Influence of a Dynamic Ocean Model on Late Paleozoic Glacial Cycles

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Abstract

The Late Paleozoic Ice Age was the last great ice age in Earth's history. There have been many attempts to simulate the waxing and waning of continental ice sheets on southern Gondwana with climate models. Most of these studies have used a mixed-layer model. We evaluate the importance that a dynamic ocean has on simulating ice sheets during this period by running experiments with two different methods for modeling the ocean. The two techniques used include the slab ocean model and an ocean general circulation model. The model results indicate that there is as much as a 22% difference in ice volume between simulations run under the same climate conditions. This can be attributed to differences in temperature, where the mixed-layer model simulates lower temperature at lower $p\mathrm{CO}_2$ concentrations (420ppm and 560ppm) and higher temperatures at higher concentrations (700ppm) than the dynamic ocean model. Temperature differences reach a magnitude of 7°C over southern Gondwana between the two modeling methods; we attribute the dissimilarity in temperature to a polar ocean gyre simulated in the dynamic ocean model that limits sea ice growth. We suggest that future studies employ a dynamic ocean model as a more realistic ocean modeling method compared to a mixed-layer model as noticeable changes in results arise.

1. Introduction

The late Paleozoic (340-250 Myr ago) has been characterized as a period of extensive continental glaciation (Crowell, 1978). The volume of ice sheets during this icehouse interval are thought to have exceeded those of the Last Glacial Maximum (Crowley and Baum, 1991). Several long-term (10^6-10^7 yrs) factors are hypothesized to have been responsible for the severity of this ice age, among them the amalgamation of Africa, Antarctica, Australia, India and South America around the South Pole and low atmospheric $p\mathrm{CO}_2$ concentrations (Crowley et al., 1989). Throughout this ice age, it is thought that on short-to-intermediate timescales (10^4-10^5 yrs) variations in orbital insolation drove cyclic episodes of ice sheet accumulation and ablation (Horton et al., 2007). Developing an understanding of the processes that led to the growth and retreat of the ice sheets during the Late Paleozoic Ice Age (LPIA) will inform efforts to understand the dynamics of our present ice ages and will aid in predictions of the coming icehouse to greenhouse transition (Crowell, 1978; Meehl et al., 2007).

Current parameters used to model the LPIA are insufficient in modeling the scope and dynamics of the ice sheets during this period. Soreghan et al. (2008) revealed that simulations employing only low atmospheric CO_2 levels and solar luminosity alone are insufficient in causing the extent of ice sheet growth observed and thus further research is needed to determine alternative factors. In addition, climate models have difficulty simulating glacial-interglacial changes (Horton and Poulsen, 2009). Beyond paleogeography, CO_2, and orbital parameter change, models have indicated that vegetation change and dynamic ocean heat transport may have a significant influence on ice sheet volume. The inclusion of ecosystem feedbacks allows for a more precise simulation of glacial-interglacial cyclicity without compromising the size of the ice sheets (Horton et al., 2010). To our knowledge, no studies have examined the use of a dynamic ocean model, and instead include a mixed-layer model (Horton and Poulsen, 2009; Horton et al., 2010). This method of modeling the ocean is not a realistic representation of ocean dynamics. It is therefore necessary to examine a dynamic ocean's effect on ice growth.

The ocean's role in transporting heat is an integral part in the formation of ice sheets. Its effect on climate includes storing heat, seasonally releasing thermal energy, and large-scale transport of heat from low to high latitudes (Barron et al., 1993). An example of the ocean storing and releasing heat seasonally includes the moderate climate of coastal cities, e.g., San Francisco and London, compared to cities of equal latitude located in the continental interior. The large-scale transport of heat from the equator towards the poles is illustrated by high latitude regions with uncharacteristically moderate climate due to warm currents passing nearby, as observed in the British Isles warmed by the North Atlantic Drift. With respect to ice sheet dynamics, the large-scale transport of heat is particularly important. This process moves significant amounts of thermal energy to the poles, affecting ice growth positively by increasing precipitation through providing latent heat or negatively by increasing the local ambient temperature. The impact of ocean circulation on climate has been studied in models, with results confirming that the ocean has a sizable contribution to heat flow that the atmosphere cannot account for (Winton, 2003). The dynamic properties of ocean circulation can both initiate and impede ice growth, and ice sheets in turn can influence ocean currents. Significant sea ice growth can lead to entrainment, thus producing vertical convection due to heat loss in the surface water (Rudels et al., 1999).

Researchers attempt to simulate the ocean through multiple methodologies. Two common methods utilize either a mixed-layer model that lacks dynamics or a more complex ocean general circulation model (OGCM) that resolves the three dimensional circulation. The former uses a diffusive heat flux to transfer thermal energy from the tropics to the polar regions. The OGCM method, contrary to the mixed-layer method, employs dynamics in order to transfer thermal energy. Researchers use the slab ocean model because of its efficiency. It only simulates a 50 meter layer, so it is able to reach an equilibrium state very quickly, and the lack of dynamics is not thought to have significant ramifications. The OGCM is used as it more realistically models ocean processes. Due to the inclusion of dynamics in the OGCM, typical ocean features can be seen such as upwelling zones and areas of entrainment.

In this study we utilize both a mixed-layer model and an OGCM to determine how ice sheet growth during the Late Paleozoic Ice Age is influenced by dynamic ocean circulation. We test the sensitivity of each modeling configuration to multiple atmospheric $p\mathrm{CO}_2$ levels. The results provide the structure to analyze the efficiency of the two models and determine any significant differences between them.

2. Methods

Climate models solve complex mathematical equations that describe the physics of the climate system. Global climate models can then describe interactions between the atmosphere, oceans, continents, biota, ice, and solar energy and determine their effects on Earth's climate. Without such models, it would be near impossible to make predictions about the climate to the same detail that is done with a climate model. Climate models have been shown to simulate accurately the modern climate (Alder et al., 2011). In addition, simulations of recent past climates accurately reproduce climate changes observed from ice core proxies (Mahowald et al., 1999). As current and recent past climate models simulate accurate results, simulations can be made with confidence about climates millions of years ago. The Late Paleozoic Ice Age has been a well studied period (Horton et al., 2007; Horton and Poulsen, 2009; Horton et al., 2010). This same period will be examined in this study, where the effects of a dynamic ocean model on the ice growth will be determined.

To determine the effect of ocean dynamics on ice sheet growth in the late Paleozoic ice age, two modeling schemes were employed: (1) a GCM coupled to a slab ocean model and (2) a GCM coupled to a dynamic ocean model. The GCM, GENESIS version 3.0, is composed of coupled atmosphere, land-surface, sea-ice and slab ocean modeling components (Pollard and Thompson, 1995; Thompson and Pollard, 1997).

The two modeling schemes employ fundamentally different methods in their simulation of the ocean. The slab ocean model consists of a 50m layer whose heat is distributed via diffusion. In the second modeling scheme, all modeling components remain the same, with the exception of the slab ocean. This component was replaced with a dynamic ocean model, the Modular Ocean Model 2 (MOM). MOM is a three-dimensional z-coordinate system ocean GCM. This dynamic ocean model is a finite difference implementation of the primitive ocean circulation equations based on the Navier-Stokes equations with the Boussinesq, hydrostatic, and rigid lid approximations (Bryan, 1969). It consists of 20 unevenly spaced levels that increasing in thickness with depth, so that the levels near the surface are well resolved (Alder et al., 2011).

Ice sheet growth on the continent is simulated by a thermo-mechanical ice-sheet model with a time step of 1 year (Decanto and Pollard, 2003). The model predicts ice temperatures to account for effects on basal sliding and rheology. The response to ice load by the bedrock is a simple relaxation toward isostasy with a time constant of 5,000 years, and lithospheric flexure is modeled by linear elastic deformation. Ice shelves are not simulated in this version of the model.

Each experiment was run under one orbital configuration and three atmospheric $p\mathrm{CO}_2$ levels. The boundary conditions for both schemes were Sakmarian (circa 290 Ma) paleogeography and paleotopography (Ziegler et al., 1997). The orbital configuration consisted of the optimal values of precession, obliquity and eccentricity to produce a Southern Hemisphere Cold Summers orbit (Southern Hemisphere summer at the aphelion with high eccentricity and low obliquity) (Horton et al., 2007). The three $p\mathrm{CO}_2$ levels used were 420, 560, and 700ppm, which are in the range of proxy estimates (Montanez et al., 2007). The BIOME4 is a dynamic ecosystem model which examines vegetation feedbacks and their effects on ice growth. In these experiments, the distribution of vegetation at each pCO_2 level is sourced from the final year of a coupled 20 year GENESIS-BIOME4 simulation. In our ocean model experiments, this initial vegetation is not update, but held constant throughout the simulations.

Due to the differing response times of the atmosphere and ice sheets, an asynchronous procedure was used to couple the GCM with the three-dimensional ice sheet model (Fig. 1). (1) GENESIS is run for 30 years. (2) The final ten years of the GCM simulation are averaged and used as the input climatology in the ice sheet model. The ice sheet model simulates 2000 years of ice growth. (3) The resulting ice sheet geometry is transferred into the GCM for the next run. This procedure (steps 1-3) is repeated three times in total (though on the second and third iterations GENESIS is compiled for 20 yrs) and results in the ice sheet simulation running for a total of 6000 years. A similar approach was used when GENESIS was coupled with MOM, but it involved both synchronous and asynchronous steps. GENMOM (the name of the GENESIS model with MOM replacing the slab ocean) was run for 40 years, with the last 10 years again averaged and passed on to the next step. This involved running MOM and the ice sheet model asynchronously for 2000 years. The results of these runs were transferred back to GENMOM to run for 30 years. These last two steps occurred once more, resulting in a total ice simulation time of 6000 years. This method for asynchronously coupling is adapted from Horton et al. (2010).

3. Results

3.1. Ice Sheet Growth

In our simulations, atmospheric $p\mathrm{CO}_2$ concentration and its effect on global average temperature is the main factor influencing ice sheet volume. This result is in accordance with previous studies that have found that low $p\mathrm{CO}_2$ levels resulted in the largest Gondwanaland ice sheets (Horton et al., 2007; Horton and Poulsen, 2009). The CO_2-temperature-ice volume relationship is present in all our simulations, regardless of the use of a dynamic or non-dynamic ocean modeling components (Fig.2). However, the response of each model to changes in $p\mathrm{CO}_2$ levels is different: ice sheets in the slab ocean model are reduced to cover smaller areas at high atmospheric carbon dioxide levels than ice sheets in MOM when compared to ice sheets at low $p\mathrm{CO}_2$ concentrations. Ice volume in the slab model undergoes a decrease of 17 million km^3 in ice volume compared to only a 10 million km^3 decrease in MOM between 420ppm and 700ppm. Some areas of the ice sheet decrease in extent more than others. The ice sheet over Australia (located between 75°E and 140°E and 35°S and 65°S) in the slab model sees the most rapid decrease in ice volume and extent (Fig. 3). At 420ppm, the slab ice sheet in this region greatly exceeds the MOM ice sheet; in contrast, the slab ice sheet is surpassed by the MOM ice sheet at

700ppm. This rapid decrease in both extent and volume of ice in this region suggests the slab ocean simulates a greater change in temperature between 420ppm and 700ppm in this area than in MOM.

3.2. Temperature

At higher atmospheric pCO_2 concentrations, the global average temperature becomes warmer in all simulations. However, the surface warming is not uniform, with certain regions undergoing extensive warming while others observe minimal increases in temperature. The temperature results are in accordance with the ice results, in that the simulations with the colder polar temperatures are also the simulations with the most ice. At 420ppm and 560ppm, Gondwanaland is significantly warmer when using MOM (Fig. 4). The temperatures simulated in MOM compared to the mixed-layer model are up to 7°C warmer over Gondwanaland when pCO_2 is at 420ppm and 4°C warmer at 560ppm. The areas off the coast of Antarctica (between 170°E and 80°W) and Western Australia (between 50°E and 80°E) reach a difference of up to 8°C, with MOM creating the warmer climate. As is the case with ice volume, there is a noticeable shift in climatic conditions at 700ppm; the slab ocean model produces warmer temperatures in the polar region compared to the MOM simulations, in contrast to the lower pCO_2 levels. On land and in the ocean, the slab simulation produces temperatures up to 5°C warmer than MOM. Over the ice sheets, it is expected that temperatures over higher elevation regions. However, colder temperatures on the continent are not restricted to areas of ice. There is a significant dissimilarity in the temperatures of the polar regions between the two models.

Additional anomalies arise between the two simulations that can be explained due to properties of a dynamic ocean. In the open ocean, there is a large area between 40°S and 60°S where the slab model produces warmer temperatures that stretch from the eastern coast of Australia to the western coast of South America (140°E to 70°W) (Fig. 4). This difference is present in all simulations, and is possibly due to mid-ocean upwelling of colder waters. The anomaly becomes more pronounced at higher atmospheric carbon dioxide levels. The differences in temperature over the ocean in polar regions are not as pronounced in the summer (an 8°C difference is only a 5°C difference at 420ppm) (Fig.5). This suggests the anomaly in temperature may be partly caused by differences in sea ice (see section 3.4).

3.3. Precipitation

At 420ppm and 560ppm the dynamic ocean model generated more precipitation around the South Pole compared to the slab ocean model, with the difference greatest at 420ppm (Fig. 6). Finally at 700ppm, the differences are negligible near the South Pole in most areas, with MOM simulating more precipitation only in isolated regions.

In contrast to the results for temperature, the modeling scheme with the most ice at a given pCO_2 level does not necessarily simulate the most favorable precipitation results in respect to growing ice. Across all pCO_2 levels, the coast of Antarctica between Australia and South America (160°E and 60°W) and the coast of India (between 50°E and 65°E) receive significantly more precipitation in the MOM experiments. The difference in precipitation is smaller in magnitude at higher carbon dioxide levels, although the disparity is present in all three levels. However, a small area on the coast of South America (the peninsula located at 60°W and 60°S) receives more precipitation in the slab ocean model runs. The South America area receiving more precipitation in the slab experiments is even larger under increased pCO_2 levels; at 700ppm, the entire tip of the peninsula receives more precipitation under the slab model. Precipitation rates are much greater in a band around 30S in the slab model experiments. This area is also warmer in the slab model runs, resulting in higher saturation vapor pressure and therefore more evaporation and precipitation. Additionally, MOM simulates a larger amount of precipitation around 10°S at all pCO_2 levels. The summer precipitation patterns mimic the annual features, only with slight variations in magnitude (Fig.7). These findings suggest that precipitation is not the main driver of ice sheet growth in these simulations. There is no direct correlation between precipitation rate and ice volume. The lack of any correlation suggests all areas receive adequate precipitation so that it is not the limiting factor in ice growth.

3.4. Sea Surface Temperature, Surface Currents and Sea Ice

The differences in modeling the ocean's heat transport between the two methodologies cause the dissimilarities in the simulations. The slab ocean model consists of a 50m deep ocean that employs diffusive heat flux. This results in a gradual change in temperature from high to low when moving from the equatorial region to the polar regions. At higher $p\mathrm{CO}_2$ levels, the overall temperature of the ocean increases uniformly throughout. As previously discussed, MOM simulates ocean currents and therefore contains ocean gyres and convection. Under all $p\mathrm{CO}_2$ levels, there is an equatorial current that runs east to west. These currents have a north and south component that moves water away from the equator, which causes upwelling (Fig.8). Thus, water near the equator is cooler than water 10° north and south of it, similar to today's oceans. When compared to the slab model, the MOM ocean has a cooler equator, but warmer water around the Tropic of Capricorn. This is caused from currents moving the warm water away from the equator, which produces an upwelling of cold water from below. The most important feature with respect to ice sheet growth is a polar gyre, which occurs between 70°W and 160°E. On the eastern side of the gyre, a southern-flowing current brings warmer water toward the poles, warming the coastline; on the western side, cold polar water is brought north, cooling the coastline. This results in a 9°C temperature gradient between the two sides of the gyre at 60°S. This temperature gradient is present at all carbon dioxide levels; although the mean temperature of this region increases, the magnitude of the gradient does not change significantly. Additionally, South America restricts the flow of water between an inlet sea and the rest of the ocean, causing a much cooler temperatures that fall below 0°C. This causes an interesting temperature gradient in South

America: at 50°E, the eastern coast of the peninsula is 9°C colder than the western coast. As temperatures become warmer at higher increasing $p\mathrm{CO}_2$ levels, the sea surface temperature in this sea also warms. However, this sea is the only place in the Southern Hemisphere where there is a substantial amount of water below 0°C at all three carbon dioxide concentrations.

The results from the sea surface temperatures and sea ice allow us to understand why there is a switch at 700ppm from the non-dynamic ocean model having more ice to the dynamic ocean producing more ice volume. As discussed previously, the temperature off the coast of the landmass in the polar region is much cooler than that of the dynamic ocean. This is easily explained by the presence of sea ice. The slab ocean model has significantly more sea ice in the simulations under the lower two atmospheric $p\mathrm{CO}_2$ levels (Fig. 9). This causes a general cooling of the entire polar region, allowing ice sheets to grow. At 700ppm, the sea ice shrinks significantly, and consequently the temperature of the slab ocean is greater than that in the MOM simulation and there is less continental ice.

4. Discussion & Conclusions

This study demonstrates the variations in results for late Paleozoic ice-sheet growth using different modeling schemes: the mixed-layer model and the dynamic ocean model. The two modeling methods have significant differences in their response to changing $p\mathrm{CO}_2$ concentrations. The slab ocean model underwent a much steeper decrease in ice volume as atmospheric carbon dioxide levels increased compared to MOM. This is seen in the fact that the slab ocean model has 22% more ice at 420ppm than MOM, but has 11% less than the dynamic ocean model at 700ppm. This difference most likely stems from the sea surface currents moving cold and warm water around the southern polar region in MOM, while the slab ocean model does not have these currents and instead has a uniform diffusion of heat. Therefore in MOM, subpolar gyres can keep cool water in the polar regions, and can produce interesting effects on the coastline. This observation is confirmed by the fact that the dynamic ocean model has a smaller difference in ice volume over a range of atmospheric carbon levels compared to the slab ocean model. In other words, it is inferred that the polar regions in MOM are less sensitive to an increase from 420ppm to 700ppm pCO_2 than the slab ocean model. This has ramifications when studying results on ice sheet growth during this period that employed a slab model. For pCO_2 levels similar to this study, a model using the slab ocean will tend to over-estimate ice sheet ablation. This has implications of glacial-interglacial changes. At low pCO_2 concentrations, these changes might be harder to simulate with the slab ocean model since ice volumes are overestimated.

Although these sensitivity experiments cannot be compared to observations, other studies have examined the accuracy of similar modeling techniques to the modern world where observation data is readily available for comparisons. The most important feature that sets the dynamic ocean model apart from the slab ocean model is its use of ocean currents. Ocean currents in MOM have been shown to accurately reproduce most modern surface currents (Alder et al., 2011). Ocean dynamics during the Paleozoic are likely similar to those in the present. Thus we are confident the dynamics presented in the MOM simulations are sound.

These differences in ice volume between the two modeling schemes suggest that previous studies that used a slab ocean model can use a dynamic ocean model to model the ocean more realistically, and this will produce new results. The differences simulated here were at most 22%. Previous studies have suggested this idea (e.g. Horton and Poulsen, 2009) and this study indicates that new results most likely will arise from the change in modeling scheme, although the new results will most likely not be incredibly different to results using a mixed-layer model. However, adding additional parameters, such as a variable biome component, that were not included in this study may have feedbacks to the ocean circulation, changing the magnitude of both parameters involved. Therefore it is not clear if the ocean will have the same effect on ice sheet growth compared to the slab ocean model when new variables are involved. Further study for the differences between these two modeling schemes is needed, such as how the results respond to different orbital configurations. Additionally, understanding the effects of a new variable may be more difficult when combined with MOM rather than the slab ocean. Although the results with MOM may be more realistic, the new parameter could enter into feedback loops with MOM, amplifying or minimizing the effect of the new variable. This would be less a factor when coupling with a slab ocean, as the dynamics of MOM enter into more feedbacks than the diffusive heat flux of the mixed-layer model.

In conclusion, the use of a dynamic ocean model (MOM) influences both simulated ice volumes and the sensitivity of ice volumes to pCO_2. MOM causes a warmer polar region at low $p\mathrm{CO}_2$ levels and ice volume is less sensitive to increases in carbon dioxide levels when compared to a slab ocean model. Temperature differences between the modeling schemes are more important than precipitation differences, with the temperature differences driving the differences in ice volume. This can be attributed to sea surface currents that bring warm water south that are affected less by a decrease in average global temperature compared to heat distribution by diffusion. Thus, there are noticeable differences between the two models. Future studies are advised to include a dynamic ocean model as it includes physics that are more realistic and produce different results compared to a mixed-layer model.

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References

Alder, J. R., Hostetler, S. W., Pollard, D., and Schmittner, A., 2011, Evaluation of a present-day climate simulation with a new coupled atmosphere-ocean model GENMOM: Geoscientific Model Development, v. 4, no. 1, p. 69-83.

Barron, E. J., Peterson, W. H., Pollard, D., and Thompson, S., 1993, Past climate and the role of ocean heat-transport - model simulations for the Cretaceous: Paleoceanography, v. 8, no. 6, p. 785-798.

Bitz, C. M., Holland, M. M., Weaver, A. J., and Eby, M., 2001, Simulating the ice-thickness distribution in a coupled climate model: Journal of Geophysical Research-Oceans, v. 106, no. C2, p. 2441-2463.

Bryan, K., 1969, A numerical method for the study of the circulation of the world ocean: Journal of Computational Physics, v. 4, p. 347-376.

Crowell, J. C., 1978, Gondwanan glaciation, cyclothems, continental positioning, and climate change: American Journal of Science, v. 278, no. 10, p. 1345-1372.

Crowley, T. J., Baum, S. K., and Hyde, W. T., 1991, Climate model comparison of Gondwanan and Laurentide glaciations: Journal of Geophysical Research-Atmospheres, v. 96, no. D5, p. 9217-9226.

Crowley, T. J., Hyde, W. T., and Short, D. A., 1989, Seasonal cycle variations on the supercontinent of Pangaea: Geology, v. 17, no. 5, p. 457-460.

DeConto, R. M., and Pollard, D., 2003, A coupled climate-ice sheet modeling approach to the Early Cenozoic history of the Antarctic ice sheet: Palaeogeography Palaeoclimatology Palaeoecology, v. 198, no. 1-2, p. 39-52.

Horton, D. E., Poulsen, C. J., and Pollard, D., 2007, Orbital and CO2 forcing of late Paleozoic continental ice sheets: Geophysical Research Letters, v. 34, no. 19.

Horton, D. E., and Poulsen, C. J., 2009, Paradox of late Paleozoic glacioeustasy: Geology, v. 37, no. 8, p. 715-718.

Horton, D. E., Poulsen, C. J., and Pollard, D., 2010, Influence of high-latitude vegetation feedbacks on late Palaeozoic glacial cycles: Nature Geoscience, v. 3, no. 8, p. 572-577.

Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S. P., Prentice, I. C., Schulz, M., and Rodhe, H., 1999, Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments: Journal of Geophysical Research-Atmospheres, v. 104, no. D13, p. 15895-15916.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E., 2007, The WCRP CMIP3 multimodel dataset - A new era in climate change research: Bulletin of the American Meteorological Society, v. 88, no. 9, p. 1383-+.

Pollard, D., and Thompson, S. L., 1995, Use of a land-surface-transfer scheme (LSX) in a global climate model - The response to doubling stomatal-resistance: Global and Planetary Change, v. 10, no. 1-4, p. 129-161.

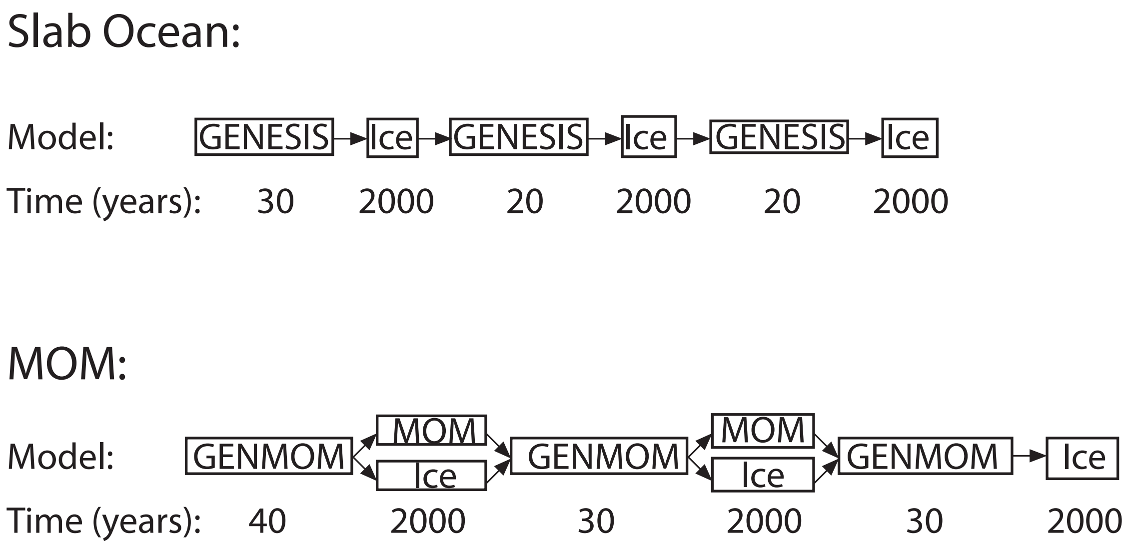
Rudels, B., Friedrich, H. J., Hainbucher, D., and Lohmann, G., 1999, On the parameterisation of oceanic sensible heat loss to the atmosphere and to ice in an ice-covered mixed layer in winter: Deep-Sea Research Part Ii-Topical Studies in Oceanography, v. 46, no. 6-7, p. 1385-1425.

Soreghan, G. S., Soreghan, M. J., Poulsen, C. J., Young, R. A., Eble, C. F., Sweet, D. E., and Davogustto, O. C., 2008, Anomalous cold in the Pangaean tropics: Geology, v. 36, no. 8, p. 659-662.

Thompson, S. L., and Pollard, D., 1997, Greenland and Antarctic mass balances for present and doubled atmospheric CO2 from the GENESIS version-2 global climate model: Journal of Climate, v. 10, no. 5, p. 871-900.

Winton, M., 2003, On the climatic impact of ocean circulation: Journal of Climate, v. 16, no. 17, p. 2875-2889.

Ziegler, A.M., Hulver, M.L., and Rowley, D.B., 1997, Permian world topography and climate, in Martini, I.P., ed., Late glacial and postglacial environmental changes – Quaternary, Carboniferous-Permian and Proterozoic: New York, Oxford University Press, p.111-146.



Slab Ocean:

MOM:

Figure 1. Modeling Technique. These diagrams show how GENESIS was coupled to the ice sheet model and how GENMOM was coupled to MOM and the ice sheet model. The arrows indicate climate data that is passed between the models in an asynchronous procedure. The Time is the number of years the model was allowed to run in order to reach an equilibrium state. In both the slab ocean model and MOM, the ice sheet model ran for a total of 6000 years.

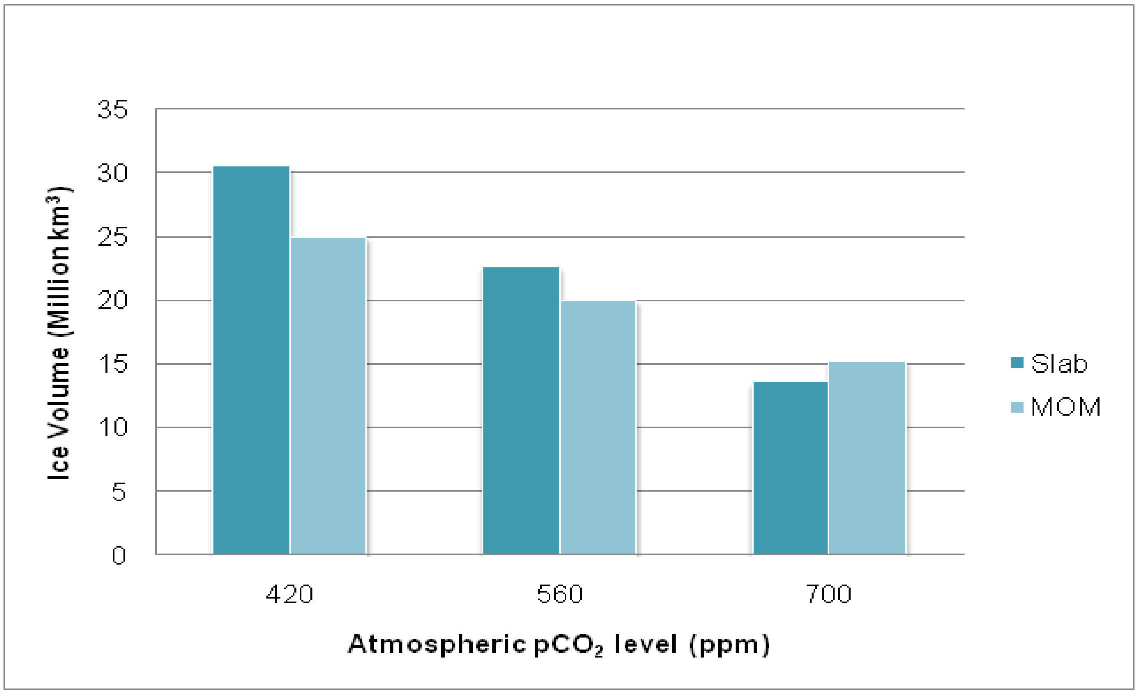


Figure 2. Ice volume (Million cubic kilometers). At each successive atmospheric carbon dioxide level (parts per million), the ice volume for both models is less. However, the difference between carbon dioxide levels is greater in the slab ocean model experiments compared to the MOM experiments. At 420ppm and 560ppm, the slab ocean model experiments result in greater ice volume, but at 700ppm the MOM experimet produced the greater ice volume.

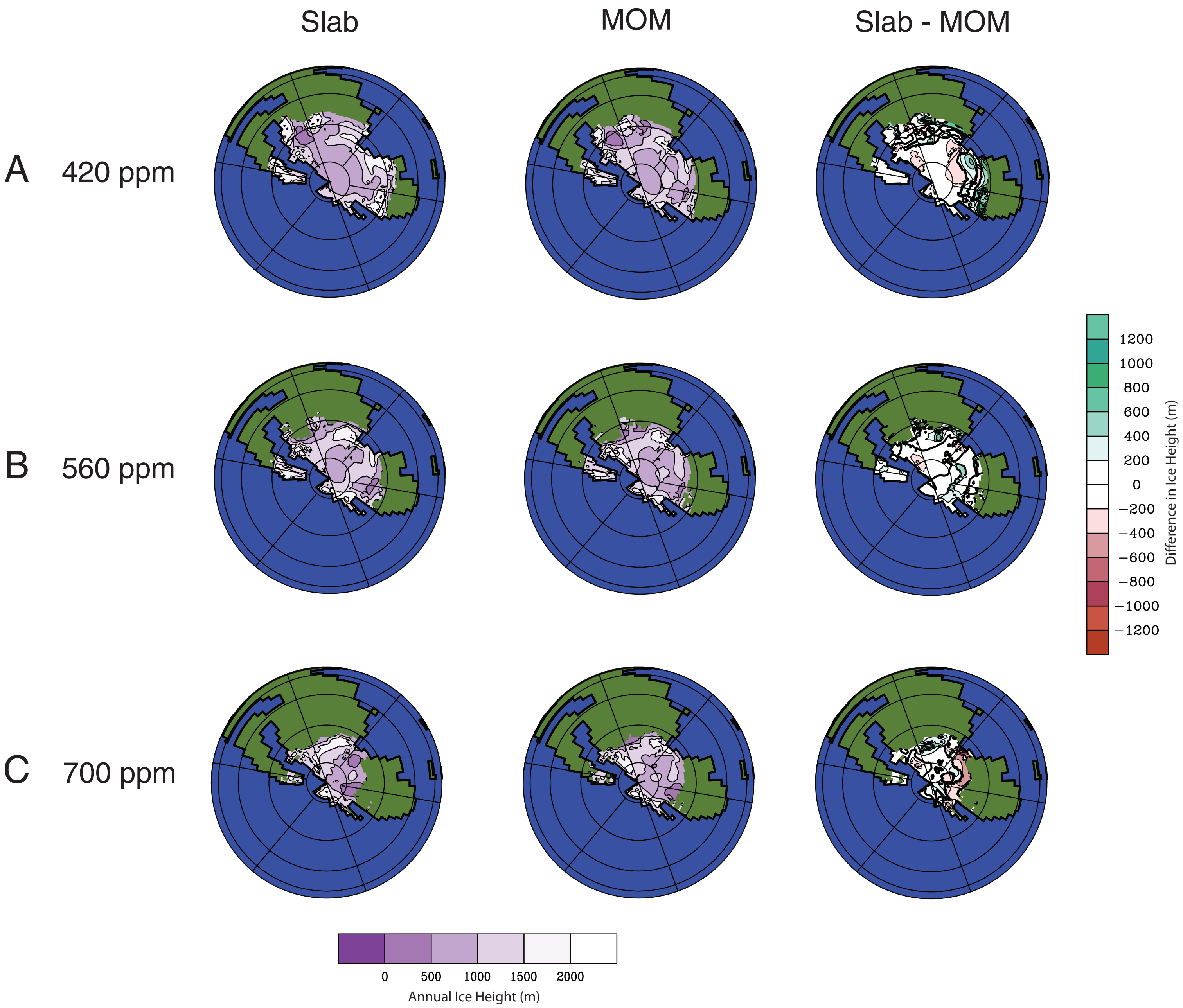


Figure 3. Annual Ice Height (meters). The annual ice height and height difference (slab ocean model minus MOM) is shown for both slab and MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. The ice covers less area at higher values of atmospheric carbon dioxide concentrations for both modeling techniques (shown in the left and middle column). The right column shows the difference in the annual ice height (meters), where positive differences (shades of green) indicate areas where the slab ocean model produced more ice, and negative differences (shades of red) indicate areas where MOM produced more ice for the experiments at a given carbon dioxide level.

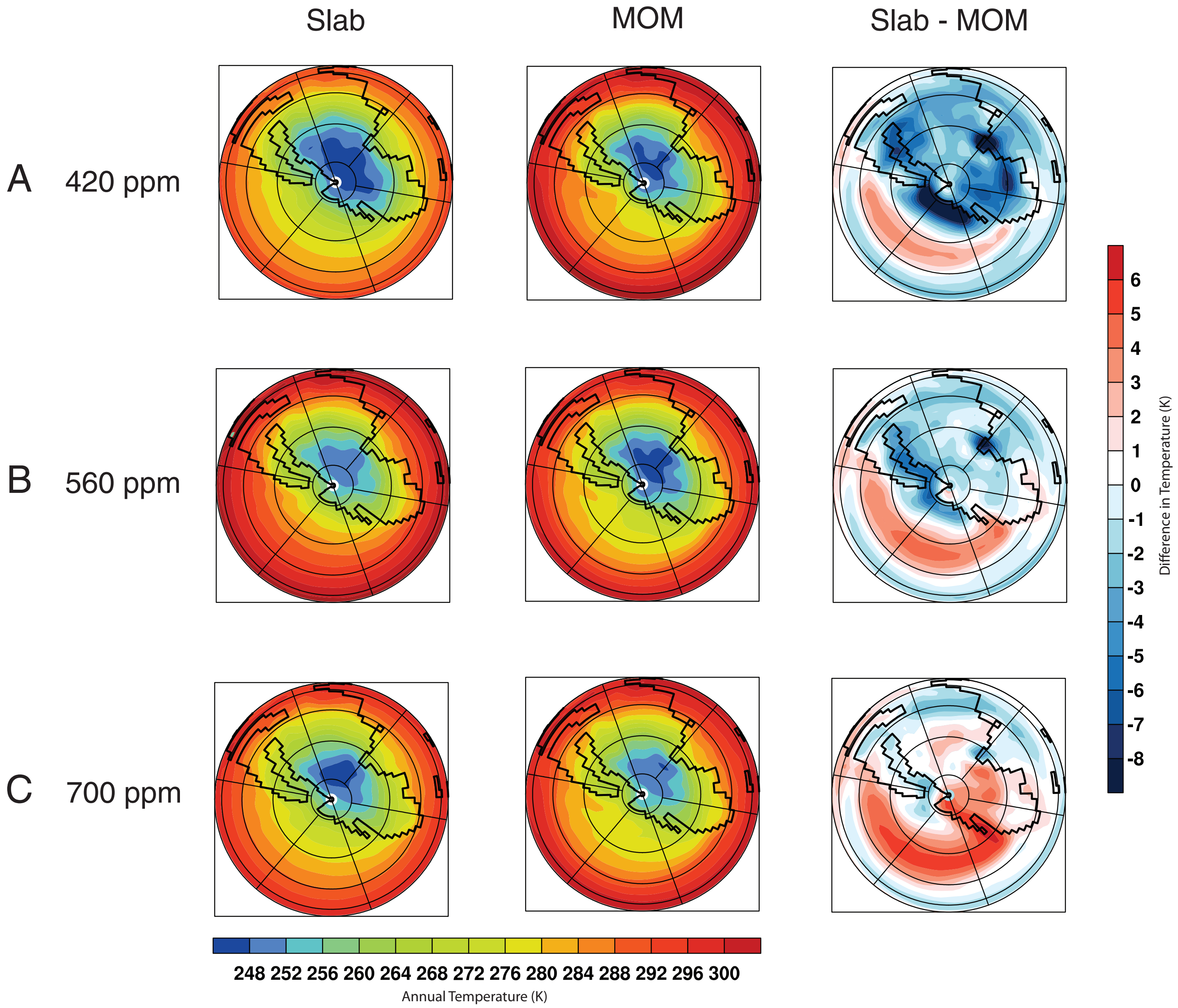


Figure 4. Annual Temperature (Kelvin). The annual temperature and temperature difference (slab ocean model minus MOM) is shown for both slab and MOM experiments at pCO2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. The temperature is greater at each successive atmospheric carbon level (seen in the left and middle columns). The difference in temperature is shown in the right column, with positive differences (shades of red) indicating the slab model experiments produced warmer temperatures and negative differences (shades of blue) indicating the MOM experiments produced the warmer temperature for simulation runs at a given temperature. At A and B, the MOM experiments produce the greater temperatures over Gonwana. This trend ends at C, where the slab ocean model simulations produce warmer temperatures over Antarctica, Australia, India and Africa.

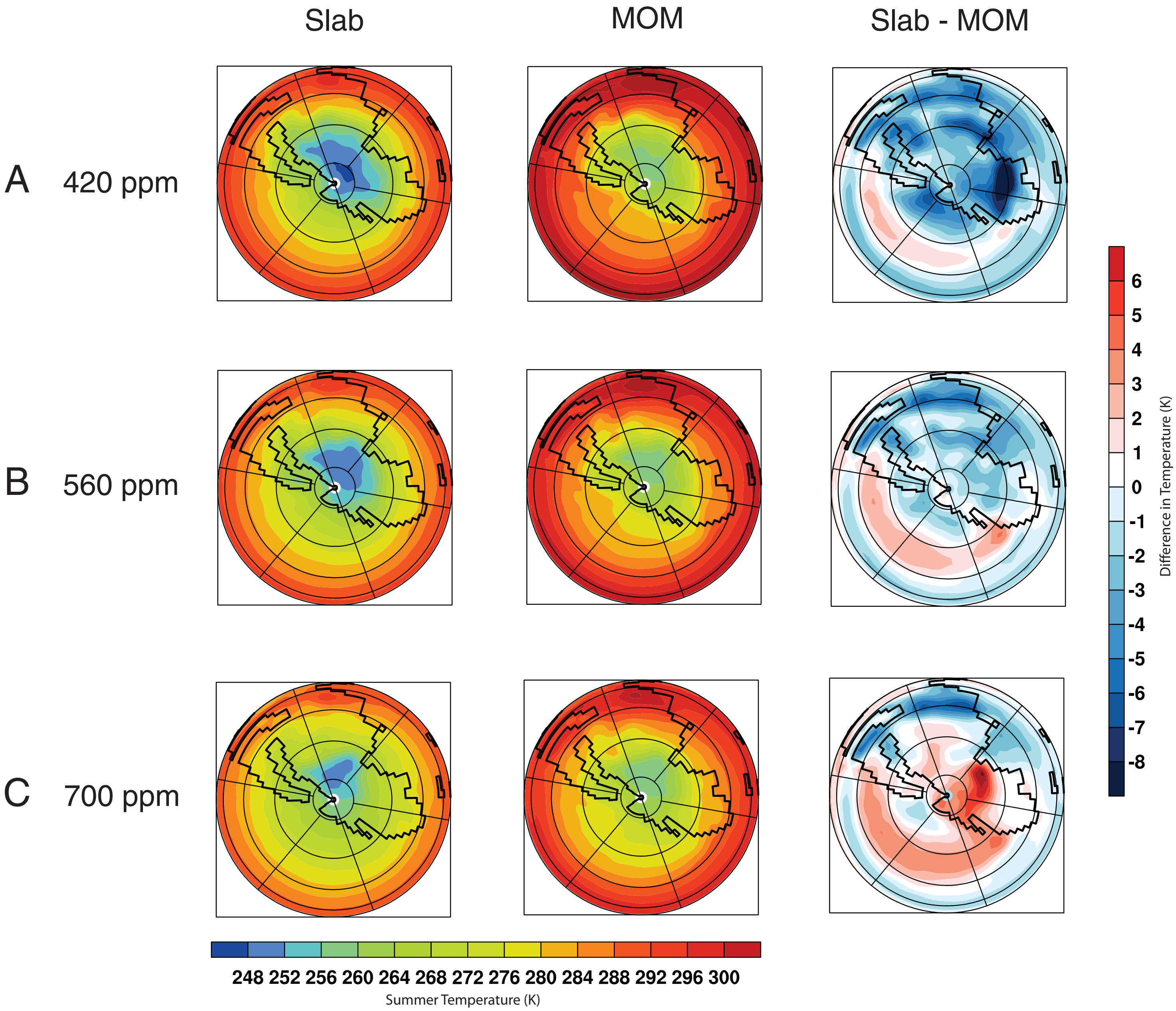


Figure 5. Summer Temperature (Kelvin). The summer temperature and temperature difference (slab ocean model minus MOM) is shown for both slab and MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. The summer temperature is the average temperature during December, January, and February. The temperature is greater at each successive atmospheric carbon level (seen in the left and middle columns). The difference in temperature is shown in the right column, with positive differences (shades of red) indicating the slab model experiments produced greater temperatures and negative differences (shades of blue) indicating the MOM experiments produced the greater temperature for simulation runs at a given temperature. As in annual temperature, the MOM experiments are warmer over Gondwana at A and B, but cooler over most of the supercontinent at high lattitudes at C. However, the difference over the ocean in the polar region is not as pronounced here as it is in the annual temperatures.

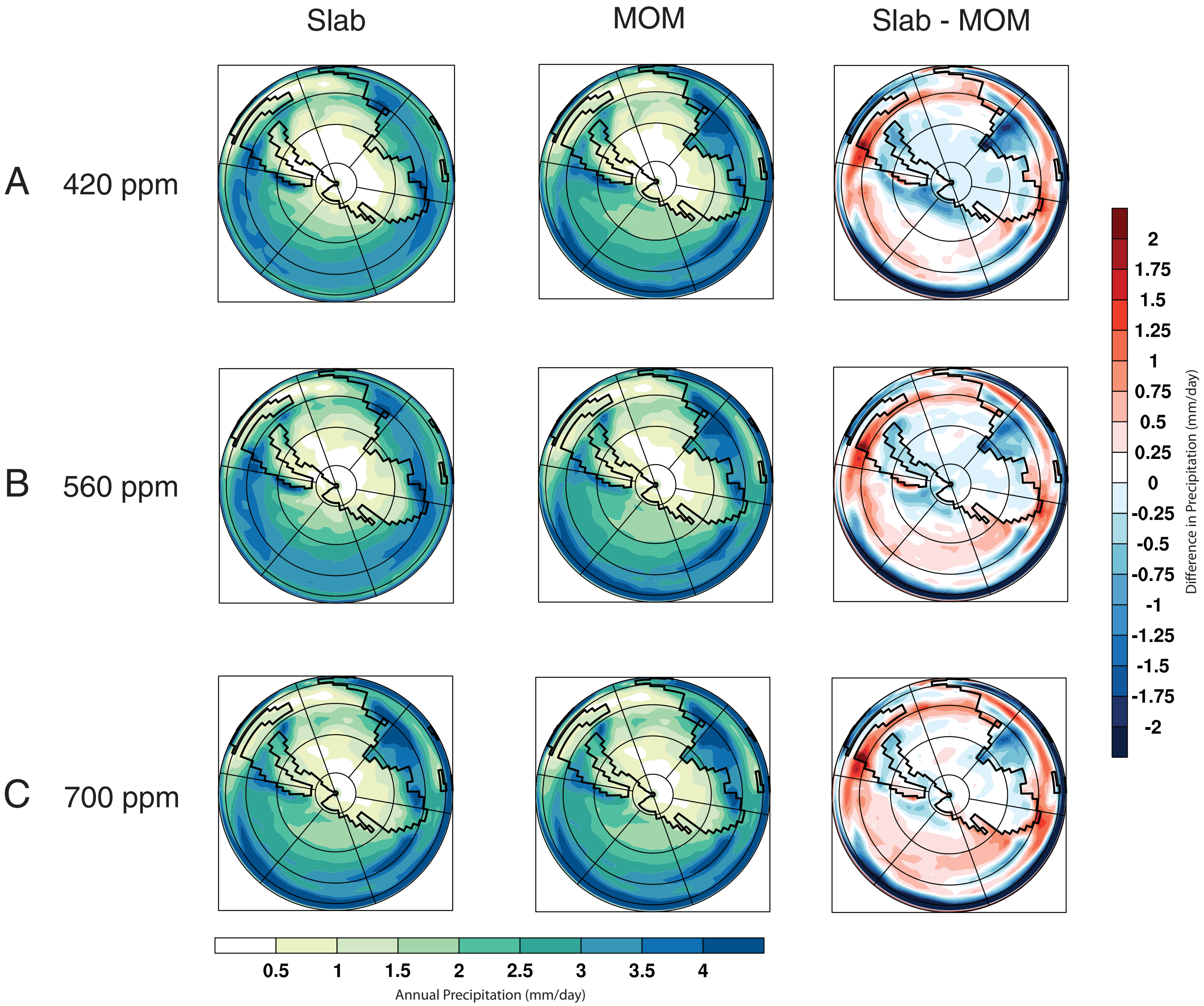


Figure 6. Annual Precipitation (millimeters per day). The annual precipitation and precipitation difference (slab ocean model minus MOM) is shown for both slab and MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. High carbon dioxide levels simulate the wettest climate. The polar region is very dry in all simulations, rarely receiving more than one mm/day of precipitation. The difference in temperature is shown in the right column, with positive differences (shades of red) indicating the slab model experiments produced more precipitation and negative differences (shades of blue) indicating the MOM experiments produced more precipitation. The MOM experiments produced a wetter climate over southern Gondwana in A and B, but the difference between the two modeling methods is negligible at C.

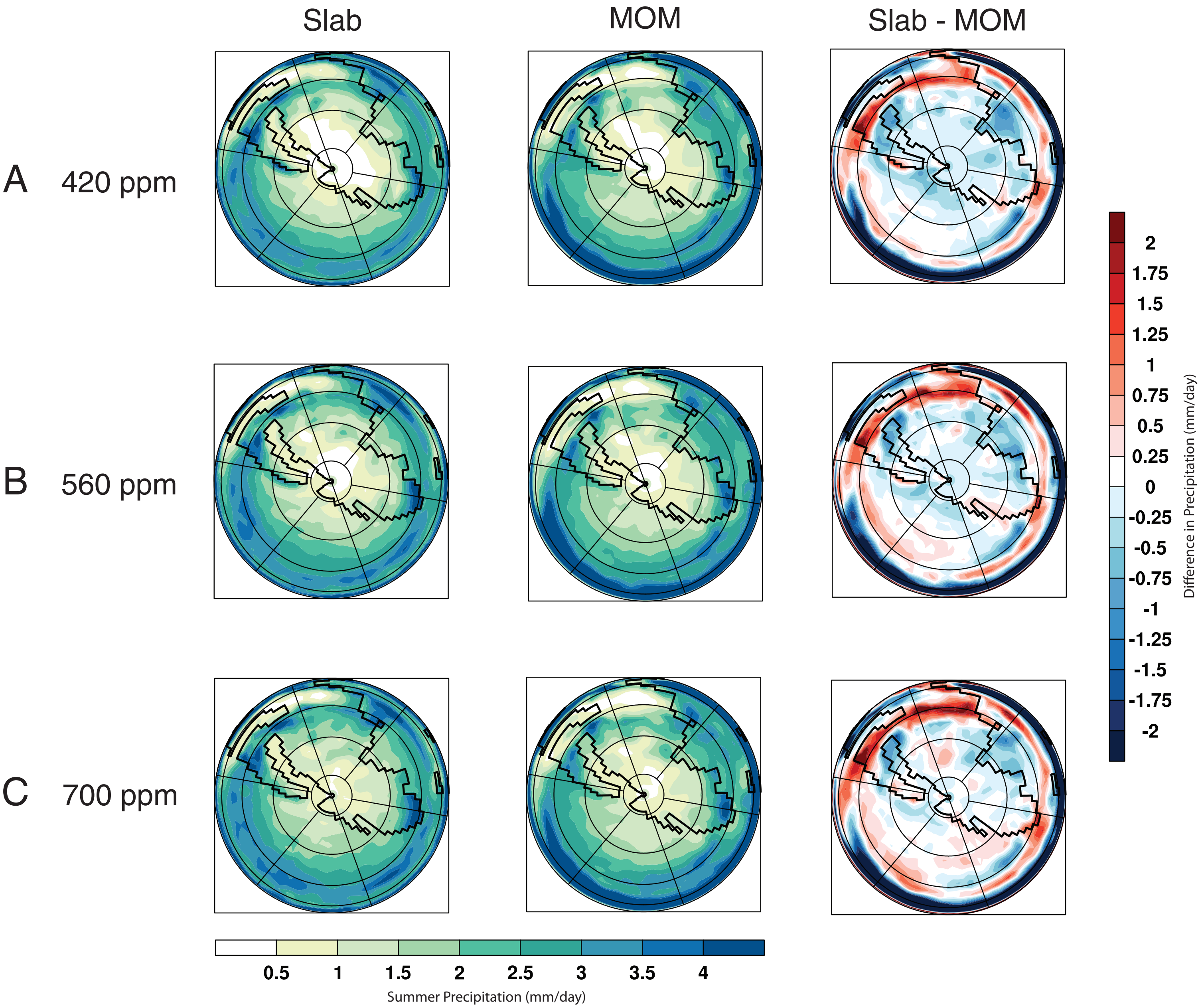


Figure 7. Summer Precipitation (millimeters per day). The summer precipitation and precipitation difference (slab ocean model minus MOM) is shown for both slab and MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. Summer precipitation is the average precipitation in December, January, and February. Similar to the annual precipitation, high carbon dioxide levels simulate the wettest climate, and the summer climate is wetter than the annual climate. The polar region is the driest in all simulations. The difference in temperature is shown in the right column, with positive differences (shades of red) indicating the slab model experiments produced more precipitation and negative differences (shades of blue) indicating the MOM experiments produced more precipitation. The MOM experiments produced a wetter climate over southern Gondwana in A and B, but the difference between the two modeling methods is negligible at C, following the same trend found in annual precipitation.

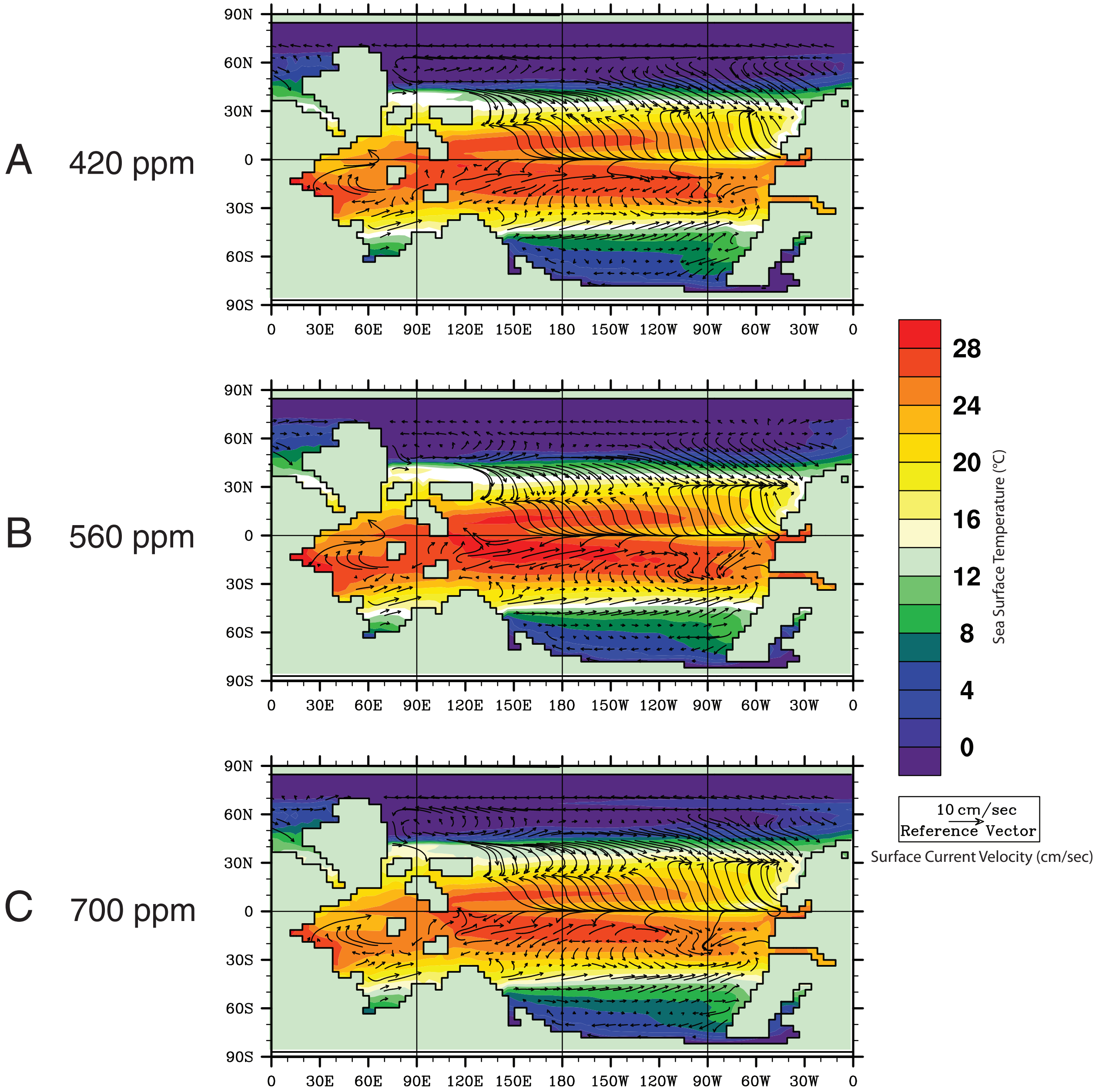


Figure 8. Sea Surface Temperature (°C) and Surface Currents (centimeters per second). The sea surface temperatures and currents for the MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. Sea surface temperatures are warmest at high carbon dioxide levels. Surface currents are generally unchanged, with the only changes occuring in the direction of currents around the equator. Present in all simulations is a polar ocean gyre in the Southern Hemisphere. This moves warmer water south along South America and colder water north along Australia. This affects precipitation and temperature in the area in addition to sea ice.

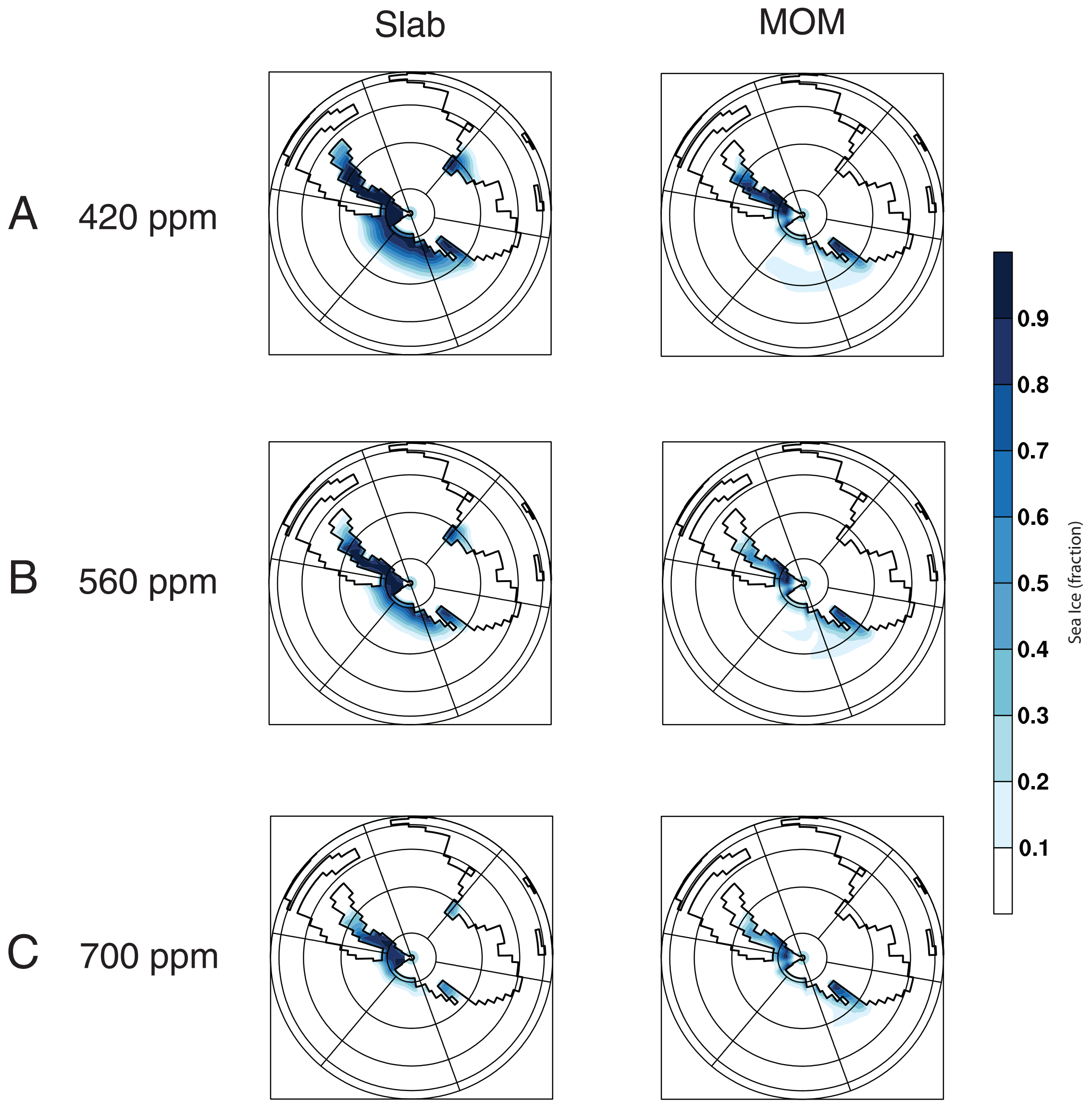


Figure 9. Sea Ice (fraction). The sea ice is ploted as a fraction of the area (0.9 indicates sea ice occupies 90% of the water's surface) for the slab experiments and the MOM experiments at pCO_2 levels of (A) 420ppm, (B) 560ppm, and (C) 700ppm. Sea ice covers significantly more area in the slab experiments at A and B, and at C the difference is not as substantial between the two models. The discrepancies between sea ice can be attributed to ocean circulation present in MOM. The polar ocean gyre can be seen clearly in the MOM simulation at A where a thin strip of sea ice extends from the coast of Australia into the open ocean. This is caused from the gyre bringing cold water into this area.