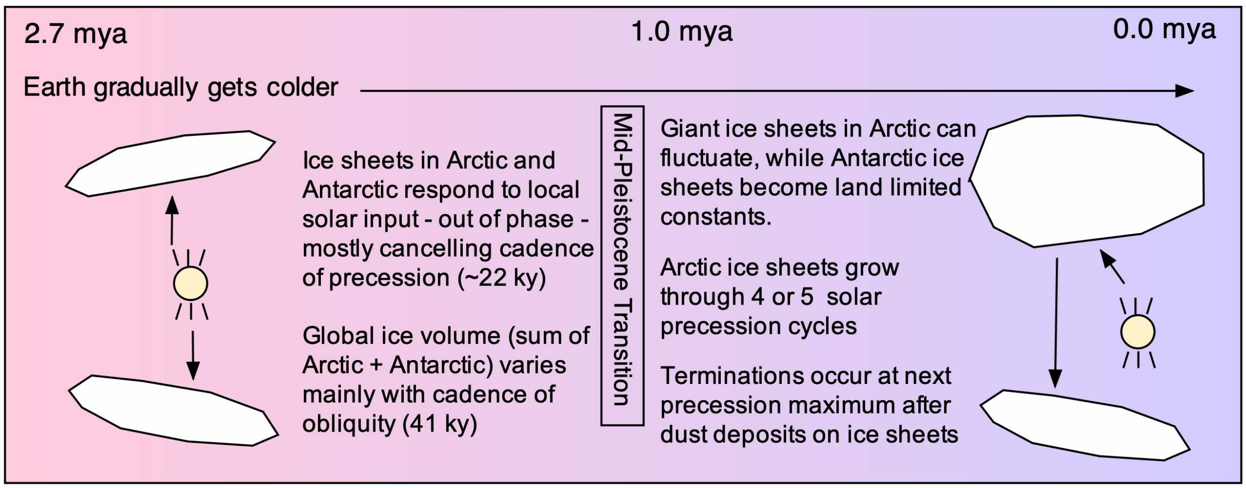
Ice Age Control Mechanisms: Pre-MPT and Post-MPT

Donald Rapp[a], Ralph Ellis[b] and Clive Best[c]

a 1445 Indiana Ave. So. Pasadena, CA USA 91030; **b** 105 e 6817 Route Pommier, St Martin Bellevue 74370, France; c: Huntingdon, Cambridgeshire, UK

Correspondence to: drdrapp@earthlink.net and ralph.ellis@me.com.



Abstract

We provide a cohesive picture of the driving forces for ice age growth and decay based on the net effect of the Solar Input to High Latitudes (SIHL) in the pre-MPT, and post-MPT periods (Mid Pleistocene Transition). While all three Earth orbit parameters (precession, obliquity and eccentricity) are always acting to determine the SIHL in either hemisphere, there are underlying reasons why the net effect of the SIHL on the variation of global ice volume with time does not display the timing of all three in an obvious fashion.

Snow is deposited by precipitation at higher latitudes, leading to accumulation of snow and ice. The accumulation expands at lower SIHL, and contracts (or expansion slows down) at higher SIHL.

Following Raymo et al. (2006), we assume that the primary feedback involved in the paleoclimate was ice-albedo, and thus the fundamental change that precipitated the MPT may well have involved ice-albedo. We assume that prior to the MPT, accumulation of polar ice was primarily determined by variations in SIHL and the corresponding ice-albedo in each hemisphere. However, after the MPT the Earth had cooled to such an extent that global ice sheet albedo became asymmetric – the extent of the northern ice sheets was so great, in comparison to the land-limited southern ice sheet, that the global climate became predominantly driven by northern SIHL and albedo.

Prior to the MPT, ice growth in the North and South alternated asynchronously every ~11 ky in accordance with the ~ 22 ky precession cycle. Ice growth and decay in the South was perhaps 30%

of that in the North through these cycles. As a result of this hemispheric asymmetry, the ***global*** ice volume showed only minor evidence of the precession cycle, and therefore the peaks in the sum of northern and southern ice volumes mainly followed a pacing of 41 ky due to the residual effect of obliquity.

After the MPT, ice sheet growth and variation was only possible in the northern hemisphere, because of the large continents situated there, while the Antarctic ice sheet had become land-limited. Thus, the global climate became controlled by ice-albedo feedback variations in the North, while Antarctica became an ice-albedo feedback constant. The ice sheets in the Arctic continued to grow through successive precessional cycles, with high snow/ice accumulations during SIHL minima and little or no reductions during SIHL maxima. The northern ice sheets grew unabated until after 4 or 5 precessional cycles, global temperatures fell to their minimum and CO_2 concentrations dropped below 200 ppm. High altitude regions became deserts, due to a lack of CO_2 and precipitation, and large amounts of dust were blown by high winds. Dust deposited on the northern ice sheets decreased their albedo, dramatically changing the energy balance, resulting in a rapid termination at the next SIHL maximum.

This picture is appealing in its simplicity.

Some researchers seem determined to interpret glacial-interglacial cycles as the result of changes in CO_2 concentration. But the evidence indicates that variations in CO_2 concentrations are not a cause of these cycles, but an effect of them. One is hard put to find a reason why CO_2 would rise and fall at just the right pacing to create ice ages and interglacials. Furthermore, the forcing of CO_2 in going from 190 ppm to 200 ppm at the very start of an interglacial is a mere ~0.3 W/m^2; far less than the 100s of W/m^2 expected from SIHL absorption following a change in the albedo feedback system. CO_2 might affect the global climate, but it is far too weak in its effect to melt vast ice sheets 3 km thick.

Key Words:

ice age

mid-Pleistocene transition (MPT)

termination

Paleoclimatology

albedo

precession

obliquity

1. Introduction: Challenges in Understanding Glacial – Interglacial Transitions

There is ample evidence that variations in *solar input to high latitudes* (SIHL) is a "pacemaker" for the alternating glacial and interglacial periods over the past ~ 2.7 my (e.g. Raymo et al., 2006). However, there are two major difficulties with the standard Milankovitch theory:

(i) The different cadence of the glacial periods prior to the MPT (41 ky) and after the MPT (88 to 110 ky) is difficult to explain based solely on SIHL.

(ii) The reason why so many precessional maxima in the SIHL fail to produce terminations in the post-MPT era; yet every fourth or fifth precessional maximum does produce a rapid termination.

These are two confusing aspects of the widely accepted theory that SIHL controls the glacial-interglacial cycles of the past ~ 2.7 my. Here, we use the mid-summer peak solar intensity at 65°N as our measure of SIHL. Justification for this choice will be given in a later section.

Our objective is to give a cohesive picture of the driving forces for ice age growth and decay for the seemingly obliquity-driven pre-MPT, and the precession/eccentricity-driven post-MPT periods. While all three Earth orbit parameters are always acting to determine the SIHL, there are underlying reasons why the net effect of the SIHL on the variation of ice volume with time does not usually display the timing of all three.

Due to precession of the Earth's axis, there is a consistent variation of the SIHL in alternate hemispheres in regular cycles of roughly 22,000 years. The amplitude of this cyclic variation is modulated by obliquity and eccentricity. The effects of obliquity are usually weaker than precession, but nevertheless subject the amplitude of the SIHL in both hemispheres to a 41 ky cyclic variation. If, for some reason, the impact of hemispherically asymmetric precession on global ice volume mostly cancel out, the global ice volume will vary with the underlying 41 ky obliquity cycle, and the effects of precession will be hidden in the ***global*** ice volume record.

In the most simplistic interpretation of solar-driven ice ages, one might expect that ice ages would occur every 11,000 years in alternate hemispheres, when the SIHL is in a precessional minimum in that hemisphere's summer, allowing large ice sheets to develop. One might then expect ice ages to occur alternately in each hemisphere, every 11,000 years – in line with the hemispherically alternating precessional cycle. But we do not observe this at all in the historical record of global ice volume over the past ~2.7 million years.

What is observed is that from about 2.7 mya to about 1.0 mya, the periodic variability of global ice volume followed a roughly 41 ky cycle, and from about 0.6 mya to the present, the global ice volume followed a much longer cycle of roughly 88 ky to 110 ky (Lisieki and Raymo (2005)). Between about 1.0 mya and 0.6 mya, a transition zone occurred in which the cycles gradually lengthened. Yet, despite the lack of obvious evidence of precession in the ice volume record, the periodic variation in SIHL due to precession was always in in force during these eras.

Therefore, further investigation is needed to understand how the Earth system hid the effects of precession via internal dynamics. Note however, that the effects of precession were almost never entirely hidden. In both the 41 ky pre-MPT, and ~88 ky to 110 ky post-MPT regimes, smaller cyclic variations in global ice volume at a 22 ky period were superimposed on the broader cycles that had greater amplitude with longer periods. Note that the benthic stack records global ice volume, not global temperature. It does imply global average temperature, but only by default -

and it cannot differentiate between the NH and SH (in both ice volume and temperature), which may alternate significantly.

So, one of the major challenges in understanding ice ages, is to identify why this persistent higher-frequency solar signal due to the ~22 ky precessional cycle appears as 41 ky obliquity cycles in the ice volume record prior to ~1.0 mya, and 88 ky to 110 ky cycles in the ice volume record after ~0.6 mya.

Raymo et al. (2006) theorized that during the pre-MPT ice age era, the development of the northern ice sheets was not extensive enough to control the Earth's climate. In particular, ice growth and decay at Antarctica responded to SIHL in the South, while ice growth and decay in the North responded to the SIHL in the North, with the two cycles being out of phase and in opposition. They estimated that the amount of ice gained or lost during precessional cycles in the South was perhaps about 30% of that in the North. But the ice sheets expanded and contracted in concert with the Milankovitch cycle, which is the sum of the ~41 ky hemispherically synchronous obliquity cycle, and the ~22 ky hemispherically asynchronous precession cycle (modulated by a slowly varying eccentricity cycle). This partial cancelation of out-of-phase precessional ice fluctuations combined with in-phase obliquity ice fluctuations results in a global (North + South) ice volume that appears to mainly follow the obliquity cycle. In addition, the geographically smaller extent of the ice sheets in this era meant that ice-albedo was not a major climatic factor, and so orbital influences were almost completely dominant in determining ice volume through the glacial-interglacial cycles.

In the post-MPT ice age era, the Earth had cooled to a critical tipping-point roughly 800 ky ago where the energy balance of the Earth was such that its natural state favored an ice age. The extensive ice sheets exerted a global influence on climate, and since Antarctic ice growth and decay no longer responded to the local SIHL, because it was land-limited, the global climate tracked the ice growth and decay in the North. In this domain, ice would continue to grow in the North, perhaps without limit, until the albedo of the ice sheets was lowered via dust deposition, which occurred late in the cycle when the CO_2 concentration dropped below 200 ppm. This reduction in albedo due to dust resulted in a huge change in the energy balance favoring melting, leading to a relatively rapid retreat of the ice sheets. At the end of each termination, the ice sheets more or less disappeared from the NH, and the climate system eventually reverted back to its previous mode of slow ice growth.

2. The Post-MPT Period

The ebb and flow of northern ice sheets was driven by variations in the SIHL in the North over the past ~400 ky, as shown in Figure 1. Figure 1 also shows estimated Antarctic temperature, but we assume this is inversely proportional to ice volume. The ~22 ky precession cycles exerted a higher frequency perturbation to the longer-term growth of the ice sheets. The NH precessional maxima (up-lobes) tended to increase the northern temperature (reduce the ice volume), while the NH precessional minima tended to reduce northern temperatures (increase the ice volume). But during this period that includes the past five ice ages, there was a seemingly relentless internal drive of the Earth's energy balance to increase the ice sheet extent. Regardless of the precession cycle, the ice sheets expanded (albeit with higher frequency overtones) until a point was reached where they disintegrated quickly.

Most precession maxima merely temporarily slowed down the rate of growth of the ice sheets, but did not produce a termination. Only about one out of four, or one out of five SIHL up-lobes produced a sudden, decisive termination. But occurrence of these terminations followed a regular pattern. While it is common to refer to this era as the "100 ky era", closer inspection suggests that the cycles were likely spaced by 88 ky or 110 ky. The spacings between the 5th and 4th, and the 4th and 3rd penultimate ice ages were about 88 ky (~four precession cycles), while the spacing between the 3rd and 2nd, and the 2nd and last ice ages was about 110 ky (~five precession cycles). Evidently, the data suggest that the combination of the colder Earth, and the relentless buildup of ice and snow at high latitudes during this period resulted in the ice sheets growing faster during NH precessional minima, but retreating only somewhat during NH precessional maxima. This trend continued through four or five precession cycles, until the next SIHL up-lobe produced a rapid termination. It should be noted that just prior to initiation of a termination, the northern (and global) temperatures bottomed out, CO_2 dropped below 200 ppm, and dust deposition increased remarkably.

Ellis and Palmer (2016) provided extensive evidence that deposition of dust on the ice sheets provided a decrease in ice-albedo that acted as a trigger to enable the next precession up-lobe to melt the ice sheets. Only at the depth of an ice age (at the lowest temperature and the lowest CO_2 concentration) after 4 or 5 precession cycles had evolved, would sufficient dust be deposited on the ice sheets to cause albedo reductions and glacial termination. There is good evidence that Antarctic dust levels peaked prior to each termination, but we only have Arctic dust data for the last termination. But since this limited Arctic dust data agrees so well with the Antarctic dust record, it is not unreasonable to assume that Arctic dust flux was closely correlated with Antarctic dust since the MPT.

It seems likely that the effects of SIHL variations were being masked by the albedo-feedback driven tendency toward glaciation in the North, until dust deposition decreased the albedo, thus allowing a SIHL up-lobe to produce a termination.

The pattern during the period from 800 kya to 450 kya was not as regular as that after 450 kya, but the spacing of major glacial-interglacial periods tended to be very roughly 4 precessional cycles.

The data for the past five ice ages indicate that the heat balance of higher northern latitudes favored glaciation, and lacking any unusual internal Earth factor, the ice sheets at higher northern latitudes would have continued to grow unabated. The data indicate that precessional up-lobes in SIHL in the North might have produced temporary slowdowns in the expansion of the ice sheets, but the long-term trend through at least four precessional periods was a continuing expansion of the ice sheets. This is illustrated in Figure 2.

The data also show that after 4 or 5 precessional cycles, the growth of the ice sheets came to a rather sudden halt, and a termination ensued in which the ice sheets melted in a period of roughly 7,000 years. This is shown in Figure 3.

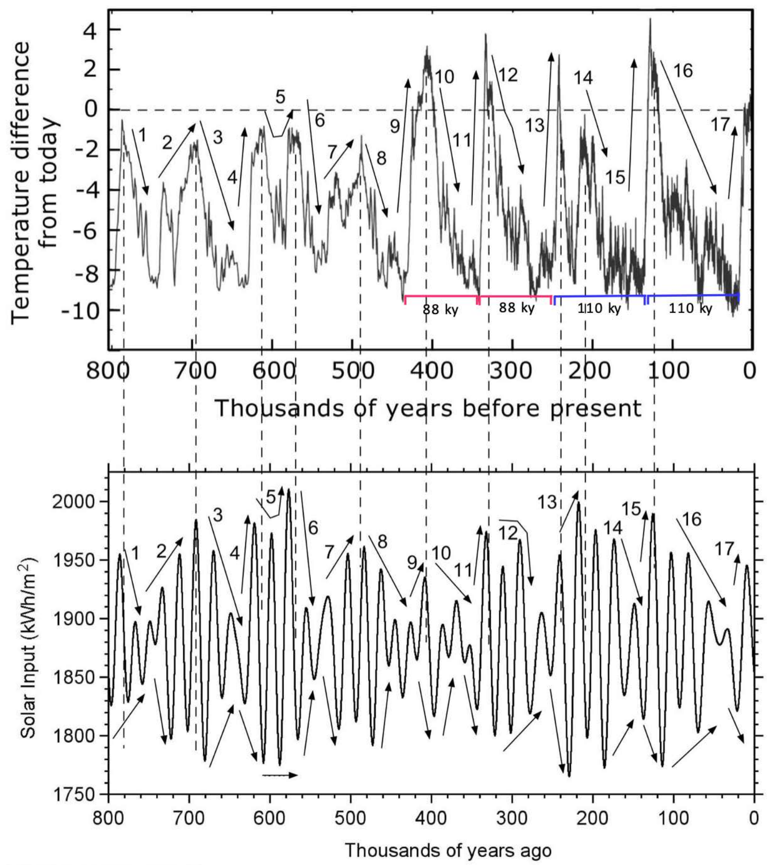


Figure 1. Comparison of mid-summer solar input to 60°N latitude to Antarctic temperature estimate over the past 800 ky.

Figures 2 and 3 provide a rough sketch of an idealized view of how we perceive the ice volume changed during the post-MPT era. In these figures, the time scale is measured in 11 ky units, representing half of a precession cycle. During a precessional minimum, the ice volume grows. During a precessional maximum, the rate of ice volume slows down or might even become negative. But the overall progress of the ice volume curve is upward through several precession cycles. After accumulation of ice over 3 or 4 precession cycles, when the CO_2 concentration is reduced below 200 ppm, large amounts of dust are deposited on the ice sheets, and at the next precession maximum, the combination of rising SIHL together with reduced albedo on the ice sheets, produces a rapid termination.

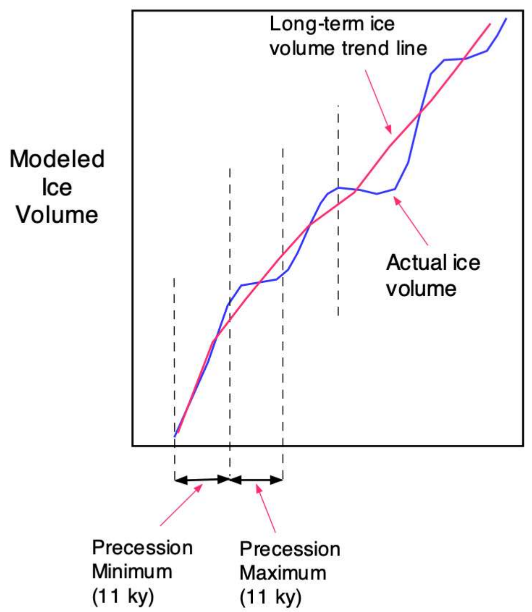


Figure 2. Alternating growth of ice sheets through precessional cycles.

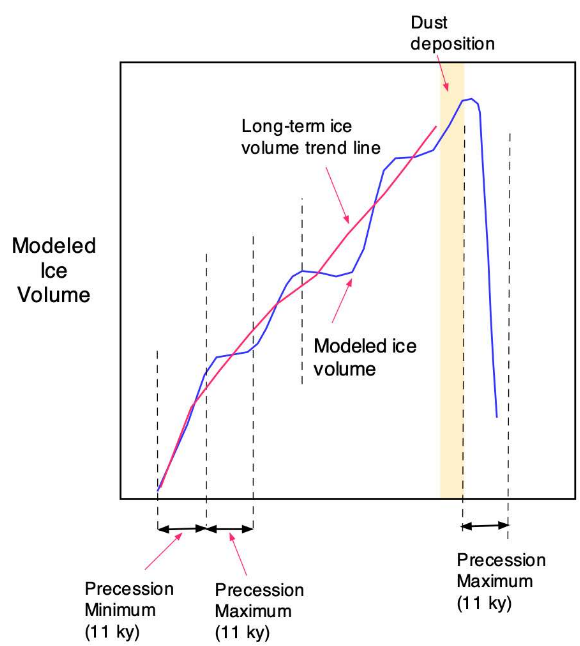


Figure 3. Dust deposition precedes modeled termination.

Figures 2 and 3 are idealized. In the real world, the trends are not so simple. Figure 4 shows a comparison of SIHL with ice volume over the past 125 ky. Each precessional half-cycle is outlined in dashed lines (red for up-lobes, and blue for down-lobes). Table 1 provides a comparison of changes in ice volume with changes in SIHL for each precessional half-cycle. The idealized model of Figures 2 and 3 applies fairly well to Figure 4.

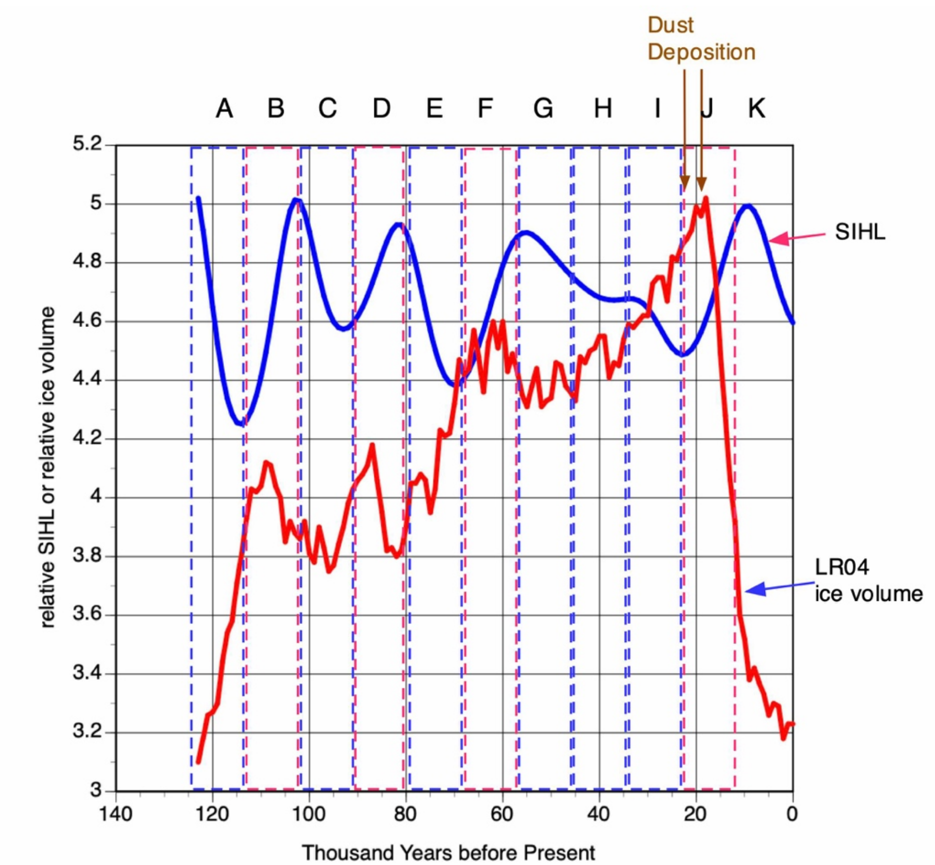


Figure 4. Comparison of SIHL with ice volume during the past 125 thousand years.

Table 1. Interpretation of comparison of SIHL with ice volume during the past 125 thousand years.

Precessional half-lobe	SIHL	Ice Volume	Other Effects
A	Sharply down	Sharply up	
B	Sharply up	Slightly down	
C	Moderately down	Moderately up	
D	Moderately up	Moderately down	
E	Sharply down	Sharply up	
F	Sharply up	Flat	
G	Slightly down	Slightly up	
H	Slightly down	Slightly up	
I	Moderately down	Moderately up	Dust deposition
J	Sharply up	Termination	
K	Sharply down	End Termination	

It might be enlightening to apply a mathematical model for the concept illustrated in Figures 2 to 4.

Imbrie and Imbrie (1980) developed a simple model that has some virtues and some faults. The Imbrie's simplistic model can be written:

$$dy/dt = -\{(1 + B)/T\}(x + y) \quad \text{if } (x + y) > 0$$

$$dy/dt = -\{(1 - B)/T\}(x + y) \quad \text{if } (x + y) < 0$$

in which:

y = ice volume

x = SIHL

T = a time constant (best fit around 17 ky)

B = a constant to assure that ice volume builds up at a slower rate than the rate that it decays (best fit around 0.6)

This was not stated clearly in the original paper, but the variables x (SIHL) and y (ice volume) can both be positive or negative, and represent deviations from average values, rather than absolute values.

Insertion of the constant *B* assures that ice buildup will take place more slowly than ice sheet decay. Note that as *B* varies from say, 1/3 to 2/3, the ratio of effective time constants (between ice buildup and ice decay) varies from 2 to 5.

The Imbries inserted a term *y* on the right side to reduce the rate of ice volume growth as the ice sheet volume increased, and increase the rate of growth as the ice volume decreased, but no physical explanations for this were offered. Nevertheless, inclusion of this term provides two benefits in fitting a model to the actual ice volume data:

(i) It shifts the peaks of ice volume slightly to more recent times, which helps to fit actual data.

(ii) It somewhat rectifies the higher frequencies of SIHL (due to precession) by reducing the rate of expansion of the ice volume when SIHL is negative, and increases the rate of expansion of the ice volume when SIHL is positive.

Despite these factors, the application of this model nevertheless still results in a relatively "spiky" plot of ice volume vs. time. When the model is applied to the most recent 800 kys, the result is as shown in Figure 5 (Rapp, 2014).

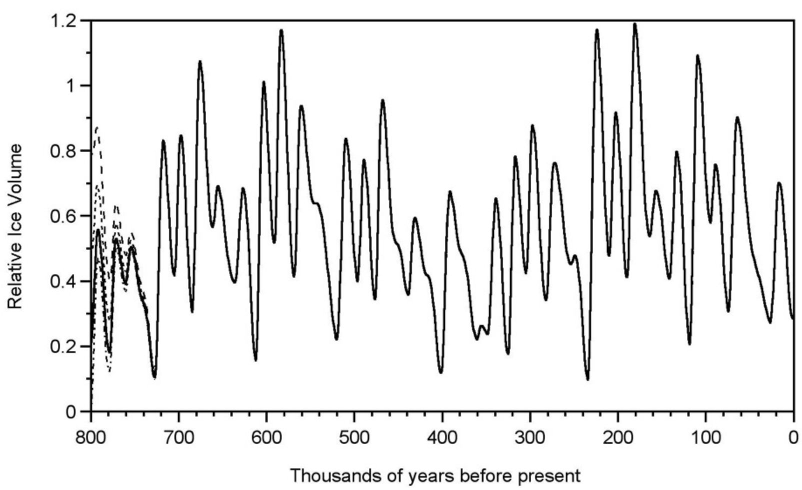


Figure 5. Predicted ice volume from Imbries' theory with T = 22,000, B = 0.6, and starting value 0.2 over the most recent 800 kys. (Other staring values shown as thin dashed lines lead to the same end result).

As we shall see in Section 3, this model works better in the pre-MPT period, when the ebb and flow of ice volume responded more directly to SIHL, whereas in the post-MPT period, ice volume continually built up over the years in a colder Earth, until a relatively sudden termination produced an interglacial. In the post-MPT period, the underlying connection of SIHL to changes in ice volume is less obvious. Ellis and Palmer (2016) provided good evidence that the trigger that initiated a termination was dust deposited on the ice sheets, thus decreasing their albedo, leading to rapid melting. The Imbries' model cannot account for this. The Imbries' model includes ice volume on the right side of the equation, but this is inadequate to describe events in the post-MPT era where ice continued to build up regardless of SIHL, and only diminished when dust deposition decreased the ice albedo. In keeping with this picture of regulation of ice ages by albedo changes rather than the SIHL cycle, Best (2018) developed a model to account for this. He began with the simple equation:

$$dv/dt = -(1 \pm b)(S)(1 - \alpha)$$

in which

v = ice volume,

α = albedo (calculated directly from Epica dust data),

S = 65°N insolation, and

b is a constant inserted to make the rate of ice growth greater during precessional minima than the rate of ice loss during precessional maxima.

The terms S and b require some explanation. It is assumed in this model that there is a long (88 ky to 110 ky) period of growth of the northern ice sheets, when albedo remains high prior to a termination. In this long, extended period of ice sheet growth, S (measured as deviation from the average) oscillates from positive to negative due to precession, but the growth during the 11 ky precessional minima outweighs the loss during the 11 ky precessional maxima due to the high net albedo. Additionally, the plus sign is used during precessional minima, and the minus sign is used during precessional maxima. This results in alternating growth of the ice sheets through many precession cycles as long as the obliquity remains high.

At some point in time, perhaps after several precessional cycles when dust deposits have built up over the ice sheets and reduced their albedo to a critical level, the ice sheets can absorb sufficient SIHL to melt during the next precessional maximum since $S > 0$, and $\alpha < 0.3$. In this short period (less than 11 ky) the entire termination takes place.

Best tried two approaches for including decreased albedo due to dust deposition in the equation based on the record of Antarctic dust in the ice cores. The first approach was based on total accumulated dust within a glacial cycle, and the second based on time lagged dust deposits. This assumes that Antarctic dust levels would be coupled to the dust levels on the ice sheets, but we lack data to confirm this. Best found the best fit if he assumed a 15 ky lag between the dust peak and the onset of termination. His result of integration is shown in Figure 6. While the agreement of this simple model with the data is not perfect, and could hardly be, the model seems to capture more reality than the Imbries' model. In particular, it eliminates the "spikiness" due to precession. Over the last four ice ages, it seems to work surprisingly well.

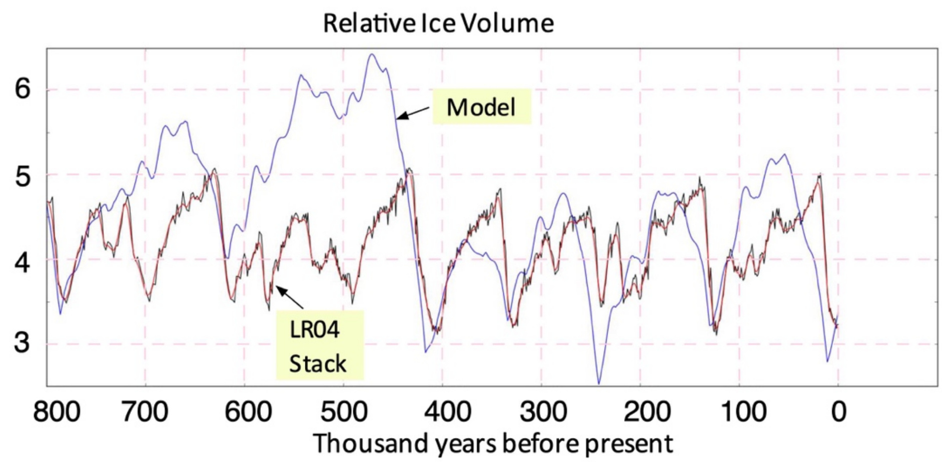


Figure 6. Comparison of Best's integrated model result (blue) to LR04 stack measurement of ice volume (black) and smoother LR04 data (red).

Our view of the last ~ 500 ky is that the energy balance of the Earth favored expansion of the ice sheets. SIHL to northern latitudes rose and declined with the precessional cycle, as modulated by obliquity and eccentricity. The high albedo of the ice sheets prevented the precessional maxima from impeding the expansion of the ice sheets other than temporarily slowing down their growth, so each precessional minimum grew more ice/snow than was lost during the following precessional maxima. This process continued for many thousands of years until the CO_2 concentration dropped below 200 ppm, which coupled with a global decrease in temperature, led to desertification of marginal and high-altitude regions. The resulting dust, combined with a presumed increasingly windy environment, was transported to the ice sheets, reducing their albedo and therefore altering the energy balance equation. Now, the increased absorption of SIHL was sufficient to melt the ice at the next precessional maximum, resulting in a relatively rapid termination. After a moderately short-term interglacial, the energy balance required that the ice sheets should slowly begin their expansion anew. The oft-quoted "100-ky" spacing of these ice ages is an approximation. Termination only occurs during one of the SIHL maxima, which have a ~22 ky cycle due to the dominance of precession. This is shown in Figure 7. The duration of an ice age is typically either 4 or 5 precessional cycles. A termination occurs at the first precession maximum following large-scale dust deposition, while precessional maxima that do not follow dust deposition do not produce terminations.

Previous investigators of the underlying causes of ice ages, terminations and interglacials have typically used either peak-midsummer solar intensity or integrated summer solar intensity as a measure of SIHL. The difference between the two is illustrated in Figure 8. It can be seen that the integrated summer solar varies less in intensity than the peak-midsummer solar intensity (note the difference in scales), and the integrated summer solar intensity cancels a large proportion of the precessional contribution, resulting in an apparent 41 ky cadence to the variations. In explanation - if we visualize the entire precessional cycle as a Great Year (a 22 kyr year), then the Great Springs of this cycle are in opposition to Great Autumns – thus if you integrate the whole summer much of the precession cancels out – leaving obliquity as the predominant cycle. But this is only part of the story, because the insolation energy is not really being cancelled out. During a full precessional Great Year there will be 5,500 years of warm springs and cold autumns, and then 5,500 years of cold springs and warm autumns. Clearly this is not entirely a cancellation, because these differential seasons will not have the same effect on the global climate. For instance, warm springs may be more efficient at melting winter snows, than warm autumns.

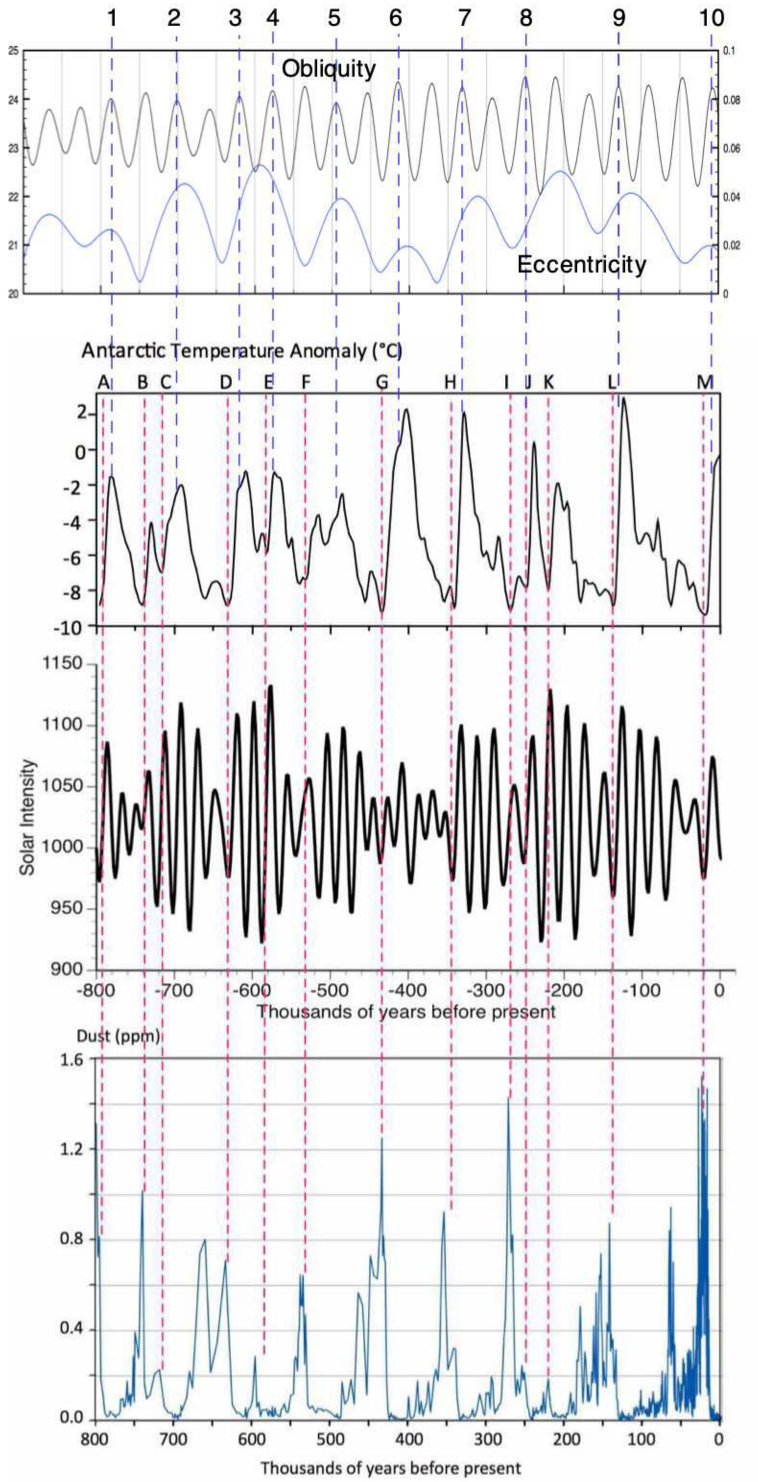


Figure 7. Upper panel: Obliquity and eccentricity. Second panel: Antarctic temperature anomaly. Third panel: SIHL. Lower panel: dust in Antarctic ice core.

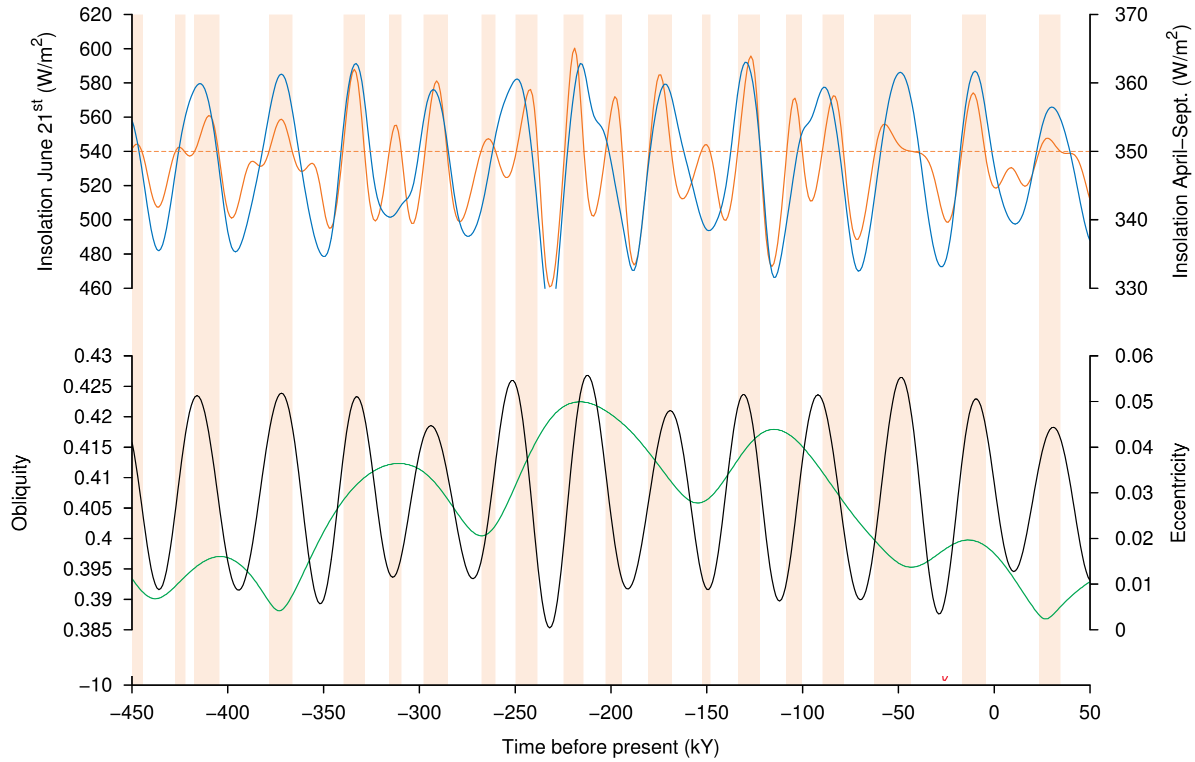


Figure 8. Comparison of mid-summer peak SIHL (upper orange) with integrated yearly solar intensity (upper blue). Also shown is eccentricity (lower green) and obliquity (lower black).

Figure 7 shows red dashed vertical lines where major terminations are initiated. The data suggest that termination occurs at the start of a precessional up-lobe in SIHL, immediately after strong dust deposition. The occurrence of strong dust deposition is marked by the letters A to M. It is also interesting to note that most of the major peaks in Antarctic temperature occur at peaks in the obliquity. This is shown by the blue vertical dashed lines identified by numbers 1 through 10. That suggests that terminations are begun with a precessional increase in SIHL soon after dust deposition, but the height of the ensuing interglacial is reached when the obliquity maximizes (when the solar elevation is at a maximum).

One of the major difficulties in understanding ice ages is the problem posed by the occurrence of terminations: when do they occur, and why do they occur? Figure 7 shows that every termination in the last 800 ky began at a precessional upswing in peak-midsummer SIHL. Yet, the only precessional upswings in peak-midsummer SIHL that produced terminations, were the ones preceded by large-scale dust deposition (Ellis and Palmer, 2016). There doesn't seem to be any way to directly predict occurrence of a termination from the integrated summer solar intensity.

If the theory is correct that terminations occur during precessional upswings in NH peak-midsummer SIHL, combined with dust deposits that reduce NH ice albedo, then solar elevation may be another important factor in glacial termination - because the absorption of SIHL on dust-contaminated ice sheets is greatly enhanced at high solar elevations. While we have no direct evidence of the state of the dust-laden ice sheets, the experiments of Peltoniemi, et al. (2015) suggest that the efficiency of melting increases greatly at higher solar elevation angles. They said:

Snow contaminated with impurities is unstable. When the Sun heats the absorbing particles, they melt or soften the ice around them, allowing the particles to move inside the snow. In this experiment, the particles sank down, leaving the topmost (on a millimeter to centimeter scale) surface whiter than expected. After the sinking, the difference between contaminated and clean snow is largest from [zenith], where one can still see the dark contaminants through the sink holes, and smallest at large zenith angles, where one sees mostly pure snow.

From this study, we draw the following conclusions:

a. Pure snow has a much higher albedo than dusty snow.

b. Minimum reflectance occurs at zero zenith angle (90° solar elevation).

c. As the Sun warms the snow, reflectance at low observer angles increases rapidly (dust sinking into the snow) so reflectance at low solar elevation angles will be much greater.

d. As the Sun lowers in the evening, the oblique angle reflectance increases five-fold.

We surmise from the work of Peltoniemi, et al. (2015) that the solar elevation is a crucial parameter for bringing about a glacial termination resulting in an interglacial. The solar elevation at solar noon at mid-summer is {90° – (latitude) + (obliquity)}. At 65°N latitude, the solar elevation at solar noon at mid-summer is {25° + (obliquity)}. As the obliquity ranges from about 22° to 24°, the sine of the solar elevation at solar noon at mid-summer ranges from 0.258 to 0.269, an increase of 4%. But what is likely to be even more important for melting dust-laden ice sheets is the number of hours per summer where the solar elevation exceeds some (unknown) threshold. Simple calculations show that if the critical solar elevation for melting were say 40°, melting would only occur in the months of May, June and July at 65°N. SIHL during other months would not contribute to melting. At 75°N, no melting would occur. If the critical solar elevation for melting were 30°, melting would only occur in the months of April, May, June, July and August at 65°N. At 75°N, melting would occur in the months of May, June and July. Table 2 shows the maximum solar elevation on the 21st of each month at 65°N, as well as the number of hours above thresholds of 30° and 40°.

Table 2. Hours per month with solar elevation above 30° or 40° at 65°N.

Month	Maximum elevation (degrees)	Hours above 40 degrees	Hours above 30 degrees
Dec	2	0	
Jan	5	0	
Feb	15	0	
Mar	25	0	
Apr	37	0	5.5
May	45	4.5	8.1
Jun	48	5.7	9.1
Jul	45	4.5	8.1
Aug	37	0	5.3
Sep	25	0	
Oct	15	0	
Nov	5	0	

These observations lend some credence to the idea that terminations originate at a precessional upswing in SIHL immediately after major dust deposition, and that this process is enhanced by high obliquity, which results in higher solar elevations and increased insolation absorption. Midday SIHL during the middle months of summer is the driving force for termination, and this is increased by greater eccentricity (i.e: precession) and greater obliquity.

3. The Pre-MPT Period

It is clear from the data of Lisiecki and Raymo (2005) that during the extended period from 2.7 mya to pre-industrial times (PIT):

(i) The Earth became generally colder. The energy balance of the Earth favored glaciation more and more as time progressed, particularly after 600 kya.

(iii) The spacing between cold periods was typically 41 ky prior to the MPT, and increased non-linearly after the MPT to typically 4-5 precession periods.

Raymo et al. (2006) provided a very attractive potential explanation for the 41 ky period. First of all, they emphasized that the ocean sediment data measured *global* ice volume, not merely *northern* ice volume. Secondly, they emphasized that prior to about 1.0 mya, global ice volume never reached high levels, and the high levels we associate with recent ice ages were not reached until after about 800 kya. A transition period (the MPT) existed between these two extremes. They then made a crucial assumption that seems very credible:

Prior to very roughly 800 kya, the buildup of ice sheets in the North was limited, and the northern ice sheets did not exert a dominant control of the global climate, as they appear to have done in the post-MPT era. In particular, the ebb and flow of Antarctic ice was controlled by the local SIHL to Antarctica, and the ebb and flow of northern ice was controlled by the local SIHL to the Arctic. (Note that after the MPT, it is theorized that Antarctic ice sheets had reached a land-limited maximum; and so Antarctic ice albedo became a constant, while Arctic ice and albedo could continue to vary and grow across the northern continents. Thus, with little or no albedo variations in the South, it was the albedo feedback from the great northern ice sheets that controlled the global climate in the post-MPT era.).

The East Antarctic Ice Sheet (EAIS) is presently ringed by extensive marine ice shelves. However, in the distant past, according to Raymo et al., "the EAIS behaved glaciologically, at that time, like a modern Greenland ice sheet… A warmer, more dynamic EAIS with a terrestrial-based melting margin, as opposed to a glacio-marine calving margin, is implied. Because such margins are strongly controlled by summer melting, Antarctic ice volume would be sensitive to orbitally driven changes in local summer insolation."

When did the transition from terrestrial melting to calving of marine shelves take place? Until now it has been assumed that it happened between 3 and 2.6 ma. Raymo et al. proposed that it may not have happened until after 1 ma.

Based on the model of Raymo et al., we can hypothesize that in the early period from 2.7 mya to about 1.0 mya, during the 41-ky cycle era, and even extending to a diminishing degree toward 0.6 mya, that:

(i) Buildup and diminution of ice/snow in both the North and South merely responded to local SIHL. And the ice/snow in the North never built up enough in volume for its high albedo to control the global climate.

(ii) In the South, ice/snow responded to SIHL much as it did in the North, as a terrestrial-based melting margin.

(iii) The global ice volume gained or lost during a complete precessional cycle is the sum of gain/loss for the North and the South. The amount of ice volume gained in the North during the favorable half of a precession cycle is balanced by a reduction in the amount of ice volume lost in the South. The amount of ice/snow lost in the North during an unfavorable half of the precession cycle is partly balanced the amount of ice/snow gained in the South. This reduces the higher frequency component due to precession in the ice volume curve, and what we are left with is simply the obliquity cycle, which enhances SIHL at both poles in synchrony.

(iv) The global total ice volume as recorded by the benthic record, is the sum of gains and losses in the North and the South, which therefore appeared to follow the obliquity signal in this era and masked the asymmetric waxing and waning of the ice sheets due to precession.

(v) During these smaller 41-ky ice age cycles, the total amount of global ice stored in both the North and the South, typically maximized at 50-60 m below present-day sea level and minimized at 0 to 20 m below present-day sea level. This was considerably less ice than the maximum depression of sea level during the last five ice ages, where sea level dropped to well over 100 m below present-day sea level.

A fundamental assumption is that prior to the MPT, the rate of variation of global ice volume in either hemisphere is proportional to solar input to high latitudes (SIHL) in that hemisphere. That is quite different from the post-MPT ice age era, where the relentless growth of ice sheets through 4 to 5 precession cycles was greatly modified and modulated by ice-albedo feedback influences.

Since the observed pattern of global ice volume shows a pattern with 41 ky periodicity, and the 22 ky periodicity only appears as relatively small perturbations superimposed on the main 41 ky variation, the challenge is to find a mechanism for reducing the expression of the 22 ky periodicity in the final ice volume curve.

The next step is to estimate the ice volume curves in the North and South from 2.7 mya to 1.0 mya. By adding these, Raymo et al. obtained the modeled global ice volume curve.

The problem with simplistic models of how ice volume changes with SIHL is that the variation of SIHL with time is dominated by the ~22 ky precession cycles. This, in turn, causes the resultant modeled plot of ice volume vs. time in any hemisphere to also show variability with a 22 ky period.

Raymo et al. applied the Imbries' model to the pre-MPT period from 2.7 mya to 1.0 mya. (There is no need to include albedo in the pre-MPT period, because ice sheet extent was limited, and the effects of albedo were small. In addition, any increase in NH albedo was countered by a reduction in SH albedo, and vice versa.) Their results are shown in their Figure 1. It can be seen from the lowermost graph that the agreement of the model with experiment is surprisingly good for the ice volume vs. time over the entire pre-MPT. Inclusion of the assumed levels of SH ice volume greatly reduces the higher frequency variation due to precession, resulting in a pattern that follows only obliquity at 41 ky cycles.

Figure 9 shows a close-up of a portion of Figure 8 from 1.5 mya to 1.4 mya, where the vertical relationship of the various curves can be followed. Because the NH and SH ice volume curves are out of phase, the peaks in NH ice volume are balanced by a partial reduction in SH ice volume, and the minima in NH ice volume are balanced by a partial increase in SH ice volume, so the curve for global ice volume shows the effects of precession only as small perturbations to the underlying 41 ky cyclic pattern.

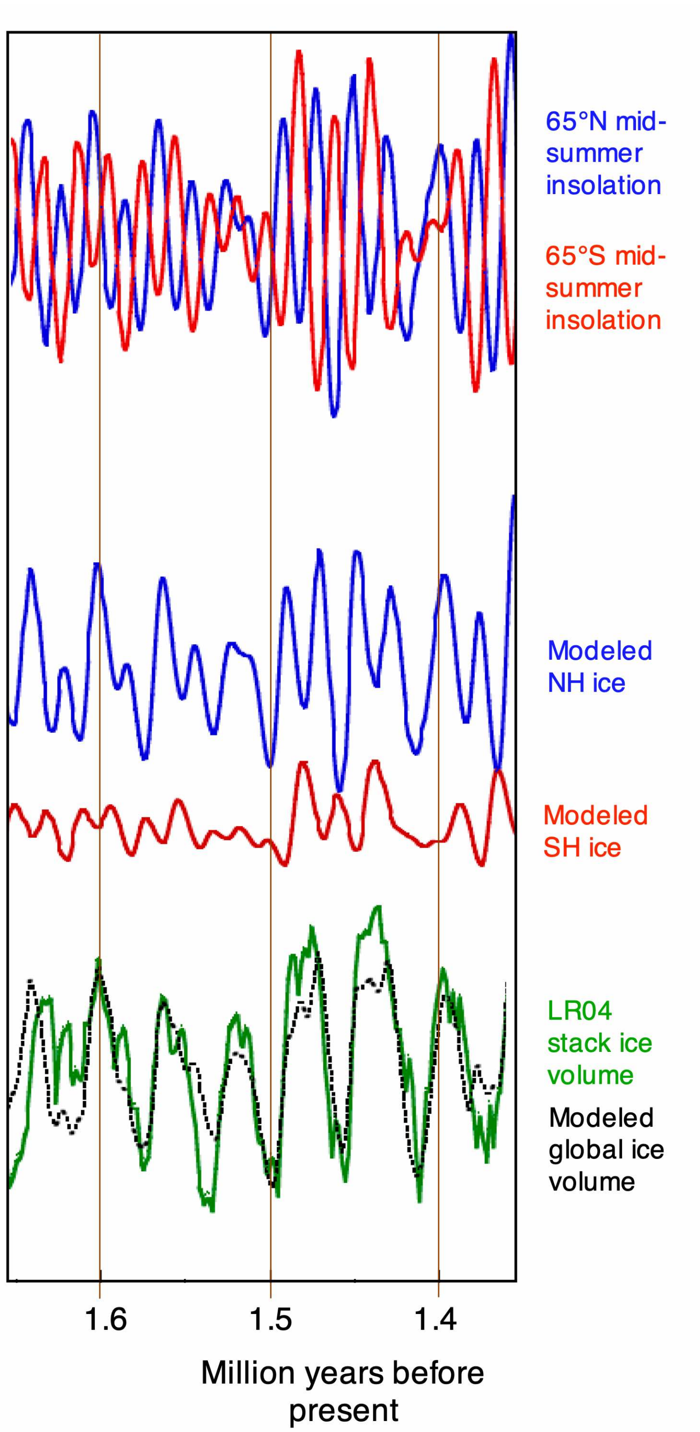


Figure 9. Close-up of curves provided by Raymo et al.

Figure 10 compares the modeled global ice volume to the obliquity. The global ice volume lags the obliquity by roughly 10 ky.

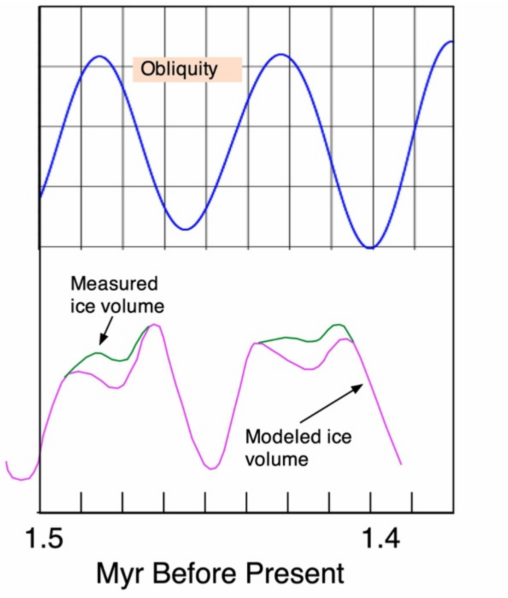


Figure 10. Comparison of obliquity to curves provided by Raymo et al.

A summary of this theory could be encapsulated in a few lines:

- Pre MPT there is a symmetric asymmetry of ice albedo in each hemisphere, producing the effect of pseudo-obliquity ice ages.

- Post MPT there is an asymmetric asymmetry of ice albedo in each hemisphere, leading to NH dominance and precessional ice ages, that only terminate when the ice albedo is lowered by dust deposits.

4. Other Ideas

Greaves et al. (2012) said: "Most hypotheses account for the origin of the MPT as a response to long-term ocean cooling, perhaps because of lowering CO_2." They differed from the conventional wisdom, and concluded: "Our results suggest that the MPT was initiated by an abrupt increase in Antarctic ice volume 900 thousand years ago." If this really occurred, it might be tied to the theory of Raymo et al. that the character of the Antarctic ice at the margins changed around the time of the MPT. It is notable that Greaves et al. did not reference Raymo et al. (2006).

Roychowdhury (2018) used a global climate model to examine various possibilities for the relationship between ice ages and SIHL. He utilized the time-integrated summer solar intensity for SIHL, while we prefer to use the peak mid-summer solar intensity for SIHL. The essence of his concept is that eccentricity controls the relative importance of obliquity and precession in determining the extent of the global ice volume. At low eccentricity (0.019 <) there is a small response to precession, and obliquity dominates in determining SIHL. At higher eccentricities, precession becomes dominant, and the hemispheres respond out of phase. But since they respond out of phase, the net result is that the precession signal is missing in the global ice volume records since the NH and SH responses are out of phase at this frequency.

There are several problems with this model. If this model were correct, we would see the 41 ky cadence of obliquity in both pre-MPT and post-MPT ice volume records, and we don't obviously see this in the post-MPT era. Furthermore, we do see evidence of a precession signal in the post-MPT era because every termination occurs on a precessional maximum.

Verbitsky et al. (2018) assumed that a feedback parameter (V varies from 0 to 1) controls the evolution of glacial cycles. As they summarized:

> *When positive feedback is weak (V ~ 0), the system exhibits fluctuations with dominating periods of about 40 ky which is in fact a combination of a doubled precession period and (to smaller extent) obliquity period. When positive feedback increases (V ~ 0.75), the system evolves with a roughly 100 ky period due to a doubled obliquity period. If positive feedback increases further (V ~ 0.95), the system produces fluctuations of about 400 ky. When the V number is gradually increased from its low early Pleistocene values to its late Pleistocene value of V ~ 0.75, the system reproduces the mid-Pleistocene transition from mostly 40 ky fluctuations to a 100 ky period rhythmicity. Since the V number is a combination of multiple parameters, it implies that multiple scenarios are possible to account for the mid-Pleistocene transition. Thus, our theory is capable of explaining all major features of the Pleistocene climate, such as the mostly 40 ky fluctuations of the early Pleistocene, a transition from an early Pleistocene type of nonlinear regime to a late Pleistocene type of nonlinear regime, and the 100 ky fluctuations of the late Pleistocene*.

It is not clear that this theory "explains" anything profound. V seems mysterious, and the authors seem to have taken liberty with the numbers (40 is 22 doubled; 100 equals 41 doubled).

5. The Role of CO_2 in the MPT Transition

The MPT transition has been a topic of investigation and discussion for some time. It is not in our interest to review all of these. Some of these papers place a great emphasis on the role of CO_2 in creating the differences across the MPT, while others go further and claim that CO_2 is actually the prime force causing glacial cycles. We believe that they have exaggerated the role of CO2, and as support for this view, we provide the discussion that follows.

5.1 Synchrony Between CO_2 and Temperature (or Ice Volume)

It is well established that during the glacial – interglacial cycles of the past half million years, the CO_2 concentration in the atmosphere (as measured by gases entrapped in Antarctic ice cores) slowly decreased over many tens of thousands of years during ice buildup, decreasing ultimately to about 190 ppm; and ultimately rather suddenly increased to about 280 ppm over a period of perhaps 7,000 years. This observation remains a topic of investigation and "is not fully explained" (Fischer et al., 2015). If one were to plot ice volume or temperature on the same axes as CO_2 concentration over 500 ky, the two curves would overlap closely. One example for the most recent termination is shown in Figure 11.

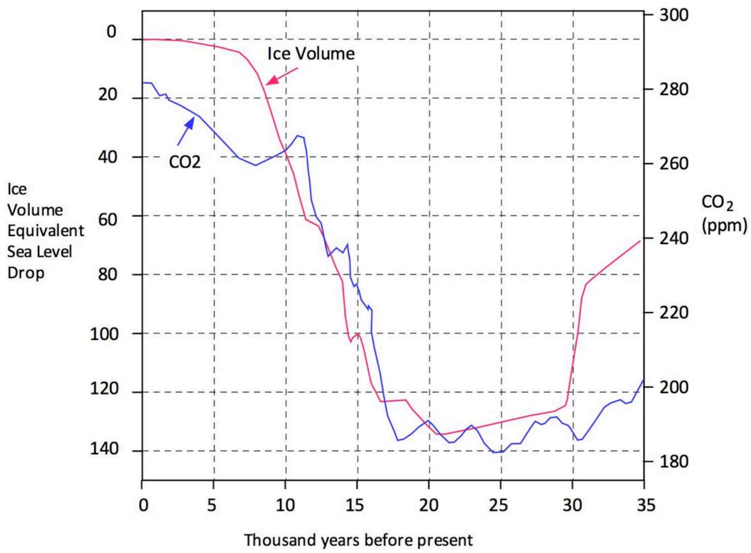


Figure 11. Comparison of ice volume with CO_2 concentration across the last termination (Köhler, 2017).

There is some evidence that the CO_2 concentration rise (or fall) during these glacial cycles, lags the temperature rise (or fall) that occurs during periods of increased warming (or glaciation) at Antarctica. The time lag was estimated to be ~500 years by Roper (2006), 800 ± 200 years by Caillon *et al.* (2003), 1,300-5,000 years by Mudelsee (2001), 800 years by Monnin *et al.* (2001), and 600±400 years by Fischer *et al.* (1999).

Flower (2009) concluded:

> Determination of lead-lag relationships is complicated by the fact that air diffuses in compacting snow long after the snow is deposited, leading to significant age differences between air and ice at a given level in an ice core. The so-called "gas age - ice age difference" ranges from about 500 to 6,000 years, depending on snow accumulation and compaction rates, with uncertainty on the order of 1,000 years. Specifically, this complicates determining the timing of air temperature increase and CO_2 rise because the former is derived from measurements on ice and the latter from trapped air. After constraining the "gas age - ice age difference" several studies have determined that initial Antarctic air temperature increase preceded CO_2 rise on glacial terminations, typically by about 600 to 3,000 years. One study used the δ^{40}Ar isotopic temperature proxy, measured on the same air samples as CO_2, and found a lead of 800+200 years at Termination 3. These observations suggest that CO_2 rise did not trigger temperature increase. However, these same studies show that approximately 80% of deglacial warming was synchronous with CO_2 rise.

These studies would seem to indicate that increased CO_2 is mainly an effect, not a cause of temperature change, although it is widely believed that it provides positive feedback to any change induced by other forcing, notably solar.

Because it is difficult to obtain precise timing of these curves, it is difficult to determine a time-lag or lead between the CO_2 concentration and the temperature (or ice volume). Very slight errors in timing of one or the other can indicate a lead or a lag that might not be real.

Gest *et al.* (2017) further explored leads and lags between Antarctic temperature and carbon dioxide during the last deglaciation. To understand possible causal relationships accurate chronologies of paleoclimate records are needed. However, as they said:

> Temperature is recorded in the ice while CO_2 is recorded in the enclosed air bubbles. The ages of the former and of the latter are different since air is trapped at 50-120 m below the surface. It is therefore necessary to correct for this air-ice shift to accurately infer the sequence of events. Here we accurately determine the phasing between East Antarctic temperature and atmospheric CO_2 variations during the last deglacial warming based on Antarctic ice core records. We build a stack of East Antarctic temperature variations by averaging the records from 4 ice cores (EPICA Dome C, Dome Fuji, EPICA Dronning Maud Land, and Talos Dome), all accurately synchronized by volcanic event matching. We place this stack onto the WAIS Divide WD2014 age scale by synchronizing EPICA Dome C and WAIS Divide using volcanic event matching, which allows comparison with the high-resolution CO_2 record from WAIS Divide. Since WAIS Divide is a high accumulation site, its air age scale, which has previously been determined by firn modeling, is more robust.

Their results show very parallel variation between temperature and CO_2 across the termination and beginning of the current Interglacial, from 20 kya to 10 kya. They claimed that CO_2 led temperature for some periods and CO_2 lagged temperature for other periods. However, like beauty, leads and lags in noisy data may lie mostly in the eyes of the beholder. It is not clear that the accuracy permits assigning specific leads and lags to the data.

More recently, Beeman et al. (2018) further refined the attempt to discern synchrony between CO_2 and temperature. In a similar fashion to Gest et al., they built a stack of temperature variations by averaging the records from five ice cores distributed across Antarctica, and developed a volcanic synchronization to compare it with the high-resolution, robustly dated WAIS Divide CO_2 record. They found that during the large, millennial-scale changes at the onset of the last deglaciation at 18 ka Antarctic temperature most likely led CO_2 by several centuries. However, a so-called Antarctic Cold Reversal (ACR) period occurred while the termination was in progress, and the relationship between temperature and CO_2 was more complex during that middle period of the termination.

The preponderance of the evidence suggests that CO_2 lagged temperature by several centuries, at least during the early stages of termination. Nevertheless, there was a very close correlation of CO_2 with temperature over the last five ice ages within the uncertainty of timing of the data (Petit *et al.* 1999).

5.2. Does CO_2 Forcing Cause Glacial – Interglacial Transitions?

Foster and Rohling (2013) stated in their Abstract that CO_2 plays a "dominant role in determining Earth's climate on these timescales and suggests that other variables that influence long-term global climate (e.g., topography, ocean circulation) play a secondary role." In their report, "these timescales" refers to the last ~500 ky. It is not immediately clear how they arrived at this assertion. It is possible that the observation that CO_2 closely tracks sea level over the past ~500 ky in their Figure 1, may have led them to infer that CO_2 was the cause of variations of sea level. Indeed, the related article (Rohling et al. (2013)) suggests this possibility. It is also possible that this group of scientists is somehow married to the belief that variations in CO_2 alone control changes in climate, even including the ice ages and interglacials of the last 500 ky.

This assertion by Foster and Rohling seems to us to be clearly erroneous. Hundreds of studies show that the ice volume has been mainly controlled by solar input to high latitudes (SIHL), while some have also highlighted the effects of ice albedo feedbacks. The temperature-dependent sources and sinks absorb or release CO_2 as the global average temperature changes due to changes in SIHL, resulting in a pattern where CO_2 mainly follows the ice volume over hundreds of thousands of years curve, with a short time lag.

Foster and Rohling said:

> Data from gas bubbles in ice-core samples provide a high-fidelity CO_2 record for the last 800,000 y that, when coupled with sea-level records of similar resolution, illustrates that CO_2 and sea level are intimately related on these timescales (Figure 1). This relationship arises because CO_2 is the principal greenhouse gas that amplifies orbital forcing and to a large extent determines the thermal state of the Earth system across glacial–interglacial cycles and thus the amount of ice stored on land.

Their Figure 1 shows sea level as a blue curve, and CO_2 as a red curve. There is no plot of "orbital forcing". Indeed, the term "orbital forcing" hardly occurs in their paper, except as a brief mention in passing. They establish that CO_2 and sea level are quite synchronous over the past 500 ky, but the role of orbital forcing seems to have somehow been dropped. If we were to take the above quote literally, we might think the authors meant that orbital forcing somehow changes the CO_2 concentration with time, and the change in CO_2 concentration changes the amount of ice stored in the ice sheets (or sea level). No mechanism is proposed for how the orbital forcing directly changes CO_2. This interpretation is at odds with a well-established conclusion by hundreds of published papers, that SIHL drives the ice volume (sea level) and changes in CO_2 are a byproduct of global temperature change induced by the effect of the ice sheets. Foster and Rohling seem to have unwittingly taken issue with the entire body of knowledge of ice ages, by adopting CO_2 as the cause, rather than the effect of "thermal state of the Earth system across glacial–interglacial cycles".

Based on their presumed sole dependence of sea level on CO_2, and nothing else, they concluded that for CO_2 levels as low as 392 ppm, long-term sea-level rise of more than 9-m above the present is expected. If their model was correct, then we could expect a 9-m rise in sea level even without further emissions of CO_2.

One of the puzzling aspects of the study of ice ages is the difficulty in explaining the synchrony of CO_2 with temperature in glacial–interglacial cycles. Basically, the problem is one of accounting for temperature-dependent sources and sinks of CO_2, and estimating the difference between the storage capacities under glacial and interglacial conditions. Quite a number of papers have been written on the subject, but none have found an entirely satisfactory explanation, although most of the relevant sources and sinks have been identified (e.g. Skinner, 2006).

It is not our purpose in this report to delve into the global mechanisms that cause CO_2 to track the temperature in glacial–interglacial cycles. The literature on that topic is extensive, although many questions remain. For our purposes, it is mainly sufficient for us to acknowledge this synchrony. However, it is necessary to point out that there are only two possibilities that need to be considered regarding timing:

(A) CO_2 lags the temperature. The temperature is controlled by solar input to high latitudes (SIHL) and ice albedo. The temperature-dependent sources and sinks absorb or release CO_2 as the global average temperature changes due to changes in SIHL, resulting in a pattern where CO_2 mainly follows cyclic temperature with a short lag, over hundreds of thousands of years. These variations in CO_2 may provide a feedback mechanism for global temperature, as has been suggested in numerous papers, but the magnitude of this feedback when calculated century by century is very small in comparison with regional albedo feedback variations on the ice sheets.

(B) CO_2 leads the temperature. The CO_2 concentration is controlled by unspecified forces while temperature follows the CO_2 concentration due to CO_2 forcing-feedbacks. But it is difficult to fold in the influence of SIHL to this model. One might hypothesize that SIHL directly affects CO_2 by some unspecified mechanism, but this seems far-fetched. Basically, the model assumes that CO_2 alone controls glacial–interglacial cycles, even though these same cycles are positively linked to the orbital SIHL cycle.

We only have two choices:

(A) The sensible choice that CO_2 follows temperature induced by changes in SIHL and ice albedo, or

(B) Some unclear primary force ("orbital forcing"?) acts to change CO_2 at precisely the right rates and timing to produce ice ages and interglacials, and changes in CO_2 force the glacial-interglacial cycles.

Whichever choice one makes, it is necessary to show that there is enough energy available to cause a termination in a mere ~7,000 years.

For Case (A), it is well documented that SIHL is the pacemaker for transitions between ice ages and interglacials. And SIHL is, of course, regulated by the thoroughly understood and documented orbital cycles of the Earth's orbit and axis. The issue remaining is whether SIHL, coupled to reduced ice albedo due to dust deposition at the end of an ice age, would have enough energy to melt through a depth of a few thousand meters of ice in a mere 7,000 years.

The heat of fusion of ice is 3.1×10^8 J/m^3. A very conservative estimate for integrated summer SIHL over 1,000 years, is 2.5×10^8 Wh/m^2 = 9×10^{11} J/m^2. If all of this SIHL were absorbed, it would be enough to melt to a depth of about 3,000 m in 1,000 years. But if the albedo were say 0.8 during glacial conditions, the melting would be 600 m per 1,000 years, assuming there was no refreezing overnight, or during winter, and there was no additional deposition of new snow. If the albedo were decreased to say, 0.2 by dust deposition, the melting would be 2,400 m per 1,000 years, when assuming the same caveats. Evidently, the actual amount of melting is far less than this estimate, otherwise there would be no ice ages. But the point is established that there is adequate energy in each SIHL to produce major melting of ice sheets if the albedo is reduced.

For Case (B), termination of an ice age is presumed to occur in 7,000 years of CO_2 forcing, where CO_2 gradually rises from ~ 190 ppm to ~ 280 ppm over that period. A widely used measure of CO_2 forcing is a logarithmic curve that can be fitted to a function (e.g. Best (2013), Lightfoot and Mamer (2014)).

ΔF (W/m^2) = 5.22 ln (C_1/C_2)

in which C_1 and C_2 are CO_2 concentrations in ppm, and ΔF is the forcing in going from once concentration to the other. If we consider the sequence of termination in which CO_2 starts out at 190 ppm, and ends up at 280 ppm, the initial forcing that initiates a termination occurs when CO2 rises from 190 ppm to 200 ppm is a mere 0.27 W/m^2. Acting continuously over 1,000 years, the total energy deposited into the ice by this forcing is 8.5 x 10^9 Wh/m^2, enough to melt 27 m of ice. The total forcing over the entire termination period of ~7,000 years is 2 W/m^2, which is very comparable to the forcing we have experienced from pre-industrial times to 2019. We note that the warming observed from pre-industrial times to 2019 was very moderate, and furthermore, is probably not entirely due to rising CO_2. More importantly, a forcing of 0.27 W/m^2 on the ice sheets is grossly inadequate to initiate a termination, and a forcing of 2 W/m^2 is grossly inadequate to bring about a total termination in ~7,000 years.

We must conclude that it is misguided to think that changes in CO_2, induced by some hypothetical process, could have enough impact on the ice sheets to cause glacial – interglacial transitions with periodic buildup and disintegration of mile-thick ice sheets.

5.3 What is the Role of CO2 in Causing the MPT Transition?

One thing that is clear from the data of Lisiecki and Raymo (2005) is that despite the quasi-periodic rise and fall of global temperatures induced by the ice sheets in the North, there was a long-term cooling trend across the entire period from 2.7 mya to PIT. This is illustrated in Figure 12. Through the changing glacial-interglacial cycles, the temperature maxima decreased only slightly, while the temperature minima decreased more emphatically.

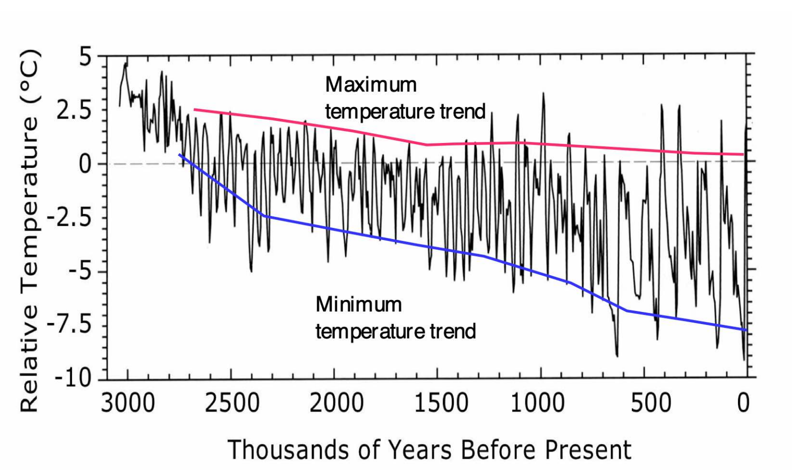


Figure 12. Long-term cooling trend across the MPT.

The paper by Hasenfratz et al. (2018) argued that the lengthening of the glacial-interglacial cycles after about 1.25 mya was due to a slowing of deep-to-surface circulation in Antarctic waters, that slowed the release of CO_2, which implies that the length of glacial-interglacial cycles is determined by CO_2 concentration. Their view seems to be that a termination was caused by a release of CO_2, and when CO_2 remained sequestered in deep waters, the ice ages were prolonged. Our view is the diametric opposite. We believe that glacial-interglacial cycles are induced by changes in SIHL and ice albedo, while the rise and fall of CO_2 is dictated by the rise and fall of global temperatures that result from the influence of the ice sheets on the global climate. While the forcing due to CO_2 might play a role in determining the extent of global warming or cooling during glacial-interglacial transitions, CO_2 itself cannot provide enough energy to induce glacial-interglacial transitions. It is notable that Hasenfratz et al. did not reference Raymo et al. (2006).

6. Conclusions

In this report we have demonstrated that glacial cycles over the last ~2 million years can be explained by orbital changes in SIHL, combined with terrestrial ice-albedo feedbacks. Summer insolation maxima due to precession are out of phase between the SH and the NH. While southern ice sheets waxed and waned in Antarctica during the early Pliocene they offset those in the Northern Hemisphere, resulting in global ice volume cycles that followed the 41ky obliquity cadence. Once Antarctica became fully glaciated (around the MPT) this pattern was broken, leading to NH dominance and longer glacial cycles lasting 4 or 5 precessional cycles. Terminations then began to depend on reduced albedo following dust accumulation on northern ice sheets during more extreme cold, arid and low CO_2 conditions. Once so primed, the following summer precessional maximum in the NH was sufficient to melt back these "dirty" ice sheets, transiting to an interglacial. We find no convincing evidence for alternative explanations.

References

Beeman, Jai Chowdhry et al. 2018. Antarctic temperature and CO_2: near-synchrony yet variable phasing during the last deglaciation *Climates of the Past Discussions*, *https://doi.org/10.5194/cp-2018-33*.

Best, Clive 2013. Radiative Forcing of CO_2 *http://clivebest.com/blog/?p=46*97.

Best, Clive 2018. Towards an understanding of ice ages *http://clivebest.com/blog/?p=8679*.

Caillon, Nicolas et al. 2003. Timing of Atmospheric CO_2 and Antarctic Temperature Changes Across Termination III *Science* 299, 1728-1747.

Chalk, Thomas et al. 2017. Causes of ice age intensification across the Mid-Pleistocene Transition PNAS, *www.pnas.org/cgi/doi/10.1073/pnas.1702143114*.

Ellis, Ralph and Michael Palmer 2016. Modulation of ice ages via precession and dust-albedo feedbacks *Geoscience Frontiers* *http://www.sciencedirect.com/science/article/pii/S1674987116300305*

Farmer, J. R. et al. (2019) "Minima prior to MPT were slightly higher than post MPT Maxima prior to MPT were about the same as post-MPT" *https://doi.org/10.1038/s41561-019-0334-6*

https://www.nature.com/articles/s41561-019-0334-6#article-info

Fischer, H. et al. 1999. Ice core records of atmospheric CO_2 around the last three glacial terminations *Science* 283 1712-1714.

Fischer, H. et al. 2015. Ice core-based isotopic constraints on past carbon cycle changes *Pages Magazine* 23, 12-14.

Flower, Benjamin P. 2009. Relationships between CO_2 and Temperature in Glacial-Interglacial Transitions of the Past 800,000 Years *http://ircamera.as.arizona.edu/NatSci102/NatSci102/text/climate_phase.pdf*

Foster, Gavin L. and Eelco J. Rohling 2013. Relationship between sea level and climate forcing by CO_2 on geological timescales *PNAS* 110, 1209-1214.

Foster, Gavin L. et al. 2018. "What Caused the Mid-Pleistocene Transistion?" *http://www.thefosterlab.org/mpt*

Gest, Lea, et al. 2017. Leads and lags between Antarctic temperature and carbon dioxide during the last deglaciation Climate of the Past, *https://doi.org/10.5194/cp-2017-71*.

Hasenfratz, Adam et al. 2019. The residence time of Southern Ocean surface waters and the 100,000-year ice age cycle *Science* 363, 1080-1084.

Imbrie, John and John Z. Imbrie 1980. Modeling the Climatic Response to Orbital Variations *Science* 207, 943-953.

Köhler, Peter et al. 2017. A 156 ky smoothed history of the atmospheric greenhouse gases CO_2, CH_4, and N_2O and their radiative forcing *Earth Sys. Sci Data* 9, 363-387).

Lightfoot, H. Douglas and Orval A. Mamer 2014. Calculation Of Atmospheric Radiative Forcing (Warming Effect) Of Carbon Dioxide At Any Concentration *Energy and Environment* 25, 1439-1454.

Lisiecki, L. E. and M. E. Raymo 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records *Paleoceanography* 20, PA1003-PA1019.

Monnin, E et al. 2001. Atmospheric CO_2 concentrations over the last glacial termination *Science* 291, 112-114.

Mudelsee, M. 2001. The phase relations among atmospheric CO_2 content, temperature and global ice volume over the past 420 ka *Quaternary Science Reviews* 20, 583-589.

Peltoniemi, J. I. et al. 2015. Soot on Snow experiment: bidirectional reflectance factor measurements of contaminated snow *The Cryosphere* 9, 2323–2337.

Petit, J. R., et al. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica *Nature* 399, 429-436.

Rapp, Donald 2014. *Assessing Climate Change*, 3rd ed., 816 pages, Springer, Heidelberg, ISBN-13: 978-3319004549.

Raymo, M. E. et al. 2006. Plio-Pleistocene Ice Volume, Antarctic Climate, and the Global $\delta^{18}O$ Record *Science* 313, 492-495.

Rohling, Eelco J. et al. 2013. A geological perspective on potential future sea-level rise *Scientific Reports* 3, 1-7.

Roper, L. David 2006. *Relationship of Antarctica Temperature to Atmospheric Carbon Dioxide and Methane http://www.roperld.com/science/CO2_Temp.pdf*

Roychowdhury, Rajarshi 2018. Eccentricity Modulation of Precessional Variation in the Earth's Climate Response to Astronomical Forcing: A Solution to the 41-ky Mystery Ph. D. dissertation, University of Massachusetts.

Skinner, L. C. 2006. Glacial – interglacial atmospheric CO_2 change: a simple "hypsometric effect" on deep-ocean carbon sequestration? *Clim. Past Discussions*, 2, 711–743. *http://www.clim-past-discuss.net/2/711/2006/*

Verbitsky, Mikhail Y. et al. 2018. A theory of Pleistocene glacial rhythmicity *Earth Syst. Dynam*. 9, 1025–1043.