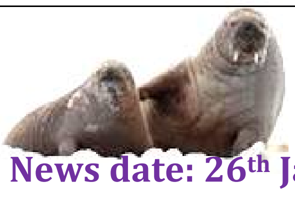
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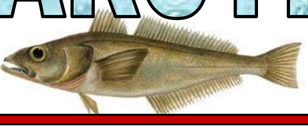


News date: 26th January, 2017 compiled by Dr. Alvarinho J. Luis

Earth's orbital variations, sea ice synch glacial periods

New research shows how sea ice growth in the Southern Hemisphere during certain orbital periods could control the pace of ice ages on Earth.

Earth is currently in what climatologists call an interglacial period, a warm pulse between long, cold ice ages when glaciers dominate our planet's higher latitudes. For the past million years, these glacial-interglacial cycles have repeated roughly on a 100Kyear cycle. Now a team of Brown University researchers has a new explanation for that timing and why the cycle was different before a million years ago.

Using a set of computer simulations, the researchers show that two periodic variations in Earth's orbit combine on a 100Kyear cycle to cause an expansion of sea ice in the Southern Hemisphere. Compared to open ocean waters, that ice reflects more of the sun's rays back into space, substantially reducing the amount of solar energy the planet absorbs. As a result, global temperature cools.

The 100Kyear pace of glacial-interglacial periods has been difficult to explain, said Jung-Eun Lee from Brown's Department of Earth, Environmental and Planetary Studies and the study's lead author. What we were able to show is the importance of sea ice in the Southern Hemisphere along with orbital forcings in setting the pace for the glacial-interglacial cycle.

Orbit and climate

In the 1930s, Serbian scientist Milutin Milankovitch identified three different recurring changes in Earth's orbital pattern. Each of these Milankovitch Cycles can influence the amount of sunlight the planet receives, which in turn can influence climate. The changes cycle through every 100Kyear, 41Kyear and 21Kyear.

The problem is that the 100Kyear cycle alone is the weakest of the three in the degree to which it affects solar radiation. So why that cycle would be the one that sets the pace of glacial cycle is a mystery. But this new study shows the mechanism through which the 100Kyear cycle and the 21Kyear cycle work together to drive Earth's glacial cycle.

The 21-Kyear cycle deals with precession -- the change in orientation of Earth's tilted rotational axis, which creates Earth's changing seasons. When the Northern Hemisphere is tilted toward the sun, it gets more sunlight and experiences summer. At the same time, the Southern Hemisphere is tilted away, so it gets less sunlight and experiences winter. But the direction that the axis points slowly changes -- or precesses -- with respect to Earth's orbit. As a result, the position in the orbit where the seasons change migrates slightly from year to year. Earth's orbit is elliptical, which means the distance between the planet and the sun changes depending on where we are in the orbital ellipse. So precession basically means that the seasons can occur when the planet is closest or farthest from the sun, or somewhere in between, which alters the seasons' intensity.

In other words, precession causes a period during the 21Kyear cycle when Northern Hemisphere summer happens around the time when Earth is closest to the sun, which would make those summers slightly warmer. Six months later, when the Southern Hemisphere has its summer, Earth would be at its furthest point from the sun, making the Southern Hemisphere summers a little cooler. Every 10.5Kyears, the scenario is the opposite.

In terms of average global temperature, one might not expect precession to matter much. Whichever hemisphere is closer to the sun in its summer, the other hemisphere will be farther away during its summer, so the effects would just wash themselves out. However, this study shows that there can indeed be an effect on global temperature if there's a difference in the way the two hemispheres absorb solar energy -- which there is.

That difference has to do with each hemisphere's capacity to grow sea ice. Because of the arrangement of the continents, there's much more room for sea ice to grow in the Southern Hemisphere. The oceans of the Northern Hemisphere are interrupted by continents, which limits the extent to which ice can grow. So when the precessional cycle causes a series of cooler summers in the Southern Hemisphere, sea ice can expand dramatically because there's less summer melting.

Lee's climate models rely on the simple idea that sea ice reflects a significant amount of solar radiation back into space that would normally be absorbed into the ocean. That reflection of radiation can lower global temperature. What we show is that even if the total incoming energy is the same throughout the whole precession cycle, the amount of energy Earth actually absorbs does change with precession, Lee said. The large Southern Hemispheric sea ice that forms when summers are cooler reduces the energy absorbed.

But that leaves the question of why the precession cycle, which repeats every 21Kyears, would cause a 100Kyear glacial cycle. The answer is that the 100Kyear orbital cycle modulates the effects of the precession cycle.

The 100Kyear cycle deals with the eccentricity of Earth's orbit -- meaning the extent to which it deviates from a circle. Over a period of 100Kyear, the orbital shape goes from almost circular to more elongated and back again. It's only when eccentricity is high -- meaning the orbit is more elliptical -- that there's a significant difference between Earth's furthest point from the sun and its closest. As a result, there's only a large difference in the intensity of seasons due to precession when eccentricity is large.

Precession only matters when eccentricity is large. That's why we see a stronger 100Kyear pace than a 21Kyear pace."

Lee's models show that, aided by high eccentricity, cool Southern Hemisphere summers can decrease by as much as 17% the amount of summer solar radiation absorbed by the planet over the latitude where the difference in sea ice distribution is largest -- enough to cause significant global cooling and potentially creating the right conditions for an ice age.

Aside from radiation reflection, there may be additional cooling feedbacks started by an increase in southern sea ice, Lee and her colleagues say. Much of the CO_2 -- a key greenhouse gas -- exhaled into the atmosphere from the oceans comes from the southern polar region. If that region is largely covered in ice, it may hold that carbon dioxide in like a cap on a soda bottle. In addition, energy normally flows from the ocean to warm the atmosphere in winter as well, but sea ice insulates and reduces this exchange. So having less carbon and less energy transferred between the atmosphere and the ocean add to the cooling effect.

Explaining a shift

The findings may also help explain a puzzling shift in Earth's glacial cycle. For the past million years or so, the 100Kyear glacial cycle has been the most prominent. But before a million years ago, paleoclimate data suggest that pace of the glacial cycle was closer to about 40Kyears. That suggests that the third Milankovitch Cycle, which repeats every 41Kyears, was dominant then.

While the precession cycle deals with which direction Earth's axis is pointing, the 41Kyear cycle deals with how much the axis is tilted. The tilt -- or obliquity -- changes from a minimum of about 22 degrees to a maximum of around 25 degrees. (It's at 23 degrees at the moment.) When obliquity is higher, each of the poles gets more sunlight, which tends to warm the planet.

So why would the obliquity cycle be the most important one before a million years ago, but become less important more recently?

According to Lee's models, it has to do with the fact that the planet has been generally cooler over the past million years than it was prior to that. The models show that, when Earth was generally warmer than today, precession-related sea ice expansion in the Southern Hemisphere is less likely to occur. That allows the obliquity cycle to dominate the global temperature signature. After a million years ago, when Earth became a bit cooler on average, the obliquity signal starts to take a back seat to the precession/eccentricity signal.

Lee and her colleagues believe their models present a strong new explanation for the history of Earth's glacial cycle -- explaining both the more recent pace and the puzzling transition a million years ago.

Source: Brown University

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Hemispheric sea ice distribution sets the glacial tempo

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The proxy record of global temperature shows that the dominant periodicity of the glacial cycle shifts from 40-kyr (obliquity) to 100-kyr (eccentricity), about a million years ago. Using climate model simulations, here we show that the pace of the glacial cycle depends on the pattern of hemispheric sea ice growth. In a cold climate the sea ice grows asymmetrically between two hemispheres under changes to Earth's orbital precession, because sea ice growth potential outside of the Arctic Circle is limited. This difference in hemispheric sea ice growth leads to an asymmetry in absorbed solar energy for the two hemispheres, particularly when eccentricity is high, even if the annual average insolation is similar. In a warmer climate, the hemispheric asymmetry of the sea ice decreases as mean Arctic and Antarctic sea ice decreases, diminishing the precession and eccentricity signals and explaining the dominant obliquity signal (40-kyr) before the mid-Pleistocene transition.

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1. Introduction

Paleoproxy data show that Earth's climate undergoes the glacial-interglacial cycle with semi-regular periodicity, with phases strongly linked to orbital variations [*Hays et al.*, 1976; *Huybers and Curry*, 2006; *Imbrie*, 1984; *Imbrie et al.*, 1992; *Lisiecki and Raymo*, 2005]. For the past ~1 Ma, the dominant periodicity has been eccentricity (~100-kyr) embedded with precession (~21-kyr) and obliquity (~40-kyr) signals. Before ~1 Ma, the dominant signal was obliquity with weak eccentricity and precession signals [*Imbrie*, 1984; *Lisiecki and Raymo*, 2005], and this shift is called mid-Pleistocene transition. Due to the predominance of northern hemispheric glaciers, the northern hemispheric insolation is usually the assumed driver of the glacial-interglacial cycle [*Milankovitch*, 1930].

The strong signal of eccentricity (and to a lesser extent, precession) during the past 1 million years has been puzzling because the effect of eccentricity on seasonal insolation is small [*Imbrie et al.*, 1992], although eccentricity modulates precession [*Lisiecki*, 2010]. However, it has been proposed that the 100-kyr cycle may be a modulation of the obliquity signal because the integrated seasonal insolation at a given location does not change with precession [*Huybers*, 2003; 2006]. While there are numerous studies that link paleoproxies to insolation forcings, there is yet no broadly accepted explanation for how ice ages start and why they follow a 100-kyr cycle and why the pace of the glacial cycle changes in mid-Pleistocene.

Two ideas that may be directly contrasted against the proposed mechanism are those of Raymo and Lisieki [*Raymo and Lisiecki*, 2006] and Huybers et al. [*Huybers*, 2006]. Raymo and Lisieki [*Raymo and Lisiecki*, 2006] argue that the observed dominance of obliquity during the (warmer) early Pleistocene/Pliocene is due to a matched reduction in the terrestrial Antarctic ice sheet, which compensates the northern hemispheric glacial change and thereby cancels the global effect of precession and eccentricity under warmer climates. Huybers [*Huybers*, 2006] argue that the obliquity cycle is more important than the other cycles because the intensity and duration of the precessional signal cancel each other out (hotter summers are shorter), and Huybers [*Huybers*, 2003] argue that only obliquity, not precession or eccentricity, shows a statistically significant effect on glacial termination.

Here, we use the NOAA/Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model [*Anderson*, 2004; *Winton*, 2003] to mechanistically understand potential causes of the 100-kyr glacial-interglacial cycle and the transition from 40-kyr to 100-kyr cycles. The southern hemisphere has more potential to grow sea ice in a cold climate because continental landmass surrounds the Arctic Circle, leaving little room for sea ice to grow in the northern hemisphere once the Arctic Ocean is frozen year-round. Sea ice growth is rapid—even seasonal; increased sea ice in the Southern Ocean affects albedo [*Budyko*, 1969], air-ice-sea fluxes [*Hunke and Ackley*, 2001; *McPhee et al.*, 1999], and CO_2 outgassing [*Ferrari et al.*, 2014; *Skinner et al.*, 2010; *Stephens and Keeling*, 2000], amplifying the initial cooling.

2. Method

To understand how insolation forcings influence global temperature, we performed climate model simulations using the GFDL Atmospheric Model version 2.1 (AM2.1) [*Anderson*, 2004] with a slab ocean configuration [*Winton*, 2003], varying orbital parameters and atmospheric CO_2 concentration. The version of the model used does not include potentially significant oceanic feedbacks, but recent work shows that current coarse resolution climate models may have trouble capturing these feedbacks [*Ferreira et al.*, 2015; *Haine et al.*, 2015; *Tomas et al.*, 2016]. The model used also does not have an active land glacier component, but it does have the ability to represent the land processes and the albedo changes due to snow and sea-ice. We expect that increasing model complexity will only modulate, not eliminate, the hemispheric geometric asymmetry at the heart of our mechanism. For each orbital parameter configuration, we performed two sets of runs: one set under present-day greenhouse concentration and another set under a warmer climate to represent the environment before 1 Ma. We note that our study aims to explain the differences in the response of the sea ice under different climate regimes, and not to accurately simulate the climate conditions for the Plio-Pleistocene. Because our simulation did not include changes in ocean circulation, glacial dynamics or active carbon cycling, we could not capture any climate change as a result of these factors. For the same reason, the model equilibrates rapidly to the orbital forcing selected. For each simulation, we ran the model for 35 years and averaged the last ten years for our analysis.

3. Results and discussion

The precession of Earth's longitude of perihelion influences the insolation within each season because Earth orbits the Sun elliptically. The impact of precession is therefore opposite on the northern and southern polar regions. Whichever hemisphere is closer to the Sun in its summer, the other is further away from the Sun during its summer. Thus, the hemispheric effects will cancel out on global average if the precession response is symmetric for the northern and southern hemispheres [*Raymo and Lisiecki*, 2006]. Furthermore, the precessional signal is somewhat compensated due to the negative relationship between the strength and length of a season [*Huybers*, 2006].

However, symmetry under precession is not expected, because the land-ocean configuration of the northern and southern hemisphere is different, so sea-ice and land-ice grow differently and initiate different climate feedbacks. Presently, seasonal variation of the southern hemispheric sea ice is much larger than that of the northern hemispheric sea ice (Figure 1; Table 1), influencing the seasonality of absorbed energy to Earth and leaving the global climate more susceptible to the precessional cycle. There is a pronounced hemispheric pattern for seasonal changes in sea ice extent under global warming [*Eisenman et al.*, 2011]. Sea ice in the Arctic Ocean may be subject to rapid summer melting, whereas austral summertime sea ice in the Southern Ocean can only retreat as far as the Antarctic continent (which occurs at present for ice off of East Antarctica and nearly so for West Antarctica). In an environment cooler than today's, Antarctic sea ice can expand at all longitudes whereas only about 1/6th to 1/12th of the longitudes are open to growing Arctic sea ice through Fram and Bering Straits and the Labrador and Greenland-Iceland-Norwegian Seas.

Although cumulative insolation is similar for June and December perihelion cases [*Huybers*, 2006] (black lines in Figure 2a), stronger summer insolation in December perihelion case can lead to a substantial Antarctic sea ice melt, increasing the actual energy that Earth absorbs (dotted vs. solid blue lines in Figure 2a). As a result, the extent of global sea ice is larger when the southern hemispheric summer insolation is low (June perihelion; Figures 3). Increased extent of Antarctic sea ice during June perihelion induces more reflection of sunlight (high albedo), and thus, there is less net solar energy into the Earth (blue lines in Figure 2b). Due to potential mitigation of asymmetry by clouds, clear sky regions (dotted) are contrasted against the all sky total response (solid in Figure 2b). Absorption of the solar energy is strongly affected by precession in the clear-sky case (blue dotted line), but precession is still evident for the all-sky case (blue solid line) where some compensation due to cloud cover occurs. The open water of the southern hemisphere has more area for a stronger sea ice-albedo feedback than the northern (Figure 3), and since the southern hemisphere receives less solar energy during the June perihelion than during the December perihelion due to increased sea ice, global temperature is lower during the June perihelion than during the December perihelion (Figure 4a). The global mean temperature decreases despite the increase in the northern polar insolation during its summer in June perihelion, because the northern sea-ice energy budget feedback is weaker than the southern. Due to less sea ice overall, the asymmetrical response between two hemispheres to precession is weakened under increased concentration of atmospheric carbon dioxide (Figures 2 & 3).

The changes in insolation due to eccentricity alone with fixed precession are small as previous studies have mentioned [*Imbrie et al.*, 1992], but when coupled with precession, ellipticity effects are amplified. The degree of asymmetrical response to precession is larger with higher eccentricity (Figure 3b), and thus, we expect that the Earth's temperature rhythm will produce an eccentricity signal (100-kyr). A strong 100-kr signal shows up in the spectral analysis because the influence of precession becomes high only when eccentricity is high. Small eccentricity leads to a small precession effect (Figure 3c). Thus, the precession signal is muted when eccentricity is low.

Obliquity affects the global temperature due to variations in latitudinal insolation [*Huybers*, 2006]. This relationship is evident in our runs varying only obliquity (Figure 4d). Global mean temperature is high under high obliquity because summer insolation increases for both polar regions, triggering the feedbacks mentioned. Because winter insolation is almost zero near the polar region, winter insolation variability has few consequences for global temperature. Thus, we affirm the hypothesis of Huybers [*Huybers*, 2006] that both the

Pleistocene and Pliocene experienced climate fluctuations with varying obliquity. Thus, while obliquity effects remain in a warmer world (Figure 4d), precession and eccentricity signals increasingly cancel between hemispheres, so the global effect decreases or disappears (Figures 4a and 4b).

Although northern hemispheric insolation has often been considered the glacial-interglacial driver since Milankovitch's proposal [*Imbrie et al.*, 1992; *Milankovitch*, 1930], several paleoproxies suggest Southern Ocean warming before terminations of ice ages or increases of CO_2 [*Collins et al.*, 2012; *Hays et al.*, 1976]. For example, high-resolution records of a Southern Ocean sea ice proxy show the maximum equatorward extension before the Last Glacial Maximum [*Collins et al.*, 2012], implying that the maximal glacial extent was a response and not the driver of southern hemispheric cooling. Additionally, simultaneous analysis of ice cores and deep ocean isotopic compositions reveal that the global ice volume, and hence the growth of northern hemispheric glaciers, follows the CO_2 increase [*Shackleton*, 2000], refuting the claim that the 100 kyr-cycle may arise from ice sheet dynamics.

In an environment warmer than today's, the response to the precessional forcing is much smaller because summertime Antarctic ice will tend to be much smaller in extent (Figures 2b, 3c and 3d). Furthermore, under warmer conditions, the Antarctic continent reduces the potential for southern hemispheric sea ice loss while the Arctic summer losses are most apparent (as in recent decades). Thus, in a warmer climate, the asymmetry diminishes because the southern sea ice extent during the summer varies little once summer sea ice there has diminished, leading to the dominance of the 40-kyr periodicity. Raymo and Lisiecki [*Raymo and Lisiecki*, 2006] make a similar argument based on changes in land glaciers. They claim that the ablation of the East Antarctic glacier in a warmer climate compensates the change of the northern hemispheric glaciers and decreases the interhemispheric asymmetry. However, glaciers are slow to grow, so we expect that glaciers respond and may strengthen feedbacks in a cooling world, given the simultaneous response of the global glaciers to temperatures [*Denton et al.*, 1999; *Mercer*, 1984; *Putnam et al.*, 2013]. In contrast, sea ice change is rapid and triggers immediate feedbacks, which may incite glacier growth. Furthermore, our modeled sea ice change tends to drive global temperature more consistently than local temperature. Smaller scale local responses, particularly in the polar region, may follow the local insolation signal.

Hemispheric asymmetry also decreases when eccentricity is low. Under low eccentricity, the obliquity signnal is dominant. Therefore, it is no surprise that previous studies argue that glacial terminations are driven by obliquity [*Huybers*, 2003]. During times of high eccentricity, southern hemispheric insolation fluctuates with the precessional cycle and thus frequently, so the duration of warming may not be long enough for glaciers to melt completely [*Raymo*, 1997].

4. Summary and conclusion

In this manuscript, we show that the pace of the glacial cycle depends on the pattern of hemispheric sea ice growth. In the past 1 million years, the dominant glacial cycle has a 100-kyr periodicity because sea ice grows asymmetrically for the two hemispheres in response to the precessional cycle (~21-kyr cycle), particularly when eccentricity (~100-kyr cycle) is high, modulating absorbed solar energy to Earth, although annual mean insolation at a given location is not significantly influenced by precession or eccentricity. Our hypothesis is based on the simple land-ocean configuration of the Earth: sea ice area in the southern hemisphere is more variable in colder climates. While further research will be necessary to explain how the ocean circulation and land glaciers respond to the increase in sea ice, our research provides a new explanation for why the global temperatures have eccentricity and precession signals.

In a warmer climate, however, the hemispheric asymmetry of the sea ice decreases as mean Arctic and Antarctic sea ice decreases, diminishing the precession and eccentricity signals and explaining the dominant obliquity signal (40-kyr) before the mid-Pleistocene transition, about one million years ago. While previous studies showed that sea ice could play a significant role in determining global temperature with varying orbital parameters [*Gildor and Tziperman*, 2001; *Kim et al.*, 1998; *Lee and Poulsen*, 2006], our hypothesis explains how sea ice distribution can modify the pace of the ice age cycle.

We note that our mechanism may not completely resolve how deglaciation is triggered. During the glacial period, icy surfaces cover both hemispheres, and thus, obliquity may be more important in determining the ice age termination [*Huybers and Wunch*, 2005]. We also do not include the dynamical response of the ocean and glaciers in our study; the dynamics of glaciers, as well as atmospheric and oceanic circulation changes, modulate the glacial-interglacial cycle. Characterizing local response is particularly difficult with our current model because the existence of glaciers tend to amplify local responses.

Our study provides how the glacial period may have started in the last million years. When the southern hemisphere receives less solar energy in winter, increased sea ice in the Southern Ocean should trigger positive feedbacks in CO_2, energy balance, and air-ice-sea fluxes [*Ferrari et al.*, 2014; *Skinner et al.*, 2010; *Stephens and Keeling*, 2000], amplifying the initial cooling. Temperature differences arising from atmospheric CO_2 changes and energy loss will propagate globally, amplifying the cooling, and leading to the growth of glaciers and the onset of an ice age [*Shackleton*, 2000].

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Table 1. The total area ($x10^6$ km^2) of monthly maximum, minimum, and the difference between maximum and minimum sea ice distribution [*Rayner*, 2003] averaged from 1980 to 2015.

	NH	SH
Max	13.27	16.39
Min	5.40	2.57
Difference	7.87	13.82

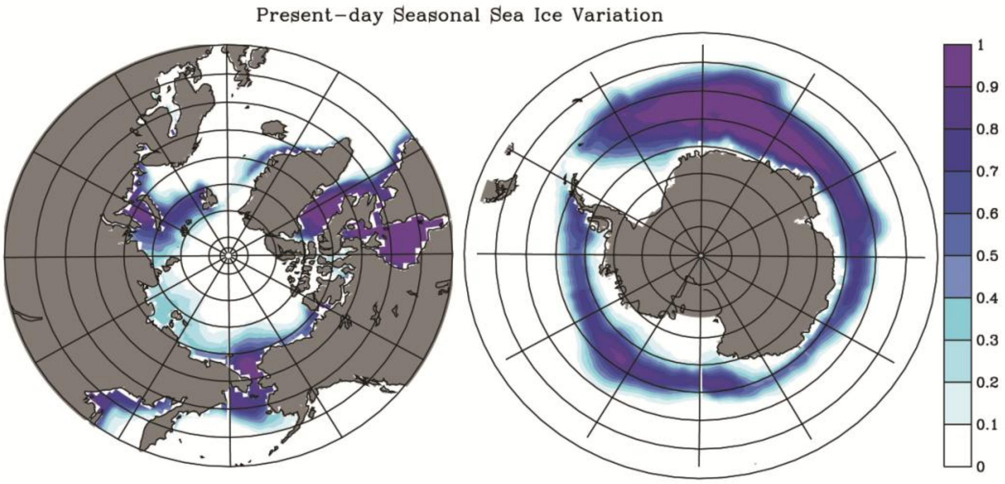

Figure 1. The seasonal difference in maximum (March for the northern hemisphere and September for the southern hemisphere) and minimum (September for the northern hemisphere and March for the southern hemisphere) sea ice extent in the northern (left) and southern hemispheres (right) averaged from 1980 to 2015.

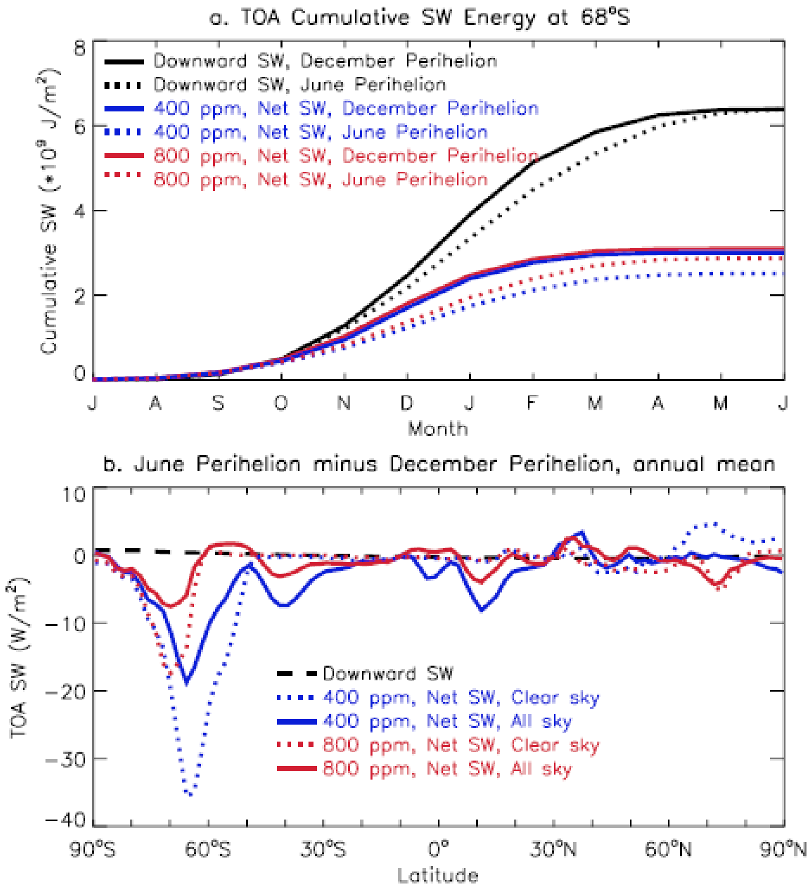

Figure 2. Top-of-the-atmosphere (TOP) cumulative shortwave (SW) energy from July at 68°S for December perihelion (solid lines) and June perihelion cases (dotted lines) (top panel) and the difference in net shortwave energy flux at the top of the atmosphere for the clear (dotted) and all-sky (solid) conditions from June perihelion and to December perihelion cases using GFDL CM2.1. Blue lines indicate the results from CO_2 concentration of 400 ppm, and red lines indicate the results from CO_2 concentration of 800 ppm. Black dashed line represents downward SW energy difference. Obliquity is 23° and eccentricity is 0.05.

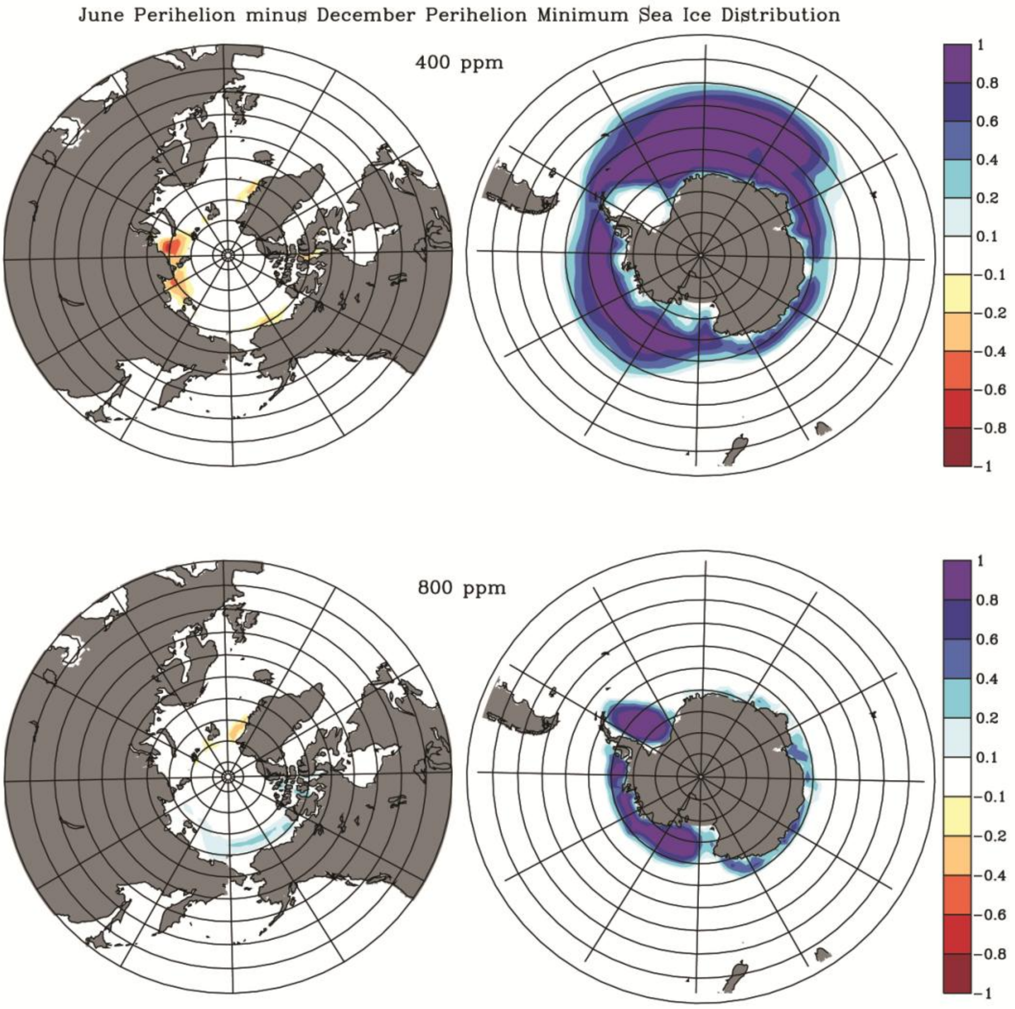

Figure 3. The difference in minimum sea ice extent (March extent for the Southern Hemisphere and September extent for the Northern Hemisphere) from the June to December perihelion using GFDL CM2.1 for 400 ppm (top panel) and 800 ppm (bottom panel) CO_2 concentration cases. Obliquity is 23° and eccentricity is 0.05.

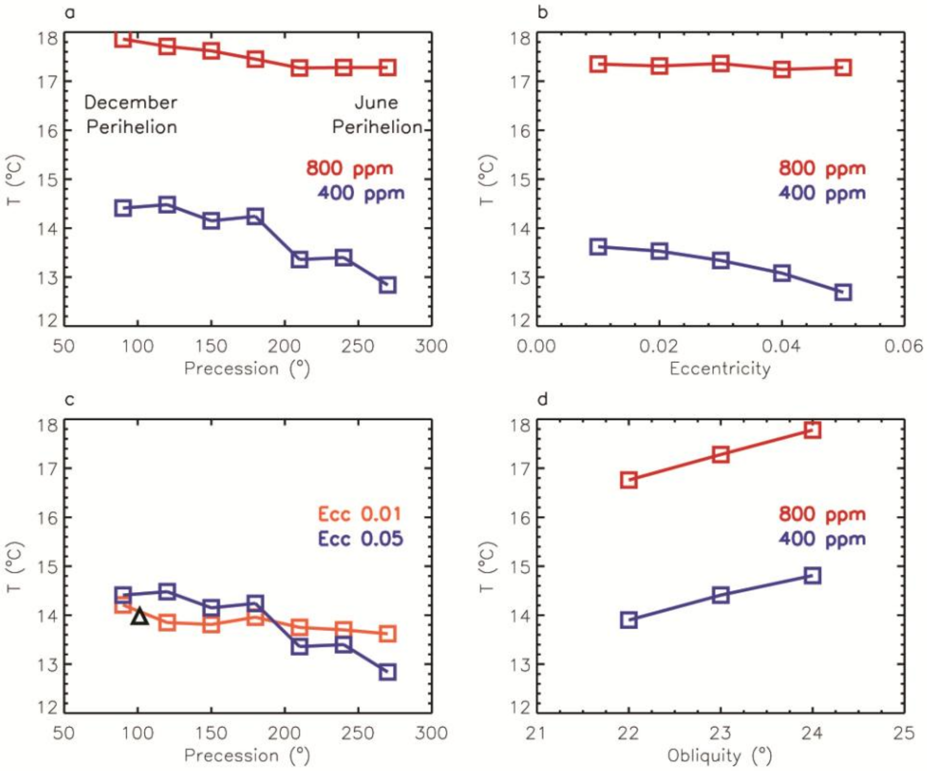

Figure 4. The relationship between global mean temperature and (a) precession in relation with vernal equinox (obliquity and eccentricity are kept constant as 23° and 0.05), (b) eccentricity of Earth's orbit around the Sun (all the cases are for December perihelion with obliquity of 23°), and (c) precession of equinox (obliquity is kept constant as 23°; eccentricity varies between 0.05 and 0.01 for the orange and light-blue line), and (d) obliquity of earth's axial tilt (all the cases are for December perihelion with eccentricity of 0.05) from GFDL AM2.1 with SOM. Blue lines indicate the results from CO_2 concentration of 400 ppm, and red lines indicate the results from CO_2 concentration of 800 ppm. Both cases in (c) are with 400 ppm CO_2. Black triangle shows the orbital parameters and global temperature in 1950, suggesting that the model has a cold bias.