Early Eocene Arctic climate sensitivity to pCO_2 and basin geography

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[1] We present results from new early Eocene (~55–45 Ma) climate modeling experiments with the NCAR Community Climate System Model. These experiments test the sensitivity of climate to a large increase in atmospheric greenhouse gases, such as may have occurred at the Paleocene-Eocene (P-E) boundary (~55.5 Ma), and also allow us to explore the role of Arctic basin configuration on climate. Experiments were run with pCO_2 at 560 and 2240 ppm, and a third experiment, at 2240 ppm, incorporates a passage to a neighboring ocean to explore the potential effect of the ocean on Arctic warming, were the Arctic not isolated. Quadrupling pCO_2 warms the Arctic by ~8°C in the annual average, doubles atmospheric moisture content in this region and eliminates Arctic sea ice, consistent with proxy estimates of warming at the P-E boundary. Opening the Arctic Ocean warms mean annual sea surface temperature by an additional ~4°C. **Citation:** Shellito, C. J., J.-F. Lamarque, and L. C. Sloan (2009), Early Eocene Arctic climate sensitivity to pCO_2 and basin geography, *Geophys. Res. Lett.*, *36*, L09707, doi:10.1029/2009GL037248.

1. Introduction

[2] The primary aim of this paper is to explore the role of high pCO_2 and basin geography on early Eocene Arctic climate using a global climate model. This work is motivated by a long-standing discrepancy between model-produced and proxy inferences of high-latitude temperatures during the warm climates of the early Paleogene (55–45 Ma), particularly at the Paleocene-Eocene Thermal Maximum (~55 Ma) (PETM) and the subsequent Early Eocene Climatic Optimum (EECO) (~50 Ma) [e.g., *Huber and Sloan*, 1999, 2001; *Shellito et al.*, 2003; *Sloan and Barron*, 1992; *Sloan and Rea*, 1995; *Sloan and Thomas*, 1998]. These two warm events have challenged climate modelers, as models of early Eocene climate typically produce temperatures 10–20°C below those estimated by proxies at high latitudes [*Huber and Sloan*, 2001; *Huber et al.*, 2003; *Shellito et al.*, 2003; *Sloan and Rea*, 1995].

[3] Early Eocene temperature estimates for Arctic terrestrial and marine regions range from 10° to 15°C [*Brinkhuis et al.*, 2006; *Eberle et al.*, 2006; *Greenwood and Wing*, 1995; *Jahren and Sternberg*, 2003; *Tripati et al.*, 2001]. TEX_{86}-derived temperature estimates from a marine sediment core dating back to the PETM suggest that summertime Arctic sea surface temperatures likely warmed through this event from 18°C to more than 23°C [*Sluijs et al.*, 2006]. Terrestrial Arctic temperature estimates at the PETM are similarly high [*Weijers et al.*, 2007]. Maintaining such warm high-latitude temperatures would likely require high atmospheric methane and/or pCO_2 through the early Paleogene [*Sloan et al.*, 1999]. There are no proxies for atmospheric methane, and large discrepancies in atmospheric pCO_2 estimates for this time period complicate our understanding of factors that affect climate. Recent estimates place CO_2 above 1500 ppm in the early Eocene [*Lowenstein and Demicco*, 2006], but this is not sufficient to heat the high latitudes [*Shellito et al.*, 2003].

[4] Various other mechanisms have been proposed for high Arctic temperatures, including more vigorous ocean heat transport, polar stratospheric clouds, and cloud feedbacks due to increased number of cloud condensation nuclei [*Kump and Pollard*, 2008; *Sloan et al.*, 1999; *Sloan and Pollard*, 1998]. The role of ocean heat transport has generally been found to play a minor role [*Huber and Nof*, 2006; *Huber and Sloan*, 2001; *Sloan et al.*, 1995] as deep ocean circulation in Eocene simulations is less vigorous than that of present day. Additionally, the closed Arctic geography during this time period makes it difficult to carry sufficient heat to the high latitudes via the ocean in modeling studies. Sedimentary deposits suggest, however, that there were periodic connections with neighboring oceans, and that by the end of the Paleocene a connection from the Arctic to the Tethys was established via the Turgay Straits through the shallow West Siberian Sea. Until the late Eocene (40 Ma), this connection was likely intermittent due to tectonic and eustatic changes [*Radionova et al.*, 2001; *Wang*, 2004].

[5] The presence of the freshwater fern, *Azolla*, in a marine sediment core from IODP Expedition 302 dating back to the PETM is an indicator that the Arctic experienced periods of general freshening during the early Eocene. Estimates of temperature from TEX_{86} show termination of these 'freshwater phases' in the Arctic coincide with an increase in temperature from ~10°C to 13°C [*Brinkhuis et al.*, 2006]. The correlation between the increase in water salinity and increase in temperature suggest that there was reduced freshwater runoff into the Arctic Ocean during warmer intervals, and/or heat transport by surface currents periodically played a role in warming the Arctic.

[6] Here we examine the response of Arctic temperatures and precipitation to pCO_2 and to an influx of warmer water from a neighboring ocean in a global climate model. We consider the role of surface currents in warming the Arctic and whether a high pCO_2 Eocene climate is synonymous with the increases in high-latitude temperature, precipita-

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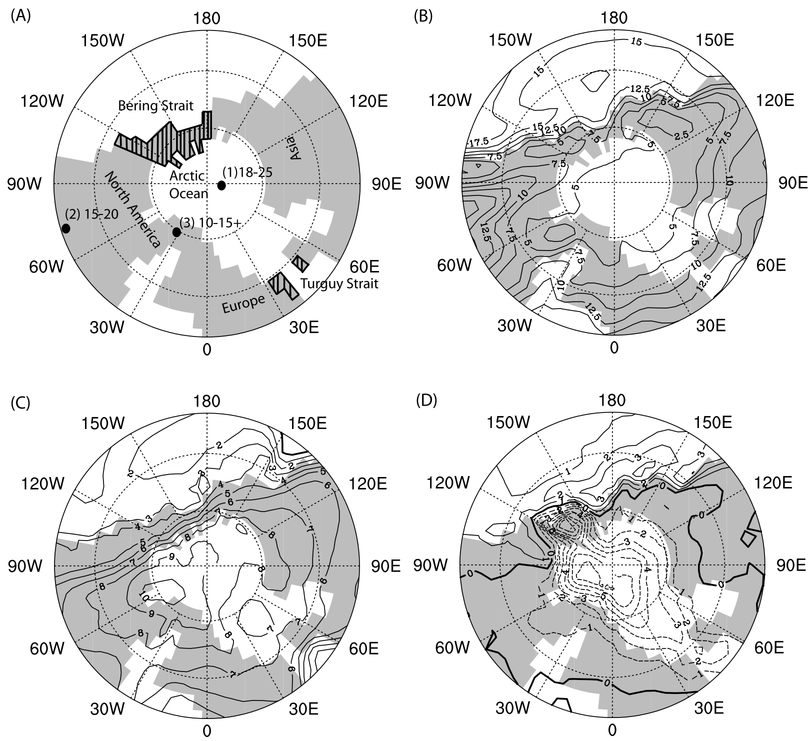

Figure 1. (a) Eocene Arctic basin geography used in experiments and ranges of temperature estimates at various locations for the PETM. Land areas are shaded in grey. Black striped regions are continental areas that were changed to ocean in OPENARC. Sources: (1) (Lomonosov Ridge) [*Sluijs et al.*, 2006]; (2) (Bighorn Basin) [*Wing et al.*, 2000] (pre-PETM estimate), [*Wing et al.*, 2005] (PETM estimate); (3) (Ellesmere Island) [*Tripati et al.*, 2001] (pre-PETM estimate), *Marwick* [1998] estimates >14°C during Early Eocene. (b) Arctic annual average surface temperature in deg C for EO2240 north of 50°N (contour interval is 2.5°C), (c) temperature differences between EO2240 and EO560, and (d) differences between EO2240 and OPNARC. Contour interval for difference plots is 1°C.

tion, and humidity suggested by proxies [*Jahren and Sternberg*, 2003; *Pagani et al.*, 2006].

2. Model and Experimental Design

[7] We employ the National Center for Atmospheric Research Community Climate System Model (CCSM) version 3.0 (described and validated by *Collins et al.* [2006]) with Eocene continental configuration (Figure 1a) and T31 (~3.75° latitude × 3.75° longitude) resolution in the atmosphere and land models. The ocean and ice component models utilize a stretched ocean grid, 25 model levels deep, with a nominal horizontal resolution of 3°. As the ocean model requires that the poles be completely over land, the North Pole in the ocean/ice grid is displaced into Eocene North America (60°N, 80°W), and the South Pole is displaced 6 degrees northward, at 84°S, 46°E. Eocene bathymetry, topography and vegetation schemes are based on those developed by *Sewall et al.* [2000]. The basic scheme used here differs from *Sewall et al.* [2000] in that we have included a ~200 m deep ocean passage way from the Arctic Ocean to the Tethys through the Turgay Straits, as is reasonable for this time period. This shallow passage way allows for little through-flow, but is incorporated to help maintain the global ocean salinity balance in the model.

[8] We conduct two experiments to test the model sensitivity to pCO_2, and a third to test the sensitivity of Arctic climate to basin configuration. In the first experiment, pCO_2 is set at 2x preindustrial (560 ppm), and in the second, it is set at 8x preindustrial (2240 ppm). These cases are hereafter referred to as EO560 and EO2240, respectively. Previous modeling studies have suggested that an increase of at least 1500 ppm is necessary to produce the warming inferred from the geologic record at the high latitudes [*Shellito et al.*, 2003; *Zachos et al.*, 2003]. Background methane was set to the preindustrial value (700 ppb), for consistency with previous studies, and we initialize all experiments without sea ice. Ocean temperatures were initialized based on global average ocean temperature profile from previous Eocene experiments conducted with CSM1.4 [*Huber and Caballero*, 2003; *Huber et al.*, 2003]. In a third experiment, we created a 2000 m deep passageway through the Bering Strait (see Figure 1a). We conduct this 'open Arctic' experiment (hereafter referred to as OPENARC) as a hypothetical scenario to allow us to define an upper bound on the impact of Arctic isolation on modeled Arctic temperatures. While it does not accurately depict conditions of the early Paleogene, this experiment does illustrate the effect of opening up the Arctic to a neighboring ocean. We hope to determine, under optimal circumstances, whether surface currents could deliver sufficient heat to warm the Arctic mean annual temperature by 3°C, as suggested by *Brinkhuis et al.* [2006].

[9] We run each experiment until the atmosphere radiative balance approaches near steady state (530 years for EO2240 and EO560 and 480 years for OPENARC). At this point, surface ocean temperatures have equilibrated. The

energy balance at the top of the model is 0.702 W/m^2 in EO560, -0.05 W/m^2 in EO2240 and -0.01 W/m^2 in OPENARC. Thus, EO2240 and OPENARC are near steady state, while EO560 is still undergoing a very slight cooling trend (<0.02°C per decade in the global mean temperature). We attribute this to an initial ocean temperature profile that is too warm for this scenario. This ultimately has some impact on equilibrated temperatures reported for the EO560 scenario. The primary implication this has for our results is that the temperature differences reported between the low and high pCO_2 scenarios represent minimal sensitivity associated with a quadrupling of atmospheric pCO_2. Ultimately, this does not have a significant impact on the overriding conclusions of this study which are based primarily on a comparison of the high pCO_2 scenarios with proxy data.

3. Results

[10] Annual average global mean temperature is 3.99°C warmer in EO2240 than in EO560. At T31 resolution, the sensitivity of the NCAR CCSM3 with a slab ocean to a doubling of pCO_2 is a global mean temperature increase of 2.32°C [*Kiehl et al.*, 2006]. We expect global sensitivity to be somewhat less than this in these experiments due to the warm nature of EO560 and due to the fact that these experiments test sensitivity at a higher level of CO_2. The greatest warming occurs in the Polar regions, due in part to reduced sea-ice albedo feedback in the high pCO_2 scenario. Through the low and middle latitudes, sea surface temperatures (SSTs) are 2°C warmer and terrestrial temperatures are 4°C warmer. Mean annual Antarctic terrestrial temperatures are ~6°C warmer in EO2240, and Arctic SSTs (Figures 1b and 1c) are as much as 8.5°C warmer. Wintertime Arctic surface air temperatures (not shown) remain mostly above freezing in EO2240, and approach freezing only along the Canadian Arctic coastline. Arctic summertime temperatures in EO2240 are as warm as 15°C along the coastline, but range between 2–7°C in the central Arctic basin. These central Arctic temperatures are still at least 3°C cooler than the lower end of mean annual temperature estimates by *Brinkhuis et al.* [2006] for the early Eocene Arctic, and ~14°C cooler than the estimates of *Sluijs et al.* [2006] for the central Arctic summertime temperatures at the PETM. However, the modeled warm summer temperatures along the Arctic coast do approach the inferred late Paleocene temperature of 18°C [*Sluijs et al.*, 2006].

[11] Annual average global mean temperature in OPENARC is comparable to that of EO2240. However, opening up the Bering Strait increases average Arctic mean annual SSTs by ~4°C (Figure 1d). Central Arctic ocean temperatures warm by as much as 5°C annually (as much as 7–9°C in the summer, and 2–3°C in the winter). Annual average SSTs reach as high as 10°C (as estimated by *Brinkhuis et al.* [2006] for the early Eocene) along the coast of northern Europe in OPENARC, compared with ~7°C in EO2240. Along the coast of North America, ocean temperature is nearly the same in both experiments. This Arctic warming is mostly due to increases in heat fluxes from the ocean to the atmosphere in the vicinity of the Bering Strait, and greater northward heat transport in the atmosphere along the Gulf of Alaska, across the region that is occupied by mountains in EO2240. While this is a hypothetical scenario, the average temperature rise of ~4°C agrees with the estimated increase in temperature associated with periodic connections to neighboring oceans during the early Eocene [*Brinkhuis et al.*, 2006].

[12] The presence of the *Apectodinium* in the Arctic core spanning the PETM, suggests that the Arctic was ice-free year-round at this time [*Sluijs et al.*, 2006]. In EO560, the central Arctic maintains ~20% ice coverage through the summer. As the first evidence for ice-rafted debris does not appear until the middle Eocene (45 Ma), this lower pCO_2 scenario may be more representative of this time period [*Moran et al.*, 2006; *St. John*, 2008]. In EO2240, there is only a small amount (<5% coverage) along the Arctic coastline even in winter. Sea ice is negligible year-round in OPENARC.

[13] Proxy studies suggest that the Arctic experienced an increase in rainfall during the PETM [*Jahren and Sternberg*, 2003; *Pagani et al.*, 2006]. Figure 2 depicts cumulative annual precipitation in the Arctic basin, which increases from 20–40 cm/yr in EO560, to 30–55 cm/yr in EO2240 (a 40–50% increase over EO560), and to 45–70 cm/yr in OPENARC (a 30–50% increase over EO2240). The increase in precipitation in the higher pCO_2 scenarios may be due to enhanced wintertime convective precipitation over an ice-free Arctic [*Abbot et al.*, 2009], as well as a northward shift in the storm track. In OPENARC, opening the Bering Strait allows for additional ocean and atmospheric heat transport through this region and enhanced convective activity.

4. Discussion and Conclusions

[14] While Arctic surface temperatures generated in these experiments are still below those inferred from proxies for the PETM and the early Eocene, the differences in temperature and precipitation between the three experiments have some important implications for further modeling studies and for continued investigation of hypotheses regarding mechanisms supporting a warm high-latitude climate.

[15] Many studies have suggested that global precipitation increased at the PETM, and that humidity, precipitation, and runoff were high during the early Eocene [*Bowen et al.*, 2004; *Brinkhuis et al.*, 2006; *Crouch*, 2001; *Jahren and Sternberg*, 2003; *Pagani et al.*, 2006]. *Jahren and Sternberg* [2003] estimated the water content of the Eocene Arctic atmosphere at about twice that of today. The EO2240 and OPENARC experiments are consistent with this, with annual zonal averaged specific humidity at 70°N reaching higher than 5 g/kg in the surface layer, compared to 2.4 g/kg estimated empirically for the modern Arctic [*Serreze et al.*, 1995]. We note that the increase in atmospheric water content over the Arctic Ocean can be attributed entirely to the rise in temperature.

[16] Analysis of hydrogen isotopes from Arctic Ocean sediments [*Pagani et al.*, 2006] and $\delta^{18}O$ in fossil forests [*Jahren and Sternberg*, 2002] point to a primary source of Arctic precipitation in the tropics and/or subtopics, and suggest that reduced rainout during transport would have reduced mid-latitude precipitation as it increased high latitude precipitation. Both of the high pCO_2 experiments in this study, EO2240 and OPENARC, show an increase in

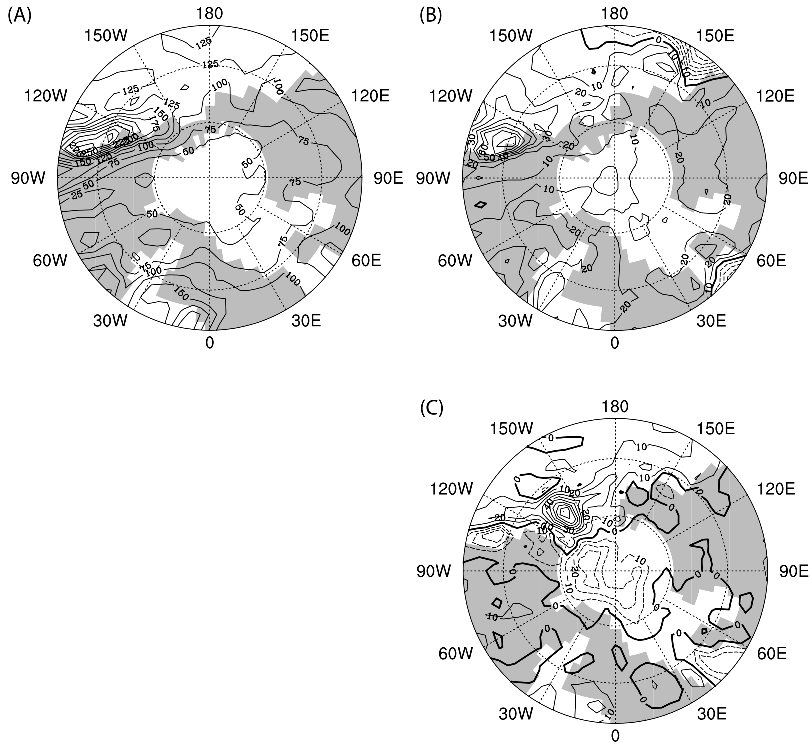

Figure 2. (a) Annual average precipitation (cm/yr) northward of 50°N for EO2240. Contour interval is 25 cm/yr. (b) Annual average precipitation difference (cm/yr) between EO2240 and EO560 (EO2240-EO560). (c) Annual average precipitation difference between EO2240 and OPENARC (EO2240-OPENARC). Contour interval for Figures 2b and 2c is 10 cm/yr.

high latitude precipitation, as well as a slight decrease in mid-latitude precipitation. EO2240, consequently, shows enhanced freshening of the Arctic, consistent with proxies at the onset of the PETM [*Pagani et al.*, 2006]. Northward moisture fluxes in mid to high latitudes, which have considerable longitudinal variation, increase in the high pCO_2 scenarios. This is likely due to the large increase in specific humidity in a warmer world.

[17] The EO560 and EO2240 experiments demonstrate that a 1680 ppm increase in atmospheric pCO_2 can produce at least ~8°C warming in mean annual Arctic surface temperature. This change in temperature is greater than that inferred by *Sluijs et al.* [2006] across the PETM, despite the low climate sensitivity in these experiments. Absolute temperatures, however, are still not representative of those inferred from proxies. If we consider only greenhouse gas loading, and assume that the temperature estimates of *Sluijs et al.* [2006] (~18°C prior to the PETM and 23°C at the PETM) represent summertime warmth, these modeling experiments suggest that prior to the PETM, atmospheric greenhouse gas concentrations must have been very high. At higher levels of pCO_2, surface temperatures will become less sensitive to additional inputs, particularly if the Arctic is ice-free initially. Thus, this work further supports the idea that there are additional mechanisms responsible for high latitude warmth at this time, and warrants further investigation of such mechanisms as polar stratospheric clouds [*Sloan and Pollard*, 1998], a dramatic shift in weather patterns as suggested by oxygen isotopes [*Jahren and Sternberg*, 2002] or tropical cooling and northward heat transport via tropical cyclones [*Emanuel*, 2001; *Korty et al.*, 2008].

[18] The OPENARC experiment supports the assertion that influx of warmer water from adjacent ocean basins can lead to an increase in MAT of 3–5°C in the Arctic basin, as may have happened during the early Eocene. Further studies with more realistic and detailed boundary conditions (coastline shape, topography, and bathymetry), as well as finer spatial and temporal resolution will provide a clearer understanding of this process from the late Paleocene through the early Eocene. *O'Regan et al.* [2008] suggest that the Lomonosov Ridge in the central Arctic was near the surface, although, still below sea level during this time. Changing the size or depth of the Arctic Ocean and/or Arctic passageways and bathymetry would allow for a more thorough examination of the role of ocean currents in transporting heat into the Arctic through the Paleogene. Overall, these experiments support the role of high pCO_2 in maintaining Arctic warmth and underscore the need for continued work to identify high latitude warming mechanisms. The fact that summertime temperatures in EO2240 along the Arctic coastline begin to approach the inferred late Paleocene temperature of ~18°C [*Sluijs et al.*, 2006; *Weijers et al.*, 2007] is promising. We suggest that further modeling studies of the late Paleocene and early Eocene consider 2240 ppm CO_2 a minimum, a pre-PETM or "background" state on which to test climate sensitivity to higher greenhouse gas levels.

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