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Temperature differences between the hemispheres and ice age climate variability

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[1] The Earth became warmer and cooler during the ice ages along with changes in the Earth's orbit, but the orbital changes themselves are not nearly large enough to explain the magnitude of the warming and cooling. Atmospheric CO_2 also rose and fell, but again, the CO_2 changes are rather small in relation to the warming and cooling. So, how did the Earth manage to warm and cool by so much? Here we argue that, for the big transitions at least, the Earth did not warm and cool as a single entity. Rather, the south warmed instead at the expense of a cooler north through massive redistributions of heat that were set off by the orbital forcing. Oceanic CO_2 was vented up to the atmosphere by the same redistributions. The north then warmed later in response to higher CO_2 and a reduced albedo from smaller ice sheets. This form of north-south displacement is actually very familiar, as it is readily observed during the Younger Dryas interval 13,000 years ago and in the various millennial-scale events over the last 90,000 years.

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1. Introduction

[2] Ice cores from Antarctica have produced two kinds of records. Records from the center of Antarctic extend back 650,000 years and cover six long cycles [*Petit et al.*, 1999; *Siegenthaler et al.*, 2005]. Records from the coast are shorter in time but resolve more of the variability over the last 90,000 years [*Indermühle et al.*, 2000; *Monnin et al.*, 2001; *EPICA Community Members*, 2006; *Ahn and Brook*, 2008]. Both kinds of records show that Antarctica warmed and cooled along with the level of CO_2 in the atmosphere. The problem is that the relationship between Antarctic temperatures and atmospheric CO_2 has been interpreted very differently over the two time scales.

[3] Figure 1 [from *Ahn and Brook*, 2008] exemplifies the shorter records. Temperature and CO_2 records from Antarctica (Figures 1b and 1c) are shown along with records from Greenland in the Northern Hemisphere. The Antarctic records feature a series of "millennial-scale events," identified by the labels A1–A7, in which the temperatures in Antarctica and the level of CO_2 in the atmosphere rise and fall together over some 5000–10,000 years.

[4] During the millennial events, Greenland cools while Antarctica warms, and vice versa. The CO_2 increases also lag slightly behind the warmings in Antarctica, as shown in more detail by *Ahn and Brook* [2007]. Thus, the greenhouse effect from atmospheric CO_2 clearly did not make Greenland *or* Antarctica warmer and cooler over the millennial time scale, and a mechanism is needed to explain why the temperatures in Antarctica rose and fell along with atmospheric CO_2.

[5] The long records from the center of Antarctica are better known [*Petit et al.*, 1999; *Siegenthaler et al.*, 2005]; two such records are reproduced in section 5. They feature big transitions every 100,000 years or so in which Antarctica warms by up to 10°C while the level of CO_2 in the atmosphere rises by up to 100 ppm. Figure 1 includes the most recent big transition, which took place between 10,000 and 20,000 years ago.

[6] One expects the warming and cooling from atmospheric CO_2 to be a global phenomenon, and indeed the whole Earth seems to warm and cool together over the longer time scales. Hence, it is natural to assume that the CO_2-temperature relationship in the long records from Antarctica is causal, i.e., that the increases in atmospheric CO_2 warmed Antarctica and the rest of the planet [*Genthon et al.*, 1987; *Lorius et al.*, 1990; *Hansen et al.*, 2007]. But the same relationship is seen during the millennial events, and the CO_2-temperature relationship during the millennial events is clearly not causal. Can two such disparate views both be correct?

[7] A close look shows that Antarctica and the polar north did not warm and cool at the same times; the two hemispheres *became* warm together over the longer cycles but only *after* the big transitions in Antarctica had already occurred. Both kinds of transitions, millennial and long term, seem to involve displacements of heat that allow the south to warm at the expense of the north. The displacements over the longer cycles are simply larger versions of the millennial displacements. Atmospheric CO_2 rises and falls via the displacements that warm and cool the south.

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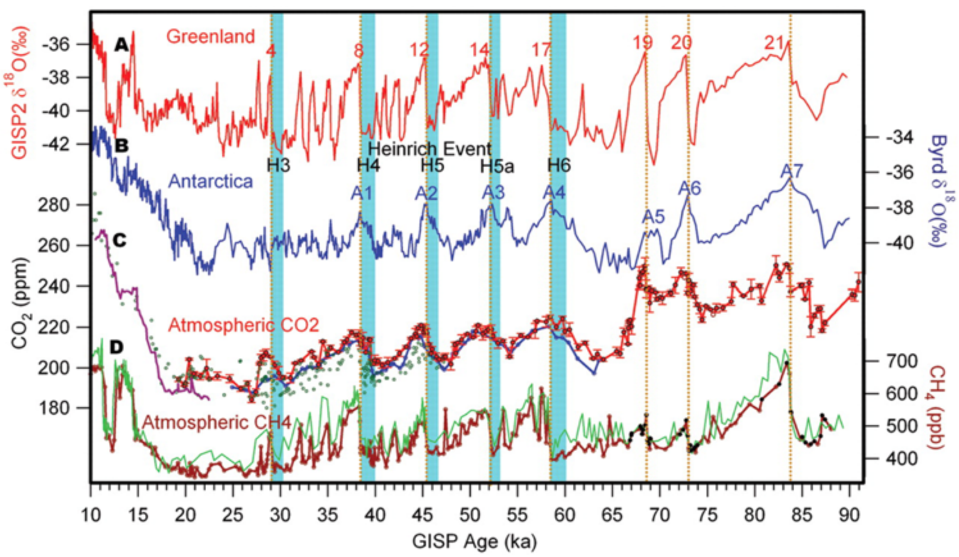

Figure 1. Millennial-scale events recorded in ice core records from Greenland and Antarctica over the last 90,000 years. (a) Proxy for air temperature over Greenland. (b) Proxy for air temperature over Antarctica. (c) Atmospheric CO_2 recorded in Antarctica. (d) Atmospheric methane from Greenland (green) and Antarctica (brown). Vertical bars denote Heinrich stadials H3–H6. Blue labels A1–A7 denote millennial-scale events in which the level of CO_2 in the atmosphere increases while Antarctica warms [*Blunier and Brook*, 2001]. Greenland warms abruptly as Antarctica cools after warm peaks A1–A7. From *Ahn and Brook* [2008, Figure 1]. Reprinted with permission from AAAS.

[8] For the purposes of this paper, the phrase "big transitions" is an explicit reference to the abrupt warmings and CO_2 increases seen in the Antarctic ice cores. "Terminations" refer to the demise of the northern ice sheets. The age of a termination is the time when the northern ice sheets are wasting away most rapidly.

2. North-South Temperature Differences During the Millennial Events

[9] The millennial-scale events in Antarctica (Figure 1) were initiated by inputs of fresh water that weakened the meridional overturning circulation in the Atlantic (hereafter AMOC) [*Bond et al.*, 1993; *Blunier et al.*, 1998]. The weakened overturning cooled the North Atlantic and initiated an out-of-phase warming in the Southern Hemisphere. *Broecker* [1998] called this out-of-phase relationship the "bipolar seesaw."

[10] According to *Broecker* [1998], the ocean's overturning is maintained by the downward mixing of heat across the thermocline, which allows old lighter water to be displaced upward by younger denser waters flowing into the interior from the poles. If the production of denser water is reduced in one hemisphere it must increase in the other to compensate. From this perspective, the seesaw should make one hemisphere warmer and then the other. This is not quite what we see, however.

[11] The Northern Hemisphere is systematically warmer than the Southern Hemisphere, especially in the sector containing the Atlantic Ocean (Figure 2). So, when the south warms during the millennial events, the temperature

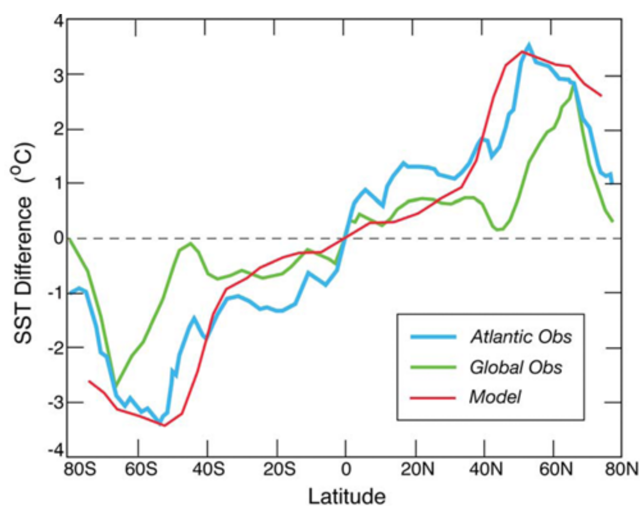

Figure 2. Zonally averaged sea surface temperature (SST) plotted as a departure from the mean SST for each latitude. The bold blue curve is derived from observed SSTs in the Atlantic Ocean. The green curve is derived from observed SSTs over the whole ocean. The red curve represents the SST difference between two model simulations, one with a circumpolar channel and an interhemispheric overturning circulation and one without. From *Toggweiler and Bjornsson* [2000, Figure 11]. Observed SSTs are averages of the upper 50 m in the *Levitus* [1982] climatology.

difference between the hemispheres is actually flattened or even reversed. When Greenland is warm and Antarctica is cold after the millennial events, the north-south temperature difference is enhanced.

[12] This asymmetry is due to the Antarctic Circumpolar Current (ACC) and the westerly winds that drive the ACC around Antarctica. The ACC circles the globe in an east-west channel that lies along the southern edge of the westerly wind belt in the Southern Hemisphere. The stress from the westerlies on the ocean draws old deep water up to the surface from the interior. New deep water sinks in the North Atlantic to compensate for the water drawn up by the winds in the south [*Toggweiler and Samuels*, 1995].

[13] The ACC's channel limits the poleward flow toward Antarctica to depths below 2000 m. Thus, the winds over the channel draw water from the middle depths of the ocean up to the surface and push it away to the north. As the upwelled water moves northward it takes up solar heat that would otherwise warm Antarctica and carries this heat across the equator into the North Atlantic [*Crowley*, 1992; *Toggweiler and Bjornsson*, 2000]. This leads to a cooler south and a warmer north.

[14] So what made Antarctica warmer and cooler over time? According to *Toggweiler et al.* [2006], the southern westerlies at the Last Glacial Maximum (LGM) were located well to the north of the ACC. In this position, the westerlies were not in a good position to draw middepth water to the surface around Antarctica. As a result, the ocean around Antarctica was very cold and was capped by a low-salinity surface layer and a thick layer of sea ice. According to *Anderson et al.* [2009], this began to change when an input of icebergs and meltwater to the North Atlantic suppressed the AMOC and cooled the Northern Hemisphere in a way that caused the Intertropical Convergence Zone (ITCZ) and the trade winds in the tropics to shift to the south. The southern westerlies then shifted to the south along with the trades. This shift put the southern westerlies squarely over the ACC, where they began drawing warmer and saltier middepth water to the surface. These warmish middepth waters displaced the near-freezing surface waters around Antarctica, melted back the sea ice, and warmed the continent.

[15] The warmish middepth water was also high in CO_2 that had been respired from sinking particles. So, southern westerlies that were more squarely over the ACC drew more CO_2-rich water to the surface, which then vented from the ocean up to the atmosphere. This is how the temperatures in Antarctica and the level of CO_2 in the atmosphere managed to rise together during the big transitions.

3. ITCZ, AMOC, and Precessional Cycle

[16] The precession of the Earth's axis tends to make the summers in one hemisphere warmer and cooler every 23,000 years; summers in the opposite hemisphere are cooler and warmer in an antiphase way. Thus, precessional cycles, like the millennial events, alter the temperature contrast between the hemispheres. The main new idea taken up in this paper is that precessional cycles and millennial events are related and that they come together every 100,000 years or so to produce to produce a giant millennial event, which features an outsized warming of Antarctica. Section 6 describes why these events are so unusual, but first an important distinction needs to be made regarding the ways that the millennial events and precessional cycles alter the north-south contrast.

[17] The ITCZ is a band of convection and enhanced precipitation that is positioned above the warmest ocean waters in the tropics. Because the Northern Hemisphere is systematically warmer than the Southern Hemisphere, the ITCZ is generally found north of the equator. This leads to a well known asymmetry in the trade winds that flank the ITCZ. During a typical year the northern trades are well to the north of the equator between 10°N and 20°N, while the southern trades extend up to the equator from the south. During El Nino years, the ITCZ shifts toward the equator from the north and the asymmetry is reduced. This causes the southern trades to shift off the equator to the south and leads to especially warm temperatures along the equator in the eastern equatorial Pacific.

[18] The warming at the end of the last ice age took the form of two steps [*Monnin et al.*, 2001] in which Antarctica warmed, cooled slightly for a couple thousand years, and then warmed again. The two steps occurred during Heinrich stadial 1 (HS1) and the Younger Dryas (YD), times when the overturning circulation in the Atlantic (the AMOC) was suppressed and the winters around the North Atlantic were extremely cold [*Denton et al.*, 2005]. Our claim, following *Anderson et al.* [2009], is that a colder North Atlantic caused the ITCZ and the trade winds to shift from their usual northern positions toward the equator and the south. The southward displacement in the tropics then led to a more poleward position for the westerly band further south.

[19] The warm summers produced by the precessional cycles have a similar effect that can be seen quite clearly in the monsoons. In this case, the increased summer insolation warms the land more than the adjacent ocean and causes the ITCZ over the land to shift into the hemisphere that is receiving more insolation [*Wang et al.*, 2006]. *Timmermann et al.* [2007] show that the same sort of response extends over the ocean. When the insolation is more intense during northern summers, the SSTs north of the equator are warmer than normal and the ITCZ and trade winds are shifted more strongly into the Northern Hemisphere. When the insolation is more intense during southern summers, the temperature contrast across the equator is relatively flat and the ITCZ and trade winds are shifted toward the equator and the south (Figure 3).

[20] *Lisiecki et al.* [2008] show that the AMOC seems to be stronger when the insolation during southern summers is more intense, i.e., the AMOC is stronger when the north is *cooler*, which is opposite to the situation during the millennial events. A widely used indicator of the strength of the AMOC over time is the changing $\delta^{13}C$ of the shells of benthic foraminifera from middepth Atlantic cores. A more positive $\delta^{13}C$ is interpreted to reflect a greater input of northern water that fills the middle depths of the Atlantic and pushes out the lighter bottom waters from Antarctica. Lisiecki et al. show that the $\delta^{13}C$ in middepth Atlantic cores

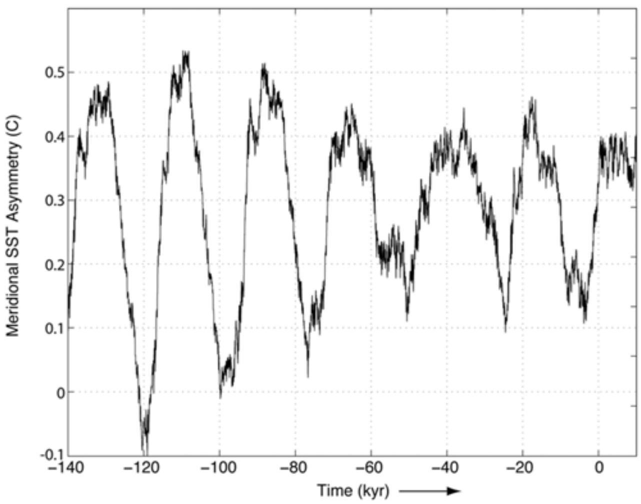

Figure 3. Sea surface temperature difference between 5°N–12°N and 5°S–12°S in the eastern equatorial Pacific over the last 140,000 years in response to orbitally induced insolation changes. Result of a model simulation. The north is warmest in relation to the south when the closest approach of the Earth to the Sun (perihelion) occurs during northern summer. The SST difference is close to zero when the perihelion occurs in southern summer. From *Timmermann et al.* [2007, Figure 4].

is more positive when the insolation during southern summers is more intense.

[21] The phasing identified by *Lisiecki et al.* [2008] is supported by oceanic temperature changes in the middle latitudes of the Southern Hemisphere. *Barrows et al.* [2007] have compiled SST proxies from four subantarctic cores and find that SSTs are cooler between 130,000 and 70,000 years ago when the insolation would otherwise have favored warmer summers. Antarctica is cooler at the same times [*Kawamura et al.*, 2007]. The simplest explanation for the cooling at 45°S is that a stronger AMOC is carrying more Southern Hemisphere heat into the Northern Hemisphere at these particular times. A stronger AMOC at these times is consistent with Lisiecki et al.'s δ^{13}C results.

[22] The reason why the AMOC responds to the precessional forcing in this way is not entirely clear. The explanation to be entertained here is that the southern westerlies are stronger or more poleward shifted when the ITCZ is closer to the equator, as they appear to be during the millennial events. But the AMOC, rather than being suppressed, is spun up instead. This makes for an important distinction regarding the properties measured in the Antarctic ice cores.

[23] Figure 4 is a schematic illustration of the ocean's overturning circulation. During the millennial events, the red circulation in Figure 4 (the AMOC) cannot spin up because it is being actively suppressed. Thus, in this case, poleward shifted westerlies spin up the deeper blue circulation instead and draw middepth water from the blue domain up to the surface right around Antarctica. The level of CO_2 in the atmosphere increases along with the temperatures in Antarctica because a stronger blue circulation reduces the accumulation of CO_2 in the ocean's interior from sinking particles [*Ito and Follows*, 2005; *Toggweiler et al.*, 2006].

[24] When the westerlies shift poleward in response to the precessional forcing, and the AMOC is *not* suppressed, the red circulation appears to spin up instead. Antarctica does not warm in this case because southern heat is being transported to the Northern Hemisphere. Atmospheric CO_2 does not increase either because the red circulation is enhanced in relation to the blue.

4. Evidence for Changes in Winds

[25] *Haug et al.* [2001] found that the inputs of titanium and iron to sediments of the Cariaco Basin (11°N) on the continental shelf north of Venezuela were sharply reduced during the Younger Dryas. They interpreted these reduced inputs as evidence for lower rainfall over northernmost South America (6°N–10°N) that was caused by a shift of the ITCZ out of the 6°–10° band toward the south. Less rainfall over South America led to less river runoff and less titanium and iron in Cariaco Basin sediments. *Lea et al.* [2003] show that the surface waters over the Cariaco Basin were 3°C–4°C cooler during HS1 and the YD and call for a rapid southward shift of the ITCZ and the northern trades to explain the cooling. Similar ITCZ shifts seem to have occurred during all the other millennial events [*Peterson et al.*, 2000].

[26] *Haug et al.* [2001] also found that the ITCZ and the trade winds were shifted northward during the early Holocene when the northern summer insolation was at a maximum. The

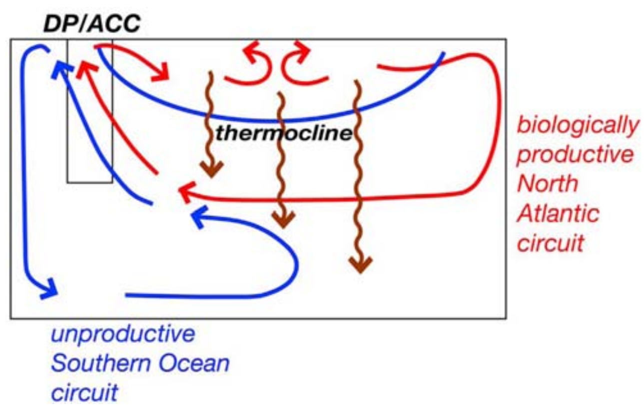

Figure 4. Diagram illustrating the ocean's overturning circulation and its relationship to atmospheric CO_2. The overturning is reduced to two components, a northern sourced circulation (red) and a deeper southern sourced circulation (blue). Both circulations are closed via upwelling within the box labeled DP/ACC (Drake Passage/Antarctic Circumpolar Current). Nutrient supply via the red circulation gives rise to CO_2 uptake from the atmosphere and sinking particles (brown squiggly lines), from which CO_2 is respired in the interior. CO_2 accumulates in the blue domain when a weak blue circulation impedes the venting of respired CO_2 back up to the atmosphere. The level of CO_2 in the atmosphere rises when the blue circulation is strong in relation to the red. From *Toggweiler et al.* [2006].

ITCZ and the trades have since shifted back toward the equator as the insolation is stronger now during southern summers than during northern summers. This supports the idea that the ITCZ responds in similar ways to changes in the temperature contrast across the equator, whether by the precessional forcing or the millennial events.

[27] In a study of the sediment composition at ODP site 1233, *Lamy et al.* [2007] found that the surface waters off the coast of Chile warmed rather abruptly during HS1 and the YD in a way that is similar to the two warming steps in Antarctica. ODP site 1233 is located at 41°S in the transition zone between warm subtropical waters and the cooler waters along the northern edge of the ACC. Lamy et al. argued that a poleward shift of the westerlies at these times displaced the cooler ACC waters to the south and brought about the warming off Chile. As with the ITCZ records above, similar warmings occurred off the coast of Chile during all the other millennial events [*Kaiser et al.*, 2005].

[28] *Anderson et al.* [2009] show that the poleward shift of the westerlies extended into the zone around Antarctica. Anderson et al. discovered two pulses of opal deposition in the region south of the Antarctic Polar Front (53°S–62°S) that took place during HS1 and the YD. The rate of opal burial during the two pulses was about five times larger than the rate of burial during the LGM (just prior to the two pulses). This points to a massive change in upwelling that increased the delivery of silica up to the surface, which Anderson et al. attribute to poleward shifted westerlies. The rate of opal burial during the two pulses is twice the rate of burial at the core top, which means that the upwelling around Antarctica was greater during HS1 and the YD than it is now. This is significant because it suggests that the southern westerlies were stronger or closer to Antarctica during HS1 and the YD when winters in the Northern Hemisphere were especially cold.

5. North-South Differences Over Glacial-Interglacial Cycles

[29] The big glacial-interglacial cycles were originally discovered in the δ^{18}O variations of ocean-dwelling foraminifera and these variations were found to evolve over time with a sawtooth-like shape [*Broecker and van Donk*, 1970]. The classic sawtooth is actually an amalgam, however, of distinctly different patterns that come from the north and south. This is seen quite readily in Figure 5 [from *Kawamura et al.*, 2007]. Figure 5 includes two records from the south and two from the north.

[30] The temperature record from Antarctica (orange curve) is plotted in Figure 5a along with the summer insolation at 65°N (red curve). The second record from the top (Figure 5b) is atmospheric CO_2. The two records at the bottom (Figures 5c and 5d) depict the volume of ice in the northern ice sheets. Figure 5c is a record of sea level. Figure 5d is a proxy for ice volume, inverted to match the sea level curve, which was derived from benthic δ^{18}O records with the temperature effect on δ^{18}O removed.

[31] The marine isotope stages are labeled above and below the Antarctic temperature curve at the top. The warm interglacials, stages 1, 5, 7, and 9, fall during the first halves of the longer cycles, while the cold glacial intervals, stages 2–4, 6, and 8, fall during the second halves. *Hays et al.* [1976] pointed out years ago that the eccentricity of the Earth's orbit and the amplitude of the precessional forcing tend to be greater during the interglacials than during the glacials. Thus, the red insolation curve in Figure 5 is observed to swing up and down more strongly during the first halves of the longer cycles.

[32] Isotope stages 5, 7, and 9 have been subdivided into substages a, b, c, d, and e to mark the times when the precessional forcing is especially strong and weak. As a point of clarification, the substage labels usually refer to the maxima and minima in foraminiferal δ^{18}O records [*Tzedakis et al.*, 2004]. *Kawamura et al.* [2007] applied the labels to maxima and minima in the Antarctic air temperature record instead, which generally coincide with maxima and minima in northern summer insolation. This makes the individual substages slightly older but does so in a way that is more useful in the analysis here.

[33] The most striking feature of the temperature pattern in Antarctica is the way that warm temperatures are front loaded into the first half of each cycle. In this regard, a big warm peak leads off each cycle during the "e" substages of stages 5, 7, and 9. Antarctica is then cold during the second half of each cycle when temperatures remain close to the glacial minimum. The same basic pattern is seen in the CO_2 record: large CO_2 increases occur during the e substages and low and relatively flat CO_2 levels extend through the glacial stages 2–4, 6, and 8.

[34] The ice volume records (Figure 5d) are quite different in this regard. The corresponding "a," "c," and "e" peaks in the north are delayed by about 5000–10,000 years with respect to the peaks in the south. More importantly, the e peaks in ice volume do not stand out like they do in Antarctica, which means that most of the buildup of ice and most of the drop in sea level is limited to the second halves of the longer cycles, i.e., stages 2–4, 6, and 8. Also, unlike the situation in the south, where the second half temperatures remained low and constant, the build up of ice in the north continues right up to the next termination.

[35] The two hemispheres therefore do not warm and cool together. This general point has been made before [*Crowley*, 1992] and is seen in the lead of Antarctic temperatures and tropical SSTs over δ^{18}O [e.g., *Hays et al.*, 1976; *Imbrie et al.*, 1992; *Shackleton*, 2000; *Lea et al.*, 2000]. Our concern here is less with the southern lead than with what it implies about the temperature contrast between the hemispheres.

[36] Antarctica is warmest on the terminations when the ice sheets in the north are melting back but are still fairly large and are still keeping the north relatively cool. During glacial onsets, Antarctica has cooled to its glacial minimum level by the ends of stages 5, 7, and 9 when the northern ice sheets are just starting to grow. Thus, terminations are times with the smallest temperature difference between the hemispheres. Glacial onsets, delineated by the isotope stage boundaries 5/4, 7/6, and 9/8, are the times with the largest temperature difference. This would appear to be no accident: the biggest climate transitions seem to occur when the

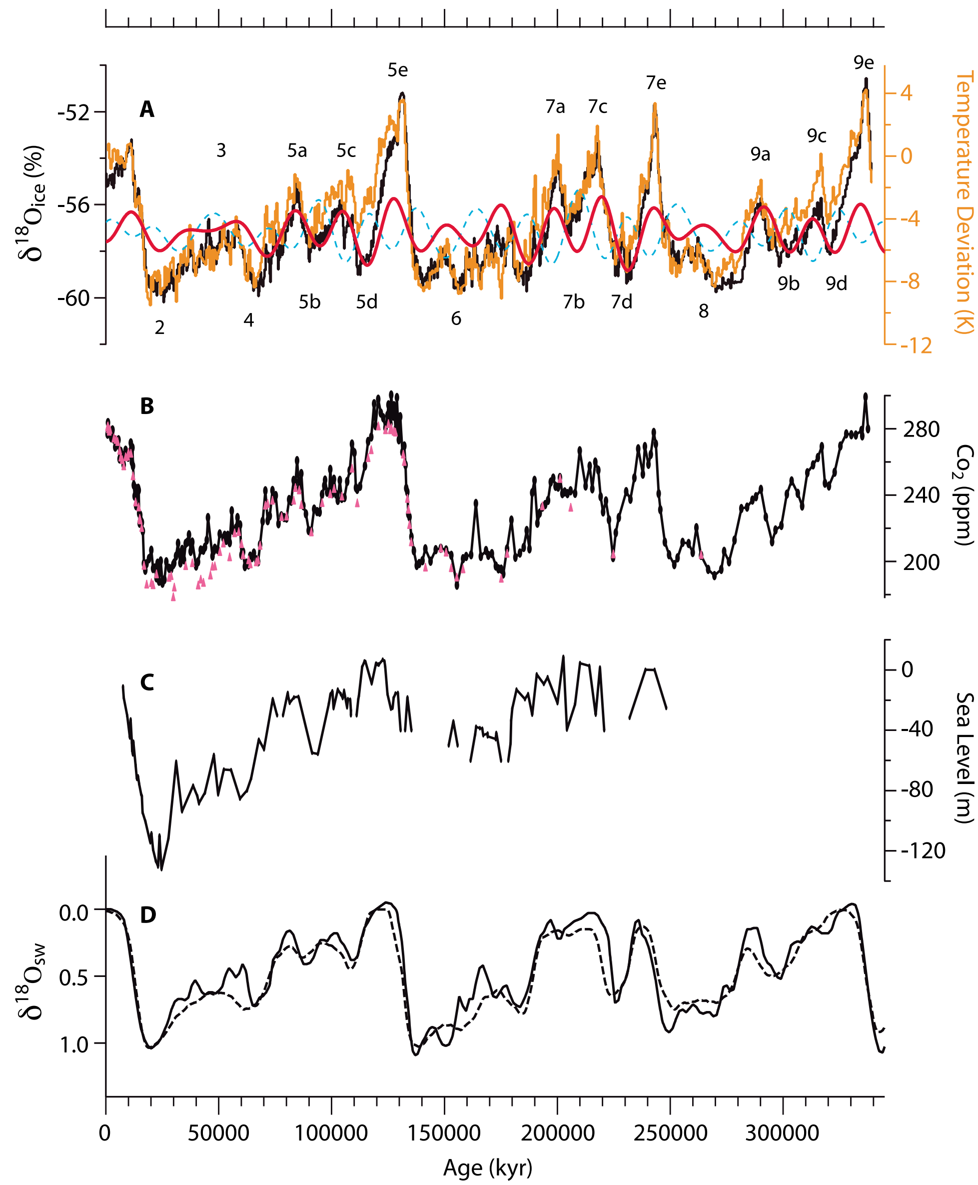

Figure 5. Comparison of (a and b) the temporal variability in Antarctic air temperature and atmospheric CO_2 with (c and d) sea level and northern ice volume over the last 340,000 years. Red curve in Figure 5a is the summer insolation at 65°N. The warmest intervals in Antarctica tend to be front loaded within the first halves of the longer cycles while the second halves remain almost uniformly cold. Northern ice volume, in contrast, remains low during the first halves of the longer cycles and then builds up gradually through the second halves. Antarctic records are from Dome Fuji ice core [*Kawamura et al.*, 2007]. Sea level curve in Figure 5c is from *Thompson and Goldstein* [2005]. Ice volume curves in Figure 5d are from *Waelbroeck et al.* [2002] and *Bintanja et al.* [2005]. Reprinted by permission from Macmillan Publishers Ltd: *Nature* [*Kawamura et al.*, 2007, Figure 2], copyright 2007.

temperature differences between the hemispheres are most extreme.

6. Terminations as Giant Millennial Events

[37] Areas of the Northern Hemisphere that are strongly influenced by the northern ice sheets should be warmest about a quarter cycle after the insolation maximum when the ice sheets have reached a minimum size and are no longer melting back [*Imbrie et al.*, 1992]. In the stage designations used in Figure 5, areas sensitive to northern ice should therefore be warmest at the ends of the a, c, and e intervals. Antarctica is warmest a half cycle earlier. Antarctica is warm when perihelion, the closest approach of the Earth to

the Sun, occurs during northern summers, i.e., at the mid points of the a, c, and e intervals [*Kawamura et al.*, 2007].

[38] So, why should Antarctica care about the insolation during northern summers? *Huybers and Denton* [2008] have argued that the temperature over Antarctica responds to the duration of southern summers, which is longer when the peak insolation during southern summers is at a minimum. *Timmermann et al.* [2009] argue that the austral spring insolation triggers an early retreat of Southern Ocean sea ice that initiates warming in Antarctica. These approaches, however, do not explain why SSTs at 45°S, thousands of kilometers away from Antarctica, are warmer [*Barrows et al.*, 2007]. The argument favored here is that the warmer temperatures at 45°S are due to a weakening of the influence of the southern westerlies on the AMOC. According to section 3, the AMOC (red circulation) should be weaker during the a, c, and e intervals when the insolation is stronger during northern summers. A weaker AMOC leaves the Southern Ocean warmer and the North Atlantic cooler.

[39] This approach leads to a natural explanation for why the e intervals stand out in the south. The e peaks occur immediately after the second halves of the longer cycles. Atmospheric CO_2 was low and the summer insolation over the ice sheets was relatively weak during the second halves and the northern ice sheets become very large. The e peaks begin to develop as the summer insolation becomes strong again for the first time in 40,000 or 50,000 years. Because the production of meltwater varies as the product of ice sheet size and the strength of the insolation, an extraordinary amount of meltwater is generated as the e intervals get underway. The extraordinary melting shuts down the AMOC and makes the North Atlantic extraordinarily cold [*Denton et al.*, 2005].

[40] The extraordinary melting and cooling in the north then produces an extraordinary change in the southern westerlies, which leads to an extraordinary increase in upwelling that one sees directly in the opal accumulation around Antarctica [*Anderson et al.*, 2009]. The shift in the westerlies melts back the sea ice and warms the ocean around Antarctica and causes a lot of CO_2 to be released up to the atmosphere at the same time. In this way, the e peaks seen in the Antarctic ice cores are a direct reflection of the extraordinary melting and cooling that took place around the North Atlantic in response to the strong summer insolation in the Northern Hemisphere.

[41] This concept is summarized in Figure 6, which summarizes the forcing and response during millennial events, precessional cycles, and terminations. The phases of the three factors have been set so that each factor gives rise to a reduced SST contrast between the hemispheres.

[42] First, consider Figure 6 (middle), which describes the forcing and response when the insolation during northern summers is at a minimum and the insolation during southern summers is at a maximum. This describes the situation before and after the e intervals. The insolation forcing in this case spins up the AMOC (red circulation) and helps cool Antarctica by transporting southern heat into the Northern Hemisphere.

[43] Millennial events in Figure 6 (left) lead to the opposite outcome. A cooler North Atlantic reduces the temperature contrast between the hemispheres and shifts the southern westerlies poleward, but in this case the AMOC (red circulation) is actively suppressed by the freshwater coming into the North Atlantic. So, the poleward shifted westerlies spin up the blue circulation instead. The ocean around Antarctica warms, Antarctica warms, and CO_2 from the blue domain is vented up to the atmosphere.

[44] Terminations (Figure 6, right) are basically giant millennial events that are forced by precession. A key element of our hypothesis is that the freshening and cooling of the North Atlantic is so great at these times that it overwhelms the normal response from the precessional forcing. Thus, the temperature contrast between the hemispheres is *reduced* instead of enhanced and the southern westerlies shift *toward* Antarctica rather than away from Antarctica.

[45] Strong evidence in support of this hypothesis was compiled years ago by *Crowley* [1992]. Figure 7 (top) [from *Crowley*, 1992, Figure 7]. It compares SSTs from the subantarctic zone of the Southern Ocean with SSTs from the North Atlantic during the latter part of stage 6 and the first part of stage 5. SSTs in the Southern Ocean reach their interglacial maximum at 130 kyr B.P. at the same time that SSTs in the North Atlantic hit their minimum. Thus, the entire interval of southern warming takes place while the North Atlantic is cooling. The cooling in the North Atlantic, meanwhile, occurs while the insolation during northern summers is ramping up from its minimum about 140,000 years ago to its maximum about 128,000 years ago.

[46] In Figure 7 (bottom), a proxy for the strength of the AMOC (in the sense of *Lisiecki et al.* [2008]) is added, which shows that the middepth $\delta^{13}C$ reaches its minimum value with respect to the rest of the ocean at the same time that the North Atlantic was coldest and Antarctica was warmest [*Mix and Fairbanks*, 1985]. Similar information from the North Atlantic appears in the work by *Oppo et al.* [1997].

[47] Crowley interpreted these changes in terms of the AMOC switching off and on. He assumed that higher levels of atmospheric CO_2 caused the warming in the south, and he was most interested in using the suppression of the AMOC before 130 kyr and the spin up of the AMOC after 130 kyr to explain the delayed warming in the north. We argue here that the southern westerlies shifted toward Antarctica when the summer insolation began melting back the northern ice sheets just after 135 kyr. The poleward shifted westerlies then warmed the south and brought about the CO_2 increase. The CO_2 increase was therefore a consequence of the mechanism that warmed Antarctica and was not the cause of the warming.

[48] This hypothesis can also explain why Antarctica and the Southern Ocean warm and cool in such an extreme way before, during, and after terminations. Figure 8 [also from *Crowley*, 1992] compares SST and $\delta^{18}O$ records from RC11-120, the Southern Ocean core used in Figure 7. The SST record from RC11-120 is noteworthy for its intense but brief interglacials that are limited to stages 1, 5e, and 7e [*Hays et al.*, 1976; *Imbrie et al.*, 1992]. The brief interglacials show that the Southern Ocean warmed dramatically during 5e but then cooled off again almost as dramatically during 5d.

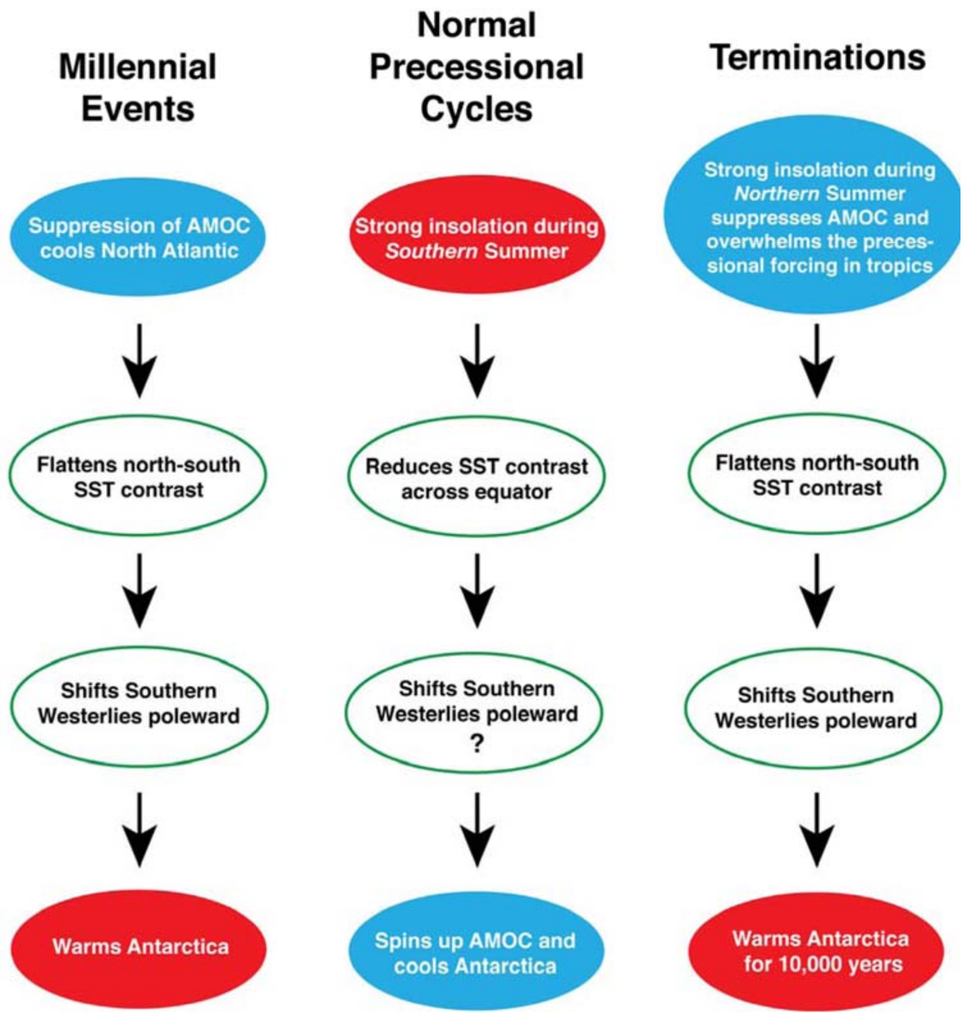

Figure 6. Summary of the forcing and response during millennial events, normal precessional cycles, and terminations.

[49] The argument here is that a reduced temperature contrast across the equator at the end of stage 6 and then again during 5d and 5b (due to strong *austral* summer insolation) spun up the AMOC and cooled the Southern Ocean. During 5e, strong *boreal* summer insolation melted the ice sheets and flooded the North Atlantic with meltwater. The AMOC would normally have weakened at this time but the strong cooling in the north made the westerlies especially strong. The westerlies were therefore stronger or in a more poleward position throughout the interval between the end of stage 6 and the beginning of 5d, at which time they were able to quickly spin up the AMOC once the AMOC was no longer suppressed. As a result, Antarctica and the Southern Ocean cooled right back down during 5d. A hypothetical north-south position for the strongest westerlies over time is shown at the bottom of Figure 8.

7. Discussion

[50] The possibility that the outsized warmings in Antarctica over the last 400,000 years were due to a redistribution of heat from north to south has important implications for the Milankovitch theory of the ice ages. It also has major implications for the role of atmospheric CO_2 during the ice ages.

7.1. Relationship to the Milankovitch Hypothesis

[51] The Milankovitch hypothesis [*Milankovitch*, 1930] attributes the ice ages to variations of the Earth's orbit and spin axis that alter the insolation over the northern ice sheets. From the Milankovitch perspective, the climate system's "center of action" is the northern ice sheets. The hypothesis here adds a second center that operates in the south via the southern westerlies, the ocean's overturning circulation, and the carbon cycle.

[52] *Milankovitch* [1930] identified three orbital variations, precession, obliquity, and eccentricity, that alter the insolation reaching the Earth over three different time scales, 23,000, 41,000, and 100,000 years, respectively. The big problem has always been that the time scale with the largest climate response (100,000 years) is associated with the

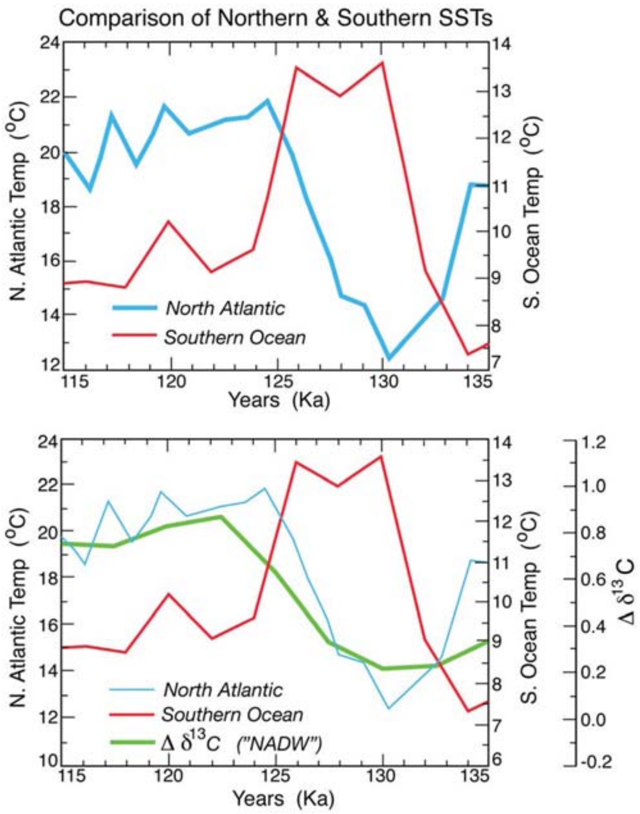

Figure 7. (top) Comparison of northern and southern sea surface temperatures during marine isotope stages 5d and 5e and the last part of stage 6 [after *Crowley*, 1992]. The plot shows SSTs from North Atlantic core V30-97 (bold blue curve) (41°N) [*CLIMAP Project Members*, 1984] and SSTs from Southern Ocean core RC11-120 (red curve) (44°S) [*Hays et al.*, 1976]. (bottom) The δ^{13}C difference (bold green curve) between V30-97 (North Atlantic) and V19-30 (eastern equatorial Pacific) has been added as a measure of NADW strength [*Mix and Fairbanks*, 1985].

weakest forcing (from the eccentricity of the orbit), while the strongest forcing (from precession and obliquity) operates over time scales that exhibit less climate variability [*Hays et al.*, 1976]. The extraordinary southern warming during the e peaks is a major reason why the response over 100,000 years is so large.

[53] Our extension to the Milankovitch hypothesis says that orbitally induced changes in the polar north and in the tropics activate the southern center by altering the temperature contrast between the hemispheres. The southern center then makes the temperatures in Antarctica rise and fall along with the level of atmospheric CO_2.

[54] The southern center also reddens the forcing from the north to produce more variability over 100,000 years. If the level of atmospheric CO_2 responded only to the westerlies, it would rise and fall back in the same way that the temperatures in Antarctica fall back after the e peaks in Figure 5. But the level of CO_2 does not fall back in the same way, as it lags behind the temperature changes, especially after the e peaks. This is because the venting of CO_2 from the deep ocean up to the atmosphere brings about massive changes in the burial of $CaCO_3$ that boost the overall CO_2 response and redden its variability out to a longer time scale [*Broecker and Peng*, 1987; *Toggweiler*, 2008].

[55] According to *Toggweiler* [2008], the $CaCO_3$ effect on atmospheric CO_2 has an internal time scale that is similar to, but independent of, the eccentricity time scale. As such, the variability in the south operates in the same frequency band as the modulation of the precessional cycle (via the eccentricity cycle). The oceanic CO_2 system "learns" about this aspect of the orbital forcing through its response to the melting during the first strong precessional cycle.

[56] These complementary time scales allow the northern ice sheets and the oceanic CO_2 system to generate a complementary kind of variability in each other: lower CO_2 helps make the ice sheets very large over 50,000 years at a time when the Earth's orbit is more circular and the precessional forcing is weak (in the sense of *Hays et al.* [1976] and *Shackleton* [2000]), and the extraordinary input of meltwater from the large ice sheets causes CO_2 to be vented up to the atmosphere when the precessional forcing becomes strong again.

[57] Our sense is that neither of these quantities, ice volume or CO_2, would exhibit much 100,000 year variability without the variability of the other. The venting of CO_2 up to the atmosphere *needs* the meltwater from large ice sheets, and large ice sheets *need* a reddened CO_2 time scale that can keep atmospheric CO_2 low for 50,000 years. The 100,000 year cycle is a phenomenon that developed when the ice sheets and CO_2 system began "talking" back and forth over their common time scale.

7.2. Role of Obliquity

[58] Millennial events were not part of the original Milankovitch hypothesis but are invoked by *Anderson et al.* [2009] to help explain Termination I. The claim made here is that terminations are giant millennial events forced by precession. This argument works best as an explanation for Terminations II, III, and IV, which occurred during times when the precessional forcing was particularly strong, but makes less sense for Terminations I and V when the precessional forcing was not very strong. To be more complete, the argument needs to incorporate the tilt (obliquity) of the Earth's axis.

[59] The tilt of the Earth's axis is greater around the last five terminations in a way that would have produced warm summers in the vicinity of the northern ice sheets at roughly the right times. This led *Huybers* [2006] to argue that obliquity is, in fact, more important during the ice ages than precession. According to *Huybers and Wunsch* [2005], precession appears to be more important only because the chronologies in marine δ^{18}O records were tuned to maximize responses in the precession and eccentricity bands.

[60] The critical distinction is whether ice sheets respond more strongly to the intensity of the summer insolation or the insolation integrated over the summer season [*Huybers*, 2006]. The forcing from precession should dominate if ice sheets respond more strongly to the intensity of the insolation around the summer solstice, while the forcing from

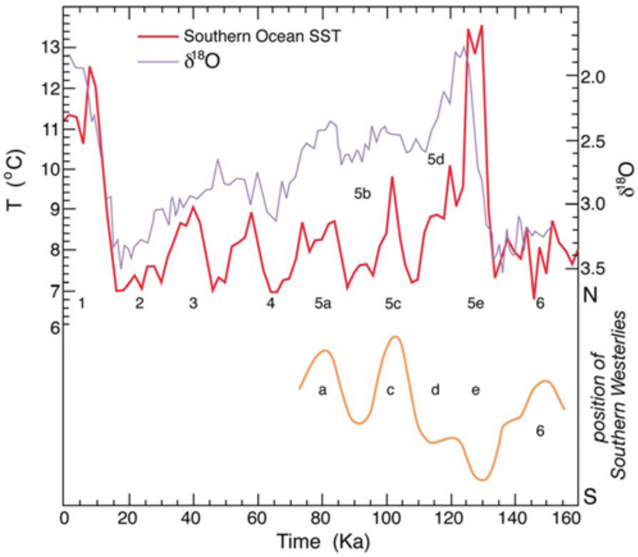

Figure 8. (top) Sea surface temperatures (red) and planktonic $\delta^{18}O$ (light purple) from Southern Ocean core RC11-120 through 160 kyr B.P. [after *Crowley*, 1992]. Marine isotope stages 1–6 are labeled. (bottom) Relative position of the Southern Hemisphere westerlies, according to the hypothesis described in the text. A position near the bottom of the plot is closer to Antarctica.

obliquity should dominate if ice sheets respond more strongly to the integrated insolation. *Huybers and Wunsch* [2005] argue that if one uses age models devoid of orbital assumptions and formally considers the dating errors associated with sediment cores, one will find that the terminations are more likely to have occurred when the obliquity and the integrated insolation was greater. This result presumes, however, a rather wide range in what the actual termination dates might be [see *Huybers and Wunsch*, 2004, Table 2].

[61] In the meantime, methods for dating the big warmings in Antarctica and the deglacial intervals in cave records from China have improved dramatically [*Bender*, 2002; *Kawamura et al.*, 2007; *Yuan et al.*, 2004; *Cheng et al.*, 2006, 2009]. Recent results show that the last four terminations occurred just before times when the northern summer insolation was most intense [see *Kawamura et al.*, 2007, Figure 4; *Cheng et al.*, 2009, Figure 2]. The fit to maximum obliquity is not quite as good; most notably, the warm peak associated with Termination III at 244 kyr occurred 8000 years after the nearest obliquity maximum. Thus, the intensity of the summer insolation over the ice sheets seems to be the more robust factor when the precessional forcing is strong.

[62] On the other hand, the forcing from precession around the time of Termination V was particularly weak. In this case, Termination V, at ~423 kyr, seems to have occurred just before the obliquity reached its peak at 417 kyr. This suggests that the integrated summer forcing from obliquity is strong enough, in general, to set off terminations.

[63] The insolation changes from obliquity are symmetric between the hemispheres and, as such, might not seem consistent with the idea put forward here. If, however, the initial response to maximum tilt causes the north to cool in relation to the south (via the input of meltwater to the North Atlantic) the obliquity forcing might also bring about shifts in the ITCZ and the southern westerlies.

7.3. Three Approaches to Climate Sensitivity

[64] Climate models display a range of sensitivities to atmospheric CO_2. At one extreme the warming predicted for a doubling of atmospheric CO_2 is as large as 5°C–6°C. At the other extreme, the warming is considerably more modest, perhaps as little as 2°C. So, which is more realistic? Of course, the Earth became warmer and cooler in the past in a way that does not depend on models. So, what does the temperature response during the ice ages say about the sensitivity of the Earth's climate to CO_2? Here we outline three ways to approach the ice age sensitivity question. Section 7.4 discusses how one can resolve between the three approaches.

[65] Antarctica warmed by 8°C–10°C during the big transitions leading up to the e peaks during stages 5, 7, and 9 (Figure 5). SSTs in the Southern Ocean warmed by about 6° at the same time (Figures 7 and 8). SSTs in the eastern equatorial Pacific warmed by 4°C–5°C [*Lea et al.*, 2000]. Because the temperature variations in all three locations follow a temporal pattern that is similar to the pattern in atmospheric CO_2, the warmings in these records were originally attributed to the greenhouse forcing from atmospheric CO_2 [*Genthon et al.*, 1987; *Crowley*, 1992; *Lea*, 2004]. It is noteworthy, however, that the records with temporal patterns most like atmospheric CO_2, i.e., those with big e peaks, come from the tropics or the Southern Hemisphere.

[66] What we call the "first approach" presumes that warming and cooling with the Antarctic pattern was a direct response to the radiative forcing from CO_2 and short-term feedbacks. Antarctica warmed more than the equatorial Pacific because of polar amplification. The first approach would support climate models with a relatively high sensitivity to CO_2. The second and third approaches recognize that Antarctica warmed along with higher CO_2 because the warmings and CO_2 increases occurred via the same mechanism. The "second approach" assumes that the warming from higher CO_2 helped push the termination process along via strong feedbacks. The "third approach" says that the warming in Antarctica was a simple response to the cooling in the north. The third approach would support climate models with a relatively low sensitivity to CO_2.

[67] *Toggweiler et al.* [2006] linked the warming and CO_2 increases in the Antarctic ice cores to a poleward shift of the southern westerlies. They imagined that the mechanism is an internal feedback in which the warming from higher CO_2 feeds back on the westerlies to produce more warming, a bigger shift, and more CO_2. The new results in the work by *Anderson et al.* [2009] suggest, however, that the westerlies shifted during Termination I in response to a cooler north, in which case a feedback is not necessary.

[68] New observations by *Cheng et al.* [2009] show that northern cooling and ITCZ shifts also occurred during Terminations II, III, and IV. This is seen in a series of $\delta^{18}O$ anomalies in cave records from central China, which *Cheng et al.* [2009] call Weak Monsoon Intervals (WMIs). The WMIs are very well dated and are found to be contemporaneous with the warmings in Antarctica and rising CO_2.

[69] The melting history of the northern ice sheets is recorded in the $\delta^{18}O$ variations in deep-sea cores, which are not very well dated. Given the strong link between the WMIs and northern cooling during Terminations I–IV, *Cheng et al.* [2009] shift the chronology for core ODP 980 from the North Atlantic [*McManus et al.*, 1999] so that ice-rafted debris (IRD) in the core during Termination II lines up with WMI II in China. This is important because the IRD in ODP 980 is found within the same interval in which the benthic $\delta^{18}O$ in the core is falling toward its interglacial values. *Cheng et al.*'s [2009] modified chronology puts the midpoint of Termination II at 133 kyr, a time when the summer insolation over the ice sheets was only halfway to its maximum level. The modified chronology also makes the melting of the northern ice sheets contemporaneous with the warmings and the CO_2 increases in the south.

[70] The *Cheng et al.* [2009] chronology makes a strong statement in support of the second approach, in which warming from higher CO_2 helps push the termination process along via strong feedbacks. It is at variance with traditional thinking (and the basis for the original chronology for core ODP 980), which puts Termination II at 128 kyr B.P. when the summer insolation was at its peak. The insolation is not as strong at 133 kyr as it is at 128 kyr. So, a termination at 133 kyr requires atmospheric CO_2 to do more of the work. *Cheng et al.* [2009, p. 252] conclude that "rising insolation and rising CO_2, generated with multiple positive feedbacks, drove the termination."

[71] *Cheng et al.*'s [2009] early termination date implies that relatively small increases in atmospheric CO_2 generated enough warming to be instrumental in melting back the northern ice sheets and, through the melting, were able to push the CO_2 mechanism along in the south. This seems problematic: how can higher CO_2 be critical in melting back the northern ice sheets and be caused by the melting at the same time? Can the feedback possibly be this strong?

[72] The mechanism outlined in this paper lends itself to the third approach. From this perspective, the two hemispheres are fundamentally out of synch. The brief warm intervals in Antarctica during Terminations II, III, and IV are not interglacials in the usual sense. Rather they are *deglacial* intervals that develop when the orbital forcing begins melting the ice sheets in the north. The cooling in the north and the displacement of heat from north to south account for all the warming in Antarctica during the big transitions. Atmospheric CO_2 is critical in melting back the ice sheets *after* the level of CO_2 has reached its peak, not before.

[73] From this perspective, atmospheric CO_2 is important mainly because of the duration of its cycle. According to *Roe* [2006], the precession of the Earth's axis generates the largest insolation anomalies and has the biggest impact on the ice sheets. These anomalies, however, can only act on the ice sheets for 10,000 years at a time. The forcing due to CO_2 is weak in comparison, but a low level of atmospheric CO_2 had 40,000–50,000 years to operate on the ice sheets during the second halves of the longer cycles. The Earth cooled during the ice ages mainly via the albedo effect of the northern ice sheets, which was brought about, in part, by the sustained low level of CO_2 during the second halves of the longer cycles.

7.4. Fates of the Three Approaches

[74] The increases in atmospheric CO_2 during the big transitions in Antarctica are known to lag several hundred years behind the warmings [*Fischer et al.*, 1999; *Caillon et al.*, 2003]. This is a big problem for the first approach above because higher CO_2 cannot be the cause of the warmings if it lags behind. Proponents of the first approach are left arguing that the error on the lag is large enough that the lead might be zero [*Hansen et al.*, 2007]. Of equal significance is the fact that the brief warm intervals in Antarctica during Terminations II, III, and IV are more sharply peaked in time than the CO_2 peaks. This is a problem for both the first and second approaches because the observed CO_2 variations, such as they are, cannot give rise to warmings that are more sharply peaked. It makes more sense to say that the warm peaks were caused in their entirety by something else.

[75] Logic aside, the fate of the third approach rests ultimately with the melting chronology. If the northern ice sheets had indeed melted back halfway by 133 kyr, as argued by *Cheng et al.* [2009], the third approach, the approach put forward here, is clearly wrong.

[76] The question is: how does one anchor the chronology of the $\delta^{18}O$ records in marine sediments? *Cheng et al.* [2009] do it by linking the IRD in ODP 980 to the WMIs in China. We would do it differently. Marine records from the tropics and Southern Hemisphere have well defined SST maxima that occur thousands of years before the minima in $\delta^{18}O$ in the same cores (Figure 8) [*Lea et al.*, 2000; *Barrows et al.*, 2007]. We would anchor these SST maxima to the warm peaks in Antarctica. The WMIs in China come to an end at the same time as the warm peaks in Antarctica and so, by our estimation, the WMIs come to an end along with the warm southern SSTs. The minima in oceanic $\delta^{18}O$ then come along thousands of years later. This means that the northern ice sheets continued to melt for thousands of years after the WMIs, as one would expect from the traditional chronology for ODP 980.

[77] This is the pattern seen during Termination I, which is absolutely dated. WMI I lasts from 17.5 to 10.6 kyr [*Cheng et al.*, 2009]; Antarctica is warmest at 11 ky [*Kawamura et al.*, 2007]; Southern Ocean and tropical Pacific SSTs are warmest between 10 and 11 kyr [*Labracherie et al.*, 1989; *Stott et al.*, 2004]; and the northern ice sheets disappear by 6–7 kyr, 4000–5000 years later [*Lambeck and Chappell*, 2001]. The sea level highstand at the end of the Termination II has also been independently dated at 122 to 115 kyr (Figure 5) [*Thompson and Goldstein*, 2005]. A highstand at this time is consistent with the assumptions here and the traditional termination date of 128 kyr.

[78] It seems to us that the meltwater that produced the WMIs came from the *initial* melting of the northern ice sheets. The combination of a suppressed AMOC and ice sheets that were still very large gave rise to the sea ice cover over the North Atlantic that produced the extraordinary northern cooling and the WMIs. The northern cooling and the WMIs ended about halfway through the terminations when the ice sheets had become smaller and the warming from atmospheric CO_2 was at a maximum.

[79] Temperature changes in the topics offer another objective way to assess the climate sensitivity. SSTs in the tropical Indian and Pacific Oceans typically increase by about 3°C between the LGM and late Holocene (as seen in core 806B in the work by *Lea et al.* [2000] and in the works by *Stott et al.* [2002], *Visser et al.* [2003], *Saraswat et al.* [2005], *Stott et al.* [2007], and *Xu et al.* [2008]). Three degrees is a fair amount of warming for a 100 ppm CO_2 increase [*Broccoli and Manabe*, 1987]. Given the remoteness of these areas from the northern ice sheets, however, most of the 3° warming might conceivably be due to higher CO_2.

[80] In this regard, the 4°–5° warming in TR163-19 from the eastern equatorial Pacific [*Lea et al.*, 2000] is atypical. Yet, the SST record from TR163-19 has prominent e peaks and, as such, is highly correlated in time with atmospheric CO_2 [*Lea*, 2004]. We would argue that the extra warming and the SST-CO_2 correlation in TR163-19 make sense: shifts of the ITCZ have a particularly large effect on SSTs in the eastern equatorial Pacific, and shifts of the ITCZ are part of the mechanism that makes atmospheric CO_2 go up and down [*Anderson et al.*, 2009]. Thus, much of the 4°–5° warming, like the warming in Antarctica, can be explained by a north-south displacement of the ITCZ.

[81] The best measure of the warming due to CO_2 should be the portion of the glacial-interglacial SST change that is common to the whole region. The compilation of Pacific SST records by *Tachikawa et al.* [2009] shows that SSTs began rising earlier south of the equator than north of the equator. Thus, Tachikawa et al.'s intratropical differences suggest that much of the 3° warming in the tropics was not due to CO_2 [*Stott et al.*, 2007]. They lend support instead to the idea that the two hemispheres were out of synch.

8. Conclusions

[82] The whole Earth did not warm and cool together during the big transitions of the ice ages. The south warmed, in particular, while the north remained cold. The north also became very cold toward the ends of the glacial stages long after the south had reached its glacial minimum. The big transitions took place when a resurgent precessional cycle produced inputs of meltwater to the North Atlantic that lasted for thousands of years. The meltwater inputs suppressed the AMOC, flattened the temperature contrast between the hemispheres, and produced a redistribution of heat from north to south that warmed Antarctica and the Southern Ocean. The same factors caused the level of CO_2 in the atmosphere to rise along with the temperatures in Antarctica.

[83] Atmospheric CO_2 was important during the ice ages because it varied with such a long time scale. The long time scale allowed the oceanic CO_2 system and northern ice sheets to interact in ways that gave rise to large temperature changes in the Earth's polar regions. The long time scale also allowed the variability in northern ice volume to enhance the variability in atmospheric CO_2, and vice versa. Without the long time scale for CO_2, the overall level of climate variability during the ice ages would have been much smaller.

[84] **Acknowledgments.** The work of Nick Shackleton (1937–2006) foreshadows much of what is presented here. His insight was to see that the Northern and Southern Hemispheres and atmospheric CO_2 contributed to the distinctive 100,000 year variability in marine $\delta^{18}O$ records in different ways [*Shackleton*, 2000]. Although largely unappreciated, subsequent ice core records and sea level reconstructions have supported his view. For all the dedication and painstaking attention to detail that led him to find and put forward this perspective, the authors would like to dedicate this paper to Nick Shackleton. The authors would like to acknowledge Dick Wetherald and Eric Galbraith for their internal reviews of the original manuscript. Frank Lamy, Lorraine Lisiecki, Valerie Masson-Delmotte, George Denton, and Jeff Severinghaus also made valuable suggestions. The authors would also like to thank Peter Huybers for his formal reviews and for his input regarding the obliquity cycle.

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