A coupled model simulation of the Last Glacial Maximum

김 성 중

한국 해양연구원 부설 극지 연구소

1.Introduction

The earth's climate has fluctuated between glacial and interglacial states and the most recent epoch, the "last glacial maximum"or LGM peaked about 21 thousand years ago. Geological and geochemical proxy data have been used to provide a broad picture of the LGM climate (e.g., CLIMAP, 1976, 1981), but these data are limited in their ability to reveal the manner in which the climate system operated. As an adjunct to the study of proxy data, physically-based climate simulation models have been used to study the mechanisms associated with such a marked climate change.

A coupled atmosphere-ocean-sea ice-land surface climate system model is used to investigate the response to the imposition of glacial boundary conditions. The integration reported here comprises some 900 years of periodically-synchronous coupled simulation. Although some quantities continue to adjust even at this time, overall features should be representative of the LGM climate. The main interest in the study is to investigate how the climate system operates under glacial conditions.

2.Modelandexperiments

The model employed in the current study is the second generation Canadian Centre for Climate Modelling and Analysis (CCCma) coupled general circulation model (CGCM2). A detailed description of the atmosphere, ocean, sea ice, and land surface components of CGCM2 is given in other papers (Kim et al., 2002, 2003). Only a brief summary is provided here. The atmospheric component of CGCM2 is a primitive equation model characterized by T32 horizontal resolution corresponding to a 3.75°Gaussian grid, and 10 vertical levels. The oceanic component is a modified version of the GFDL MOM version 1.1. The horizontal grid spacing is 1.875º x 1.875º with 29 vertical layers. CGCM2 includes a dynamic-thermodynamic sea ice model. Sea ice dynamics is represented using the cavitating fluid rheology of Flato and Hibler (1992), while sea ice thermodynamics is represented by a slightly modified version of the 0-layer scheme of Semtner (1976). The atmosphere and ocean components interact once per day exchanging heat, fresh water, and momentum. Monthly heat and freshwater flux adjustment fields are applied for all coupled model experiments.

The results of two experiments are analyzed. The control simulation has a specified CO_2 concentration of 330 ppm, and a contemporary land mask and topography. The other experiment employs LGM boundary conditions with a decreased CO_2 concentration of 235 ppm, a modified land mask based on sea level decrease by 120 m (Fairbanks, 1989), and ice sheet topography using the ICE-4G reconstruction of Peltier (1994). Orbital parameters and vegetation and soil types are unchanged.

3.Results

Surface air temperature (SAT) decrease, more than 30°C, is found over the Laurentide and Fennoscandian ice sheet due to the change in elevation and the higher surface albedo (Fig. 1). The strong land sea contrast and the cold tongue over the equatorial Pacific, a La Niña-like feature, is manifest early in the transient adjustment and persists as equilibrium is approached. The simulated temperature distribution exhibits more structure over the oceans including a La Niña-like response in the tropical Pacific as a result of ocean feedback processes.

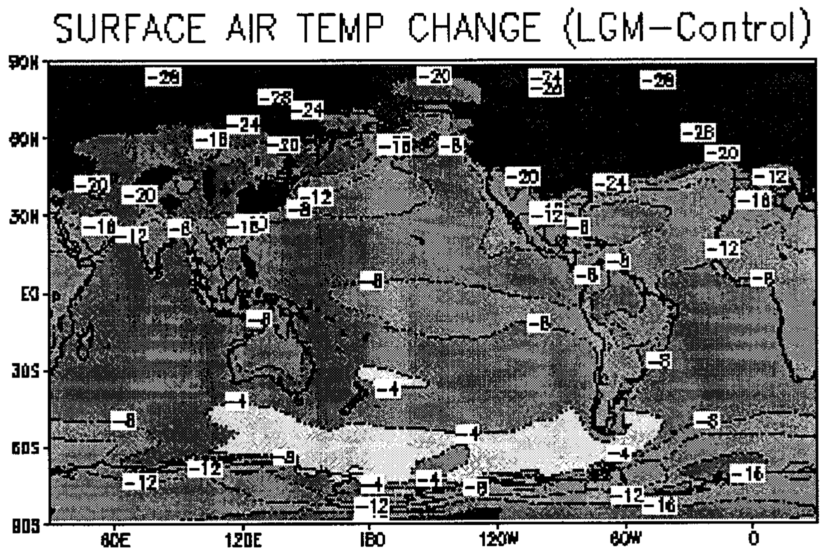

Fig. 1 Geographic distribution of the change in annual mean surface air temperature.

The global and tropical mean SST changes in the simulation are -5.6°C and -6.5°C, respectively, which are larger than CLIMAP (1976) (-2.5°C and -1.7°C), CLIMAP (1981) (-1.3°C and -1.0°C). However, the larger tropical cooling in the LGMC simulation is in better agreement with recent proxy evidence, the balance of which suggests tropical cooling less than 5°C. More particularly, the ocean dynamics in the coupled model produces stronger and more realistic SST structures in the simulated LGM climate as measured by the spatial variances and correlation.

Many lines of paleoclimate proxy evidence suggest that it was generally drier during the LGM (Crowley and North, 1991) and an overall drier LGM climate is consistent with an increase in atmospheric dust concentration recorded in the Greenland and

Antarctic ice cores and an increase in wind-blown eolian sediments in deep sea cores. As the surface temperature decreases, the global hydrological cycle weakens by 15% in the coupled model. Precipitation decreases markedly at three distinct latitude bands, i.e. near the equator associated with a weakening of the ITCZ, in the NH between 50° and 70°N associated with the presence of the continental ice sheet, and at southern high latitudes. The P-E change in some land areas influences the change in river discharge. The marked increase in precipitation over evaporation south of the Laurentide ice sheet increases the discharge from the Mississippi river to North Atlantic from 8.8 to 42.6 x 10^3 m^3 s^{-1}, an increase of more than a factor of 3. The discharge in the North Atlantic from the Amazon river also increases by about factor of 2. The change in the large-scale hydrological budget in both model versions agrees broadly with available proxy evidence.

Sea surface salinity (SSS) changes broadly mirror the changes in P-E with a decrease in the Atlantic and an increase over most of the remainder of the ocean. The increase in SSS in the Arctic Ocean is primarily due to a decrease in river discharge, while its increase in the tropical western Pacific is due primarily to the decrease in precipitation over the western Pacific associated with the La Niña-like response in agreement with proxy evidence. SSS decreases substantially in the North Atlantic in consistent with proxy evidence (de Vernal et al., 2000). The freshening results in the weakening of the North Atlantic overturning circulation from 12 Sv to 6 Sv in the LGM. In response to the marked reduction in the strength of the overturning circulation in the NH, the overturning circulation associated with the AABW outflow predominates the global ocean domain. Many lines of proxy evidence have shown that the North Atlantic overturning circulation was much weaker and shallower during the LGM.

The weakening of the North Atlantic overturning circulation results in the reduction of northward heat transport by about 0.8 PW in the LGM. The reverse happens in the SH, where the change in the meridional overturning dominates the increase in the southward heat transport and the intensified overturning circulation transfers about 40% more heat toward the south in the LGM. NH sea ice cover expands during the simulation and the area considerably exceeds that of the control run by the end of the simulation. In the SH sea ice cover decreases remarkably during the first century due to enhanced oceanic convection and the associated upward flux of heat. As the deep ocean cools convection slows and the Antarctic sea ice cover slowly recovers until it exceeds the control run values.

4.Summary

The response of the CCCma coupled climate model to the imposition of LGM conditions is investigated. The global mean SAT and SST decrease by about 10°C and 5.6°C in the coupled model. Tropical SST decreases by 6.5°C, whereas CLIMAP reconstructions suggest that the tropics cool by only about 1.7°C, although the larger tropical cooling is consistent with the more recent proxy estimates. With the incorporation of a full ocean component, the coupled model gives a realistic spatial SST pattern, capturing features associated with ocean dynamics that are seen in the CLIMAP reconstructions. The larger decrease of the surface temperature in the model is associated with a reduction in global precipitation rate (about 15%). The tropical Pacific warm pool retreats to the west and a mean La Niña-like response is simulated with less precipitation over the central Pacific and more in the western tropical Pacific. The more arid ocean climate in the LGM results in an increase in SSS almost everywhere. This is particularly the case in the Arctic Ocean where large SSS increase is due to a decrease in river discharge to the

Arctic Ocean associated with the accumulation of snow over the ice sheet, but in the North Atlantic by contrast SSS decreases markedly. This remarkable reduction of SSS in the North Atlantic is attributed to an increase in fresh water supply by an increase in discharges from the Mississippi and Amazon rivers and an increase in P-E over the North Atlantic ocean itself. The discharges increase in association with the wetter LGM climate south of the Laurentide ice sheet and in South America. The fresh water capping of the northern North Atlantic results in a marked reduction of deep convection and consequently a marked weakening of the North Atlantic overturning circulation. In the LGM, the maximum overturning stream function associated with the NADW formation decreases by about 60% relative to the control run, while in the Southern Ocean, oceanic convection is stronger in the LGM due to reduced stratification associated with an increase in SSS and a decrease in SST and the overturning stream function associated with the formation of AABW and the outflow increases substantially.

References

CLIMAP (1976) The surface of the Ice-Age Earth. Science 191: 1131-1136

CLIMAP (1981) Seasonal reconstructions of the Earth's surface at the last glacial maximum. Geol Soc Amer Map Chart Ser, MC-36

Crowley TJ, North GR (1991) Paleoclimatology. Oxford Monographs on Geology and Geophysics 18. Oxford University Press, New York

De Vernal A, Hillaire-Marcel C, Turon J-L, Matthiessen J (2000) Reconstruction of sea-surface temperature, salinity, and sea-ice cover in the northern North Atlantic during the last glacial maximum based on dinocyst assemblages. Canadian J Earth Sci 37: 725-750

Fairbanks RG (1989) A 17000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342: 637-642

Flato GM, Hibler III WD (1992) Modelling pack ice as a cavitating fluid. J Phys Oceanogr 22: 626-651

Kim S-J, Flato GM, Boer GJ, McFarlane NA (2002) A coupled climate model simulation of the Last Glacial Maximum, Part 1: Transient multi-decadal response. Clim Dyn 19: 515-537

Kim S-J, Flato GM, Boer GJ, McFarlane NA (2003) A coupled climate model simulation of the Last Glacial Maximum, Part 2: approach to equilibrium. Clim Dyn 20: 635-661

Peltier WR (1994) Ice age paleotopography. Science 265: 195-201

Semtner AJ (1976) A model for thermodynamic growth of sea ice in numerical investigations of climate. J Phys Oceanogr 6: 379-389