemisphere westerly wind to boundary conditions for the last glacial maximum, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.04.001

proxy evidence shows that during glacial time, ocean circulation was slower (Lynch-Stieglitz et al., 2007) and ventilation was weaker (Sikes et al., 2009). Liu et al. (2015) claim that the oceanic upwelling is driven by low-level wind stress rather than westerly winds and the de-correlation between the winds and wind stress could be due to the expanded sea ice towards equator in the LGM by undermining the efficacy of wind in generating wind stress. The mismatch between the ocean circulation and wind change in the LGM is not clearly resolved, but it is obvious that the understanding of wind change is crucial.

The location and strength of the southern hemisphere (SH) westerly are important in determining the SO upwelling rate, that consequently influences the glacial-interglacial carbon cycles. To investigate whether there was any change in the location and strength of SH westerly winds in the LGM, both observation and modelling efforts have been given. One school of observation evidence has suggested the northward shift of westerly winds. Toggweiler (2009) claimed that in the LGM, the westerly wind axis was displaced to equatorward. Since the Antarctic Circumpolar Current (ACC) is constrained by the Drake Passage, the northward wind shift would weaken the SO upwelling and thus leads to the reduction of dissolved inorganic carbon (DIC) concentration at the surface. This subsequently plays a role in reducing atmospheric CO_2 with less outgassing. By analyzing lacustrine palynologic records along the western Chile, McCulloch et al. (2000) suggested the northward wind shift. By analyzing pollen types using the sample from the south America, Moreno et al. (1999) also obtained the northward displaced SH westerly wind by 7–10° in the LGM. From data compilation, Kohfeld et al. (2013) suggested the 3–5° shift to the north. Heusser (1989) also obtained a northward shift of the SH westerlies. The northward shift of SH westerly winds was illustrated by the cooler tropical temperature than in the SO that weaken the Hadley cell circulation and its downward branch shifted equatorward (Toggweiler and Russell, 2008), or equatorward compression of frontal bands by the increase in sea ice cover around Antarctica in the LGM (Chiang and Bitz, 2005).

On the other hand, another school of evidence suggests opposite results, i.e. poleward shifts of SH westerly winds in the LGM (e.g., Markgraf, 1987, 1989; Harrison, 1993; Harrison and Dodson, 1993). Note, however, that the local moisture-based terrestrial records has a high uncertainty in indicating a change in SH westerly wind as shown in the contrasting results of Heusser (1989) and Markgraf (1989) and this uncertainty is from the local orographic effect on moisture distribution (Liu et al., 2015).

Numerical experiments have been performed to examine the change in the westerly winds in its strength and position and as in the data reconstructions, the model results are varying from model to model. Using Canadian Center for Climate Modelling and Analysis (CCCma) coupled Atmosphere-Ocean General Circulation Model, Kim et al. (2002, 2003) obtained the equatorward shift of the SH westerly winds. Using another AOGCM, Williams and Bryan (2006) also obtained the same response. However, using NCAR and MRI AOGCMs, Shin et al. (2003) and Kitoh et al. (2001) obtained the poleward shift of SH westerly winds, respectively. Using NCAR AGCM-only model (CCM3) with prescribed LGM boundary conditions, Kim and Lee (2009) obtained the 3–4° equatorward shift. Using AOGCM-only models, Drost et al. (2007) obtained equatorward shift, whereas Wyrwoll et al. (2000) obtained poleward shift. By analyzing the model results from the second phase of Paleoclimate Modelling Intercomparison Project (PMIP2), different SH wind responses were obtained (Rojas et al., 2009).

Besides the location of the SH westerly wind, a change in its strength is important as well in driving the Ekman pumping of the SO water. Toggweiler et al. (2006) and Toggweiler and Russell (2008) suggested weakening of the SH westerly wind in the LGM, associated with the larger cooling in the tropics relative to the polar regions that gives a decrease in meridional temperature gradient. The weakening of the wind is also consistent with the enhanced ocean stratification during the LGM (Burke and Robinson, 2012). However, another study suggested the stronger glacial winds associated with the increase in meridional pressure gradient by the large equator-to-pole temperature gradient (e.g., McGee et al., 2010). Dust records from ice core suggest a strengthened westerly during the LGM (e.g., De Angelis et al., 1987; Petit et al., 1999; Delmonte et al., 2002; Wolff et al., 2006).

Numerical model results are different as well. Using CCCma AOGCM, Kim et al. (2002, 2003) obtained a weaker westerly winds in the SH in the LGM. Using NCAR CCM3 AGCM with prescribed SST and sea ice conditions from CLIMAP (1981) reconstructions, Kim and Lee (2009) obtained the weaker SH westerly wind by 20–30%. However, there have been evidence for the stronger SH westerly wind from numerical simulation and proxy records. Using NCAR CGCMs, Shin et al. (2003) and Otto-Bliesner et al. (2006) obtained stronger SH westerly winds. Some authors claimed that the SO westerly winds were intensified in the LGM due to an increase in the equator-to-pole temperature gradient (e.g., Keeling and Visbeck, 2001).

As summarized above, the location and strength of the SH westerly wind in the LGM remains still unclear, though their information is critical in accounting for the atmosphere CO_2 budget. In this study, we examined the responses of SH westerly winds to LGM boundary conditions using the state-of-the-art numerical model. To evaluate which boundary conditions are more important in the position and strength of SH westerly winds, we also attempted sensitivity experiments by setting glacial sea ice, ice sheet, and tropical SST conditions.

2. Models and experiments

In this study, we used NCAR Community Atmosphere Model version 5 (CAM5), which is the latest version in a series of global atmosphere models developed at National Center for Atmospheric Research (NCAR) for numerical experiments. CAM5 improves significantly the representation of atmospheric processes with model physics of CAM version 4. As the atmosphere subcomponent of CESM1.0, CAM5 includes more realistic formulations of radiation, boundary layer, and aerosols compared to CAM version 4 (CAM4). The aerosol scheme is prognostic (Liu et al., 2012) and cloud microphysics includes both direct and indirect effect of sulfate and black and organic carbon (Morrison and Gettelman, 2008; Gettelman et al., 2010). We utilize CAM5 with model physics of CAM4 in order to maintain consistency with CCSM4 experiment from the CMIP5, which used CAM4 physics and provides surface boundary conditions of sea surface temperature and sea-ice cover to this study. This configuration using consistent physical processes will help to reduce an uncertainty in simulation due to air-sea decoupling compared to the CCSM4 experiment in the CMIP5. There is time–evolving land use change in the twentieth and twenty-first century climate simulations (Lawrence et al., 2011). Finite volume dynamical core with 1.9° × 2.5° horizontal resolution and 26 hybrid sigma vertical level is adopted in this study.

Table 1 lists experimental setup that included in the current study. The preindustrial simulation (PI) includes orbital parameters and land surface boundary conditions for the preindustrial time that are provided by CMIP5 experimental design. Sea surface temperature (SST) and sea ice conditions are from CCSM4 experiment, which was used in the CMIP5 experiment. The last glacial maximum experiment referred to as LGM includes orbital parameters for 21,000 years ago and LGM SST and sea ice conditions obtained from CCSM4 experiment for the CMIP5 experiment. We also

Please cite this article in press as: Kim, S.-J., et al., Sensitivity of southern hemisphere westerly wind to boundary conditions for the last glacial maximum, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.04.001