Ameliorating Future Little Ice Ages While Reducing Global Warming

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Part I: Solar Insolation and Ice Ages

For **Part II: Last Major Ice Age and Predictions for the Next Major Ice Age** go to http://www.Roperld.com/science/IceAgesPredict.pdf
For **Part III: Ameliorating Global Warming** go to http://www.Roperld.com/science/AmeliorateGlobalWarming.pdf

Introduction

The increasing release of industrial gases, especially CO_2, into the atmosphere is causing a rapid warming of the earth. See *Global Warming, A Beginner's Guide to Our Changing Climate* by Fred Pierce, 2002, which is a summary of the 1991 report of the Intergovernmental Panel on Climate Change (http://www.grida.no/climate/ipcc_tar/wg1/index.htm).

It appears that the earth is poised to enter a long (about 100,000 years) Major Ice Age (see below). Also, it appears that there are "little ice ages" about every 2000 years, the minimum of the last of which occurred from 1450 to 1850 (http://www.vehiclechoice.org/climate/cutler.html). If that is so, then it might be wise to store industrial CO_2 in cavities in the earth and in forests to be released into the atmosphere as needed to ameliorate future episodes of intense cooling of the earth.

Definitions:

- **Ice Age** = a period of time during which the temperature is $2C^{\circ}-10C^{\circ}$ colder than at present and ice sheets and glaciers extend much beyond their present boundaries.
- **Little Ice Age** = a period of time, of the order of 2,000 years, during which the temperature is about $2C^{\circ}$ colder than at present and ice sheets and glaciers extended beyond their present boundaries.
- **Minor Ice Age =** a period of time, of the order of 20,000 years, during which the temperature is about $3C^{\circ}$ colder than the warm periods (Minor Interglacials) around it and about $5C^{\circ}$ colder than at present.
- **Major Ice Age** = a period of time, of the order of 100,000 years, during which the temperature is $4C^{\circ}-10C^{\circ}$ colder than at present and ice sheets and glaciers extend much beyond their present boundaries.
- **Interglacial** = a period of time, of the order of 10,000 years, during which the temperature is $2C^{\circ}-4C^{\circ}$ higher than the previous temperature minimum and ice sheets and glaciers somewhat diminish from what they were at the previous temperature minimum.
- **Major Interglacial** = a period of time, of the order of 10,000 years, during which the temperature is up to $3C^{\circ}$ warmer than the present and ice sheets and glaciers are at a minimum or disappear.

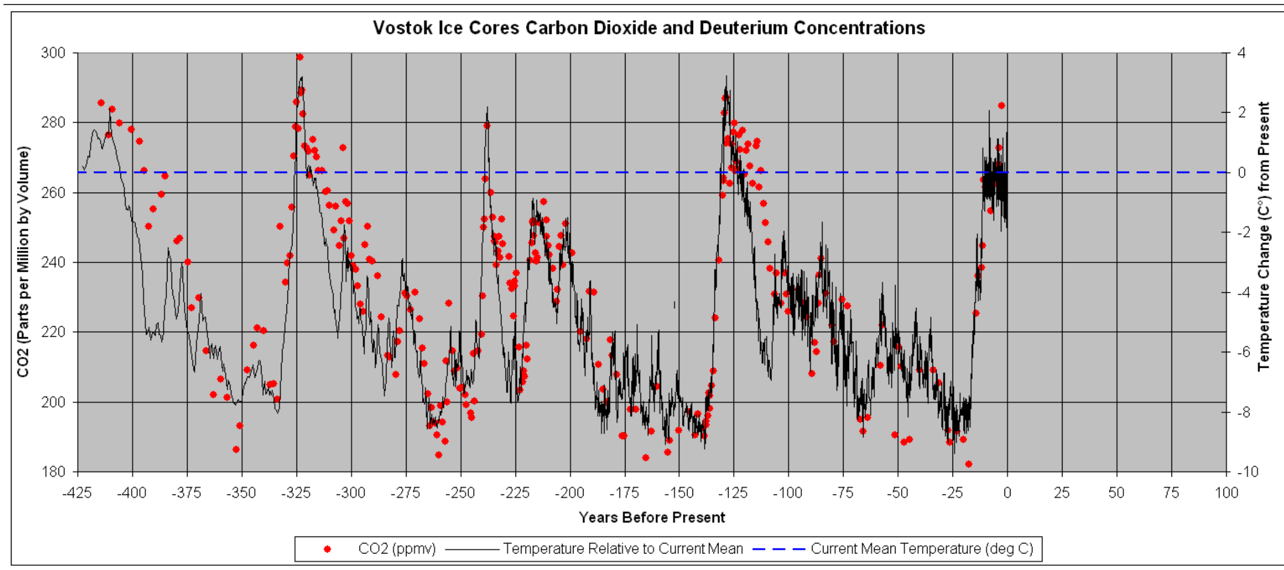
- **Minor Interglacial** = a period of time, of the order of 20,000 years, during which the temperature is about $3C^{\circ}$ warmer than the colder periods (Minor Ice Ages) around it.
- **Insolation** = incident solar power per horizontal surface area at the top of a planet's atmosphere. Unit = Watts/m^2 or kilojoules/m^2/day (Conversion factor: multiply 86.4 x W/m^2.)
- **Irradiance** = power emission from the Sun per area of the Sun.
- **ybp =** years before the present
- **yap =** years after the present

Some crucial questions are:

- Is the earth poised to enter an ice age?
- Is it possible to store enough CO_2 in earth cavities to do the periodic job of amelioration of ice ages as needed?
- Is it possible to extract the CO_2 when it is needed to ameliorate declines in insolation?

Is the Earth Poised to Enter a Long Major Ice Age?

Carbon dioxide (CO_2) and deuterium concentrations have been measured in ice cores at the Vostok Station in Antarctica (http://www.ngdc.noaa.gov/paleo/icecore/antarctica/vostok/vostok_data.html), within 12° latitude of the North Pole. Times were calculated for the deuterium data.



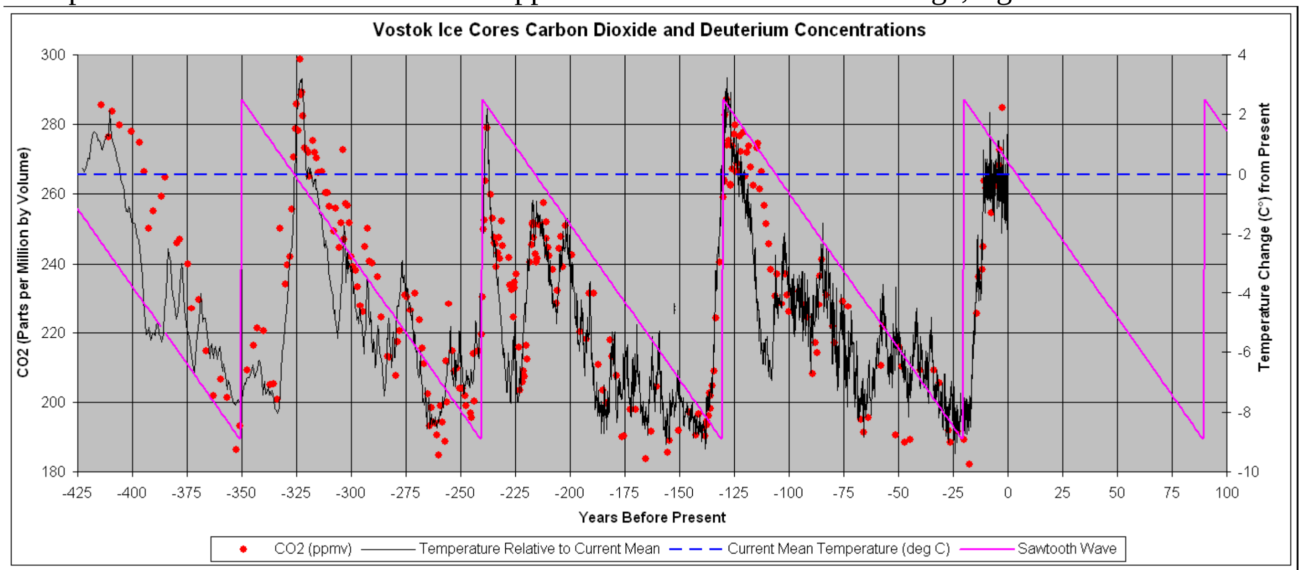
These data imply four ice ages about 100,000 years duration over the last 400,000 years or so, with high-temperature interglacials of about 10,000 years duration. It is interesting to note that higher temperatures correlate with higher CO_2 concentrations; there appears to be a feedback relationship between the two variables. Thus, man-released CO_2 (by increased human population, domestic animals, and burning of wood, coal and petroleum), which is seen as the increasing value for the last few thousand years, adds to temperature increase. (See below for more recent values.) Thus, the temperature has remained rather stable for the last few thousand years, contrary to the case for the previous four temperature maxima (interglacials).

The sawtooth-wave nature of the data is a well-known phenomenon of nonlinear systems (systems with feedback). It occurs often in the study of fluids, plasmas, biological systems and electronic circuits. (For example, http://www.darpa.mil/mto/aosp/wisconsin.html shows an electronic circuit that creates a similar sawtooth wave. Another example for nerve excitation: Fig. 2 in http://jn.physiology.org/cgi/content/full/79/5/2358?ijkey=RSx0jaqiEBG6M). For a discussion about climate triggering, see http://www.pik-potsdam.de/~stefan/Publications/Journals/stochres.pdf.)

The simple mathematical equation for a general sawtooth wave can be found in http://www.cfxweb.net/modules.php?name=News&file=article&sid=184. An approximate equation for the deuterium-temperature data shown in the graph above, can be written as

$$\mathrm{T}(\mathrm{t}+\Delta) = T(t) - \frac{A}{t_1}\Delta$$ for backward times. (Change the sign for forward times.)

A = the peak value of the temperature and t_1 = the time at the midpoint of the most recent (approximated) linear fall. To a first linear approximation $T(t) = at + b$. Applying this equation, with parameters a and b determined to approximate the most recent ice age, I get:



This gives a crude prediction for the next Major Ice Age. Below I will concoct some more accurate ways to predict the next Major Ice Age.

Recent unpublished ice-core data extends this ice-age periodicity back to about 780,000 ybp, which shows four more approximately sawtoothed ice ages.

These data make it clear that the earth is at a warm peak, poised for a downward slide into another Major Ice Age over the next 100,000 years or so. However, one must consider possible fine structure for little ice ages in the more recent future, as I shall do below.

I have only plotted an approximate long-term envelope sawtooth; it is obvious that other short-term peaks are embedded in the long-term sawtooth.

Sawtooth waves occur when there is a trigger or threshold and much feedback in a system. It is interesting that the sharp change is for temperature increases and the slow fall is for temperature decreases. This indicates that the temperature rise is due to a trigger/threshold and the temperature fall involves much feedback but could involve several triggers. Feedback for temperature rising triggering seems much simpler and larger than the multiple-feedbacks for temperature decreasing.

It appears that the atmospheric CO_2 increase caused by the rising temperature provides a positive feedback causing the temperature to rise faster. It appears that the major trigger for the initial cooling is probably abrupt stoppage of ocean currents from the tropics to the arctics as insolation increases (http://www.firstscience.com/site/articles/gribbin.asp), although there could be more than one trigger, especially for the shorter-term peaks.

Some of the feedback agents are:

- Cloud cover (http://www.doc.mmu.ac.uk/aric/gccsg/6-9-2-2.html)
- Ice cover (the cryosphere) (http://www.doc.mmu.ac.uk/aric/gccsg/1-3-2.html)
- Ocean energy storage and transfer (http://www.doc.mmu.ac.uk/aric/gccsg/1-3-1.html)
- Atmosphere energy storage and transfer (http://www.doc.mmu.ac.uk/aric/gccsg/1-2-4.html)

Whatever the combined effects of the feedbacks, it appears that they are more numerous and complex when temperature is decreasing than when it is increasing.

The above graph makes it appear highly probable that the long-term near future is for another long ice age. It appears that there is no such thing as a "long interglacial." Instead, for Major Ice Ages there is a rapid rise in temperature, followed by a slower decline in temperature over a long time. However, there can be a rapid initial drop in temperature, which then is checked by a small rise, as part of a small sawtooth. I will discuss the short-term future below.

Solar Insolation as the Driving Energy for Climate Change

The only sources of energy available to force climate changes are solar insolation, internal energy of various kinds stored in the earth, collisions of asteroids and comets with the earth (see below for more about this), and possibly massive impingement of cosmic rays on the earth (see below). There are four kinds of earth internal energy: heat, binding energy of various chemicals, binding energy of nuclei, and radioactivity. One such chemical is coal, from which humans have released its binding energy into the atmosphere by burning it. Heat energy was involved in climate change in the past when massive volcanic eruptions occurred. An example of climate change by asteroid/comet collisions (see below) changing the climate was the Chixalub collision in the Yucatan about 65,000,000 ybp, which caused the extinction of the dinosaurs and many other species of plants and animals. So, calculating solar insolation will not yield all energy that drives the climate, but solar power incident on the earth is probably the most important periodic component, which the graphs below will make plausible.

In order to get a better understanding of future ice ages, one needs to look at the past history and future predictions for solar insolation on the earth and compare it to the past temperatures shown in the graph above, in order to try to predict future temperatures. (See: http://www.geo.arizona.edu/palynology/geos462/21climastro.html and http://www.jhu.edu/~eps/staff/hinnov/hinnovresearch/earthsorbitalparameters.htm)

So, it is important to be able to calculate insolation, which, amazingly, can be done with high accuracy for a period of 30 mega-years. The following insolation plots are for Milankovitch earth-orbit theory, whose insolation calculations have been shown to correlate closely with climate variables. I used the FORTRAN program (insola.f) and input parameters (Laskar 1998 solution) given in http://xml.gsfc.nasa.gov/archive/catalgs/6/6063/index_long.html for insolation calculations. The source web page states that this solution is good for -20×10^{6} years to $+10\times10^{6}$ years. (I compiled the code for Windows using Absoft FORTRAN. I had to recode much of it to read directly from the four ASCII data files, since I could not get the code to work using a binary file created from the ASCII files by the code preinsol.f for a Unix computer. A description of the Windows insolation-calculation programs and download links for them are at http://www.roperld.com/science/InsolationCodes.pdf. The program was set to use 1350 watts/m^2 as the solar constant, which I used. Later I found the paper http://www.ras.org.uk/pdfs/Solanki.pdf, which indicates a better value for the solar constant as 1367 watts/ m^2; it only affects the overall normalization, which is not important for this study.

The Mean Longitude of the Sun (MLS) is the parameter that specifies the time of year in the calculations. Its value as shown in the 2nd and 4th rows in the following table for the dates in the 1st and 3rd rows:

21 Mar	21 Apr	21 May	**21 Jun**	21 Jul	21 Aug
0°	30°	60°	**90°**	120°	150°
21 Sep	21 Oct	21 Nov	**21 Dec**	21 Jan	21 Feb
180°	210°	240°	**270°**	300°	330°

I used the code to calculate the insolation for the **middle of summer** and the **middle of winter** for many earth latitudes $\phi\left(5^\circ \text{ intervals}\right)$ for a given time.

For **summer** I used:

- $MLS=-\frac{18}{5}\phi+180^\circ$ for $-25^\circ\le\phi\le25^\circ$,
- $MLS=270^\circ$ for $\phi<-25^\circ$ and
- $MLS=90^\circ$ for $\phi>25^\circ$.

For **winter** I used:

- $MLS=90^\circ$ for $\phi\le0^\circ$ and
- $MLS=270^\circ$ for $\phi>0^\circ$.

For example, for **summer**:

- latitude -90° (South Pole) has $MLS=270^\circ$ and
- latitude +90° (North Pole) has $MLS=90^\circ$.

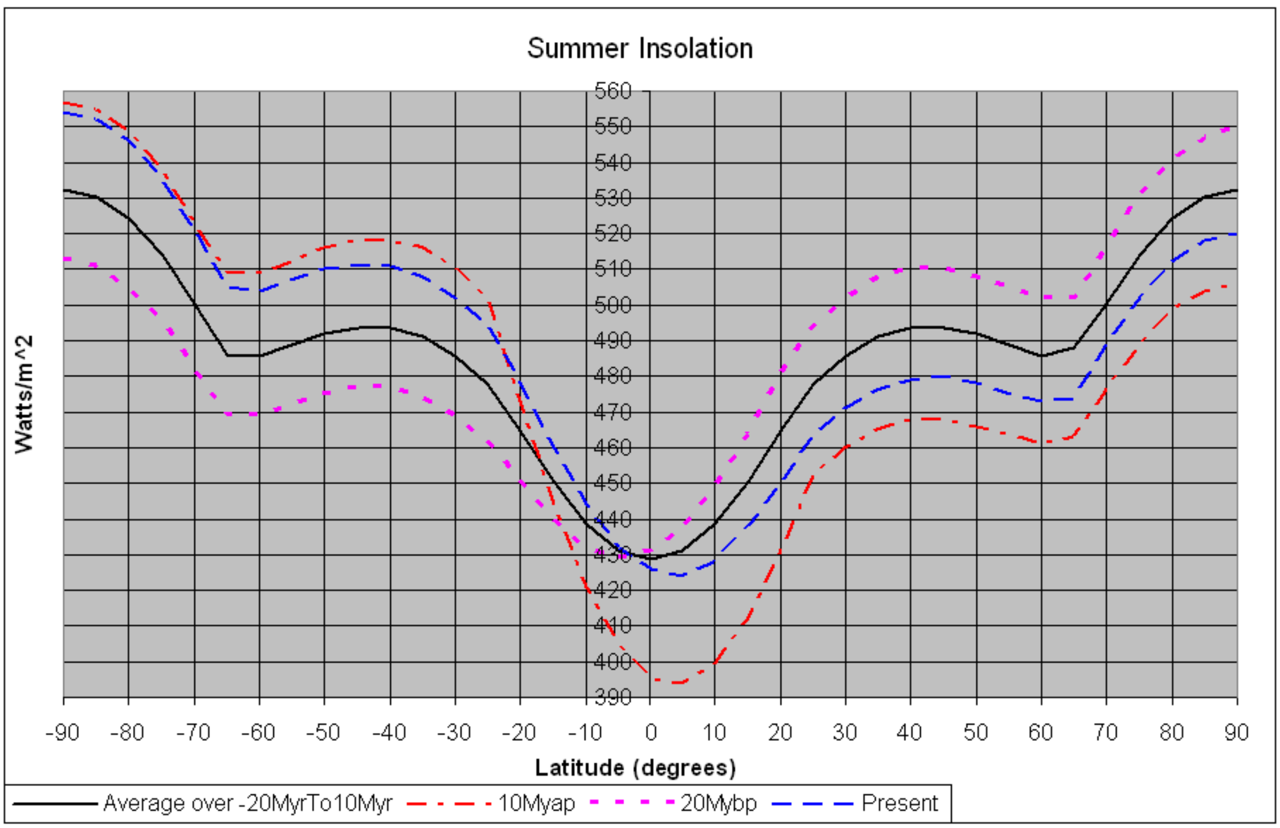
And for **winter**:

- latitude -65° has $MLS=90^\circ$ and
- latitude +65° has $MLS=270^\circ$.
- ($\phi>65^\circ$ and $\phi<-65^\circ$ are dark in the middle of winter.)

The following table shows the MLS “**summer**” assignments for different latitudes:

Latitude(°)	-90	-85	-80	-75	-70	-65	-60	-55	-50
MLS(°)	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**270**	**270**
Latitude(°)	-45	-40	-35	-30	-25	-20	-15	-10	-5
MLS(°)	**270**	**270**	**270**	**270**	**270**	**252**	**234**	**216**	**198**
Latitude(°)	0	5	10	15	20	25	30	35	40
MLS(°)	**180**	**162**	**144**	**126**	**108**	**90**	**90**	**90**	**90**
Latitude(°)	45	50	55	60	65	70	75	80	85
MLS(°)	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**
Latitude(°)	90								
MLS(°)	**90**								

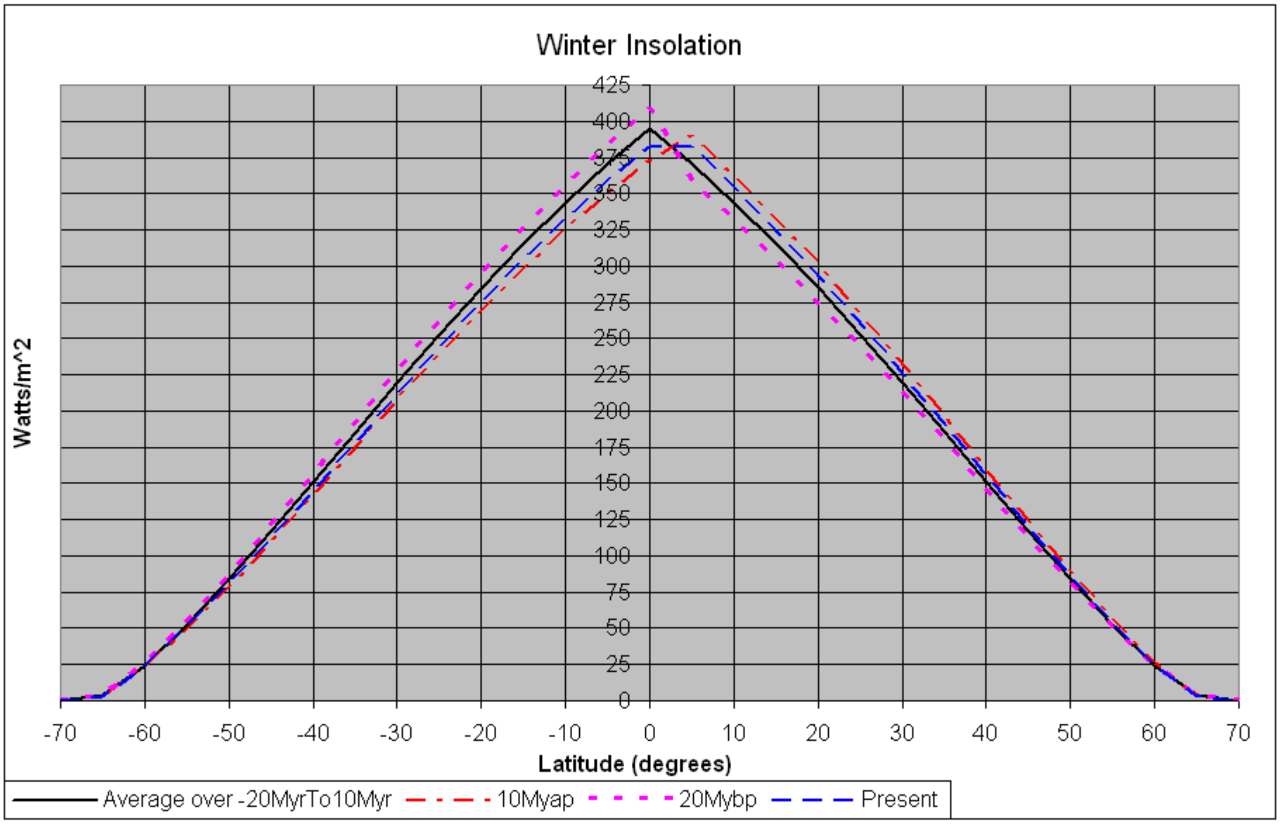
The average summer insolation over the entire time period and for three specific years as functions of latitude are shown here:



Note the effects of 24 hours of daylight near the poles ($\phi > |65^{\circ}|$). Notice the symmetry with latitude when averaged over long times; this is because the time period (30×10^{6} years) is much longer than any of the periods in the orbital motion. At present insolation is about 6% larger at the South Pole in its summers than it is at the North Pole in its summers.

This gives a good estimate of the range of summer insolation for different latitudes over the time period calculated

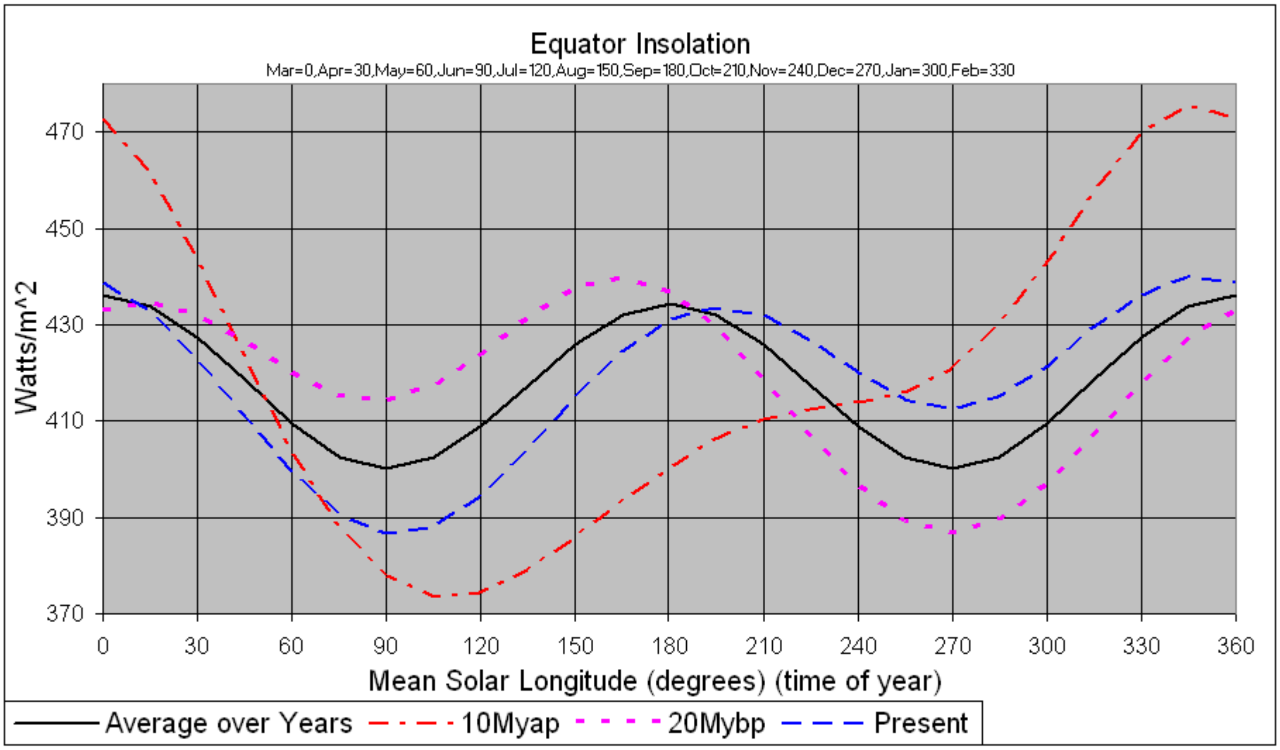
The average winter insolation over the entire time period and for three specific years as functions of latitude are shown here:

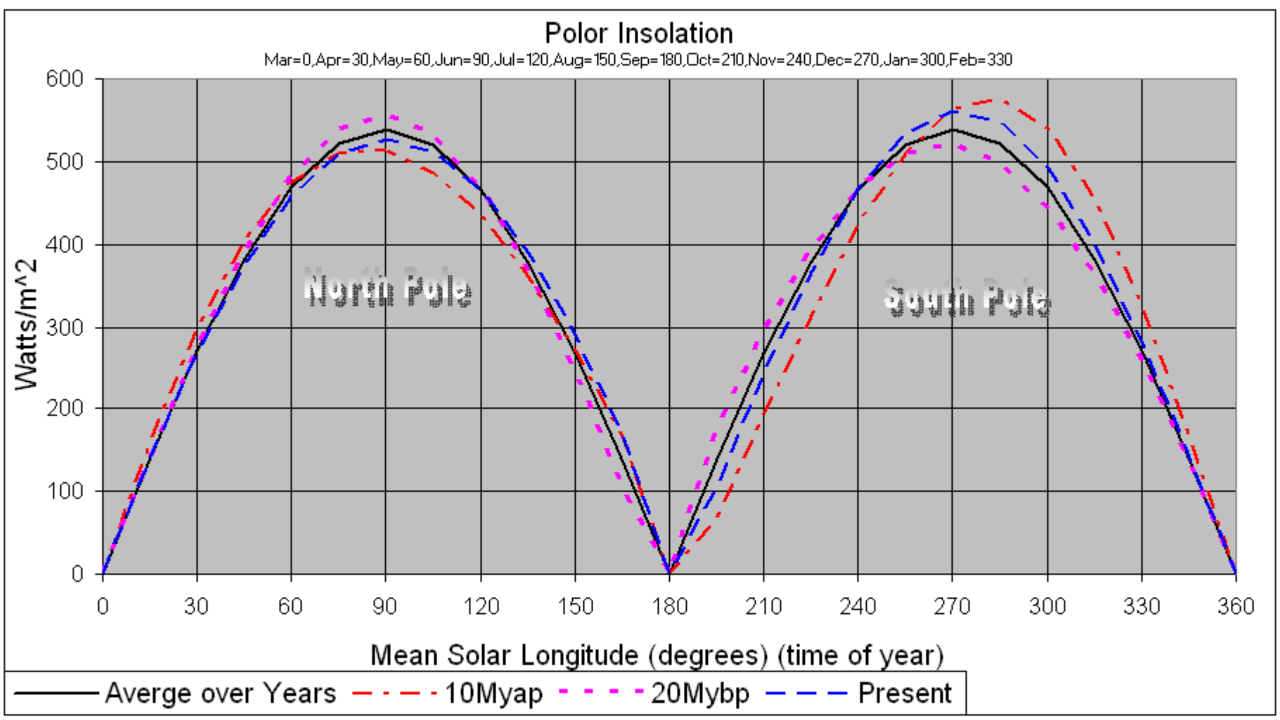


Notice the symmetry with latitude when averaged over long times; this is because the time period (30×10^6 years) is much longer than any of the periods in the orbital motion. There is not much difference over time at any latitude for winters.

This gives a good estimate of the range of winter insolation for different latitudes over the time period calculated.

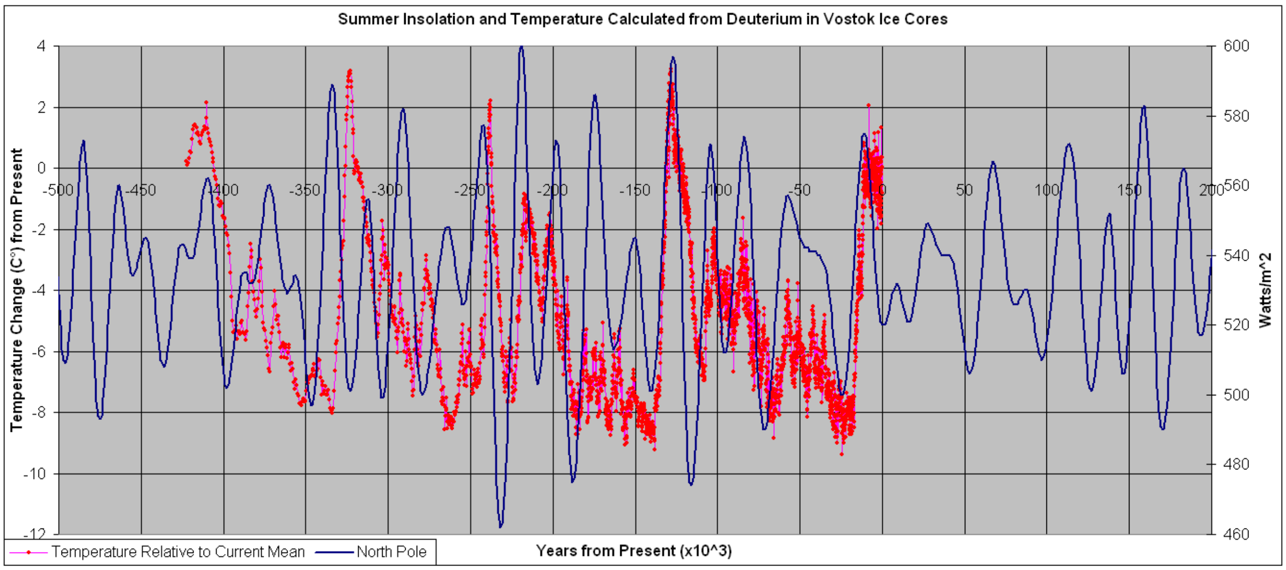
Two other interesting graphs are:





Note the symmetry about MLS=180° (21 September) for the average over all years, because the time span (30×10^6 years) is much longer than the Milankovitch periods. For the same reason, the 21 Sept. (MLS=180°) and the 21 March (MLS=0°) values are the same and the 21 June (MLS=90°) and the 21 December (MLS=270°) values are the same for the average over all years.

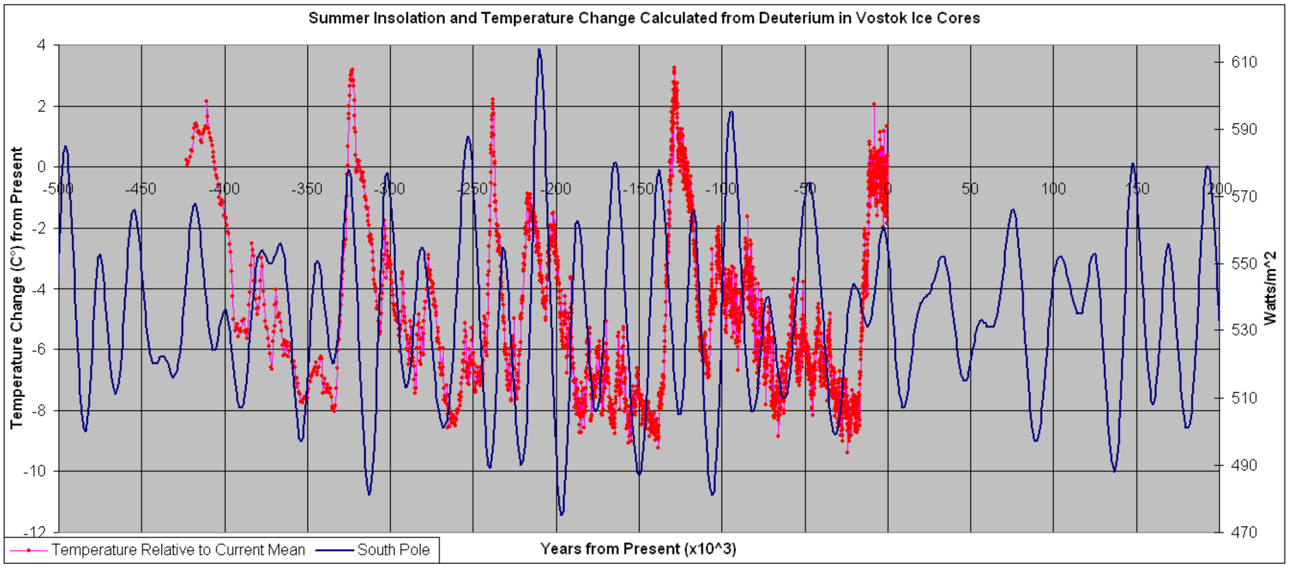
Insolation in the northern latitudes is supposed to be a major driving force for climate, because of the concentration of land mass there where ice can accumulate. Consider the summer insolation at the North Pole from 500×10^3 years before the present to 200×10^3 years into the future, along with the temperature, compared to present mean temperature, determined by deuterium concentration in Vostok ice cores mentioned above:



The temperatures calculated from deuterium concentration in the Vostok ice cores are not expected to be highly accurate, especially for long times in the past; but the correspondence between the warm peaks and the insolation peaks appears to be quite good. Correlation coefficients will be given below.

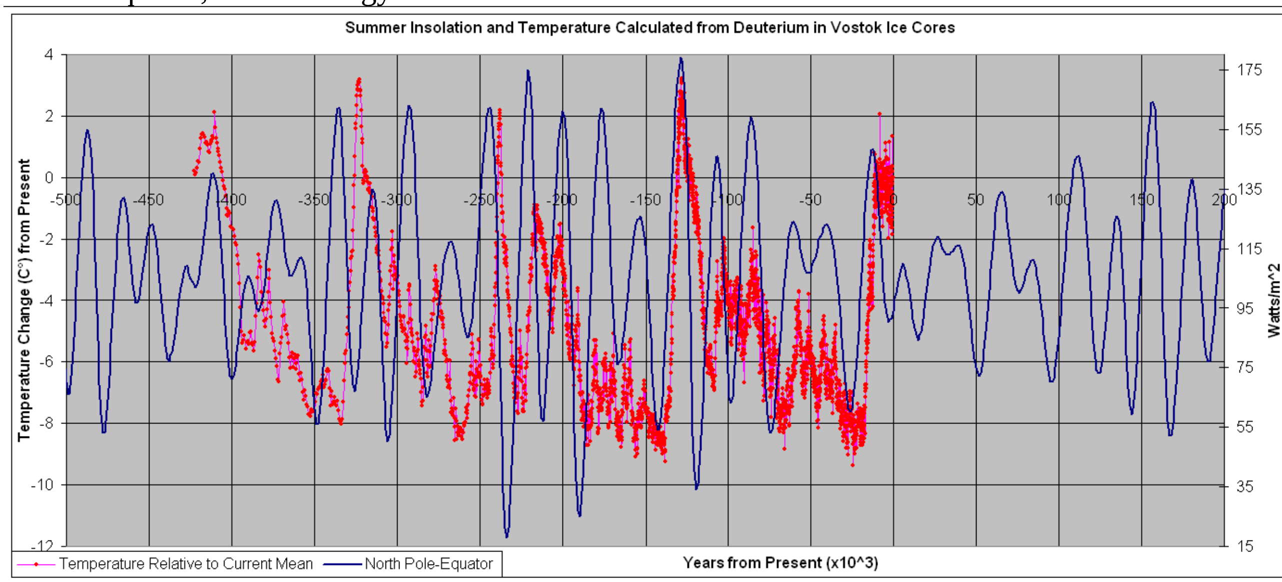
Note that the four previous ice ages, as represented by the deuterium temperature-change measurements, started quickly as the insolation peaks decreased, but then the temperature-decrease slowed down until a point was reached when increased insolation triggered a fast warming. Note that the insolation peaks over the next 20,000 years will be quite low compared to a similar period during the last two Major Ice Ages. In fact, the insolation over the next 200,000 years will form a smaller set of peaks than at any time in the last 350,000 years. This implies that the immanent Major Ice Age will be quite different than the last one.

One might think that the South Pole insolation should be involved, more than the North Pole, with the formation of snow in Antarctica:



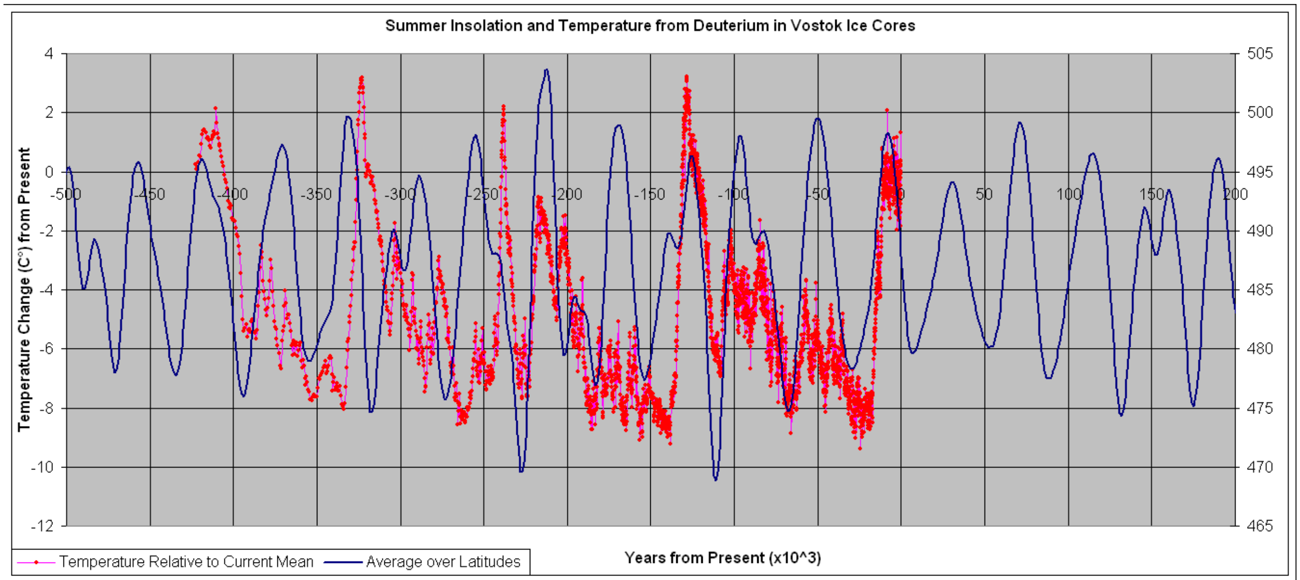
It appears that the North Pole insolation is more closely related to the deuterium temperature measurements than is the South Pole insolation. Correlation coefficients will be given below.

One could argue that the climate is driven by the difference of insolation between the polar regions and the equator, as this energy difference drives the winds and ocean currents:



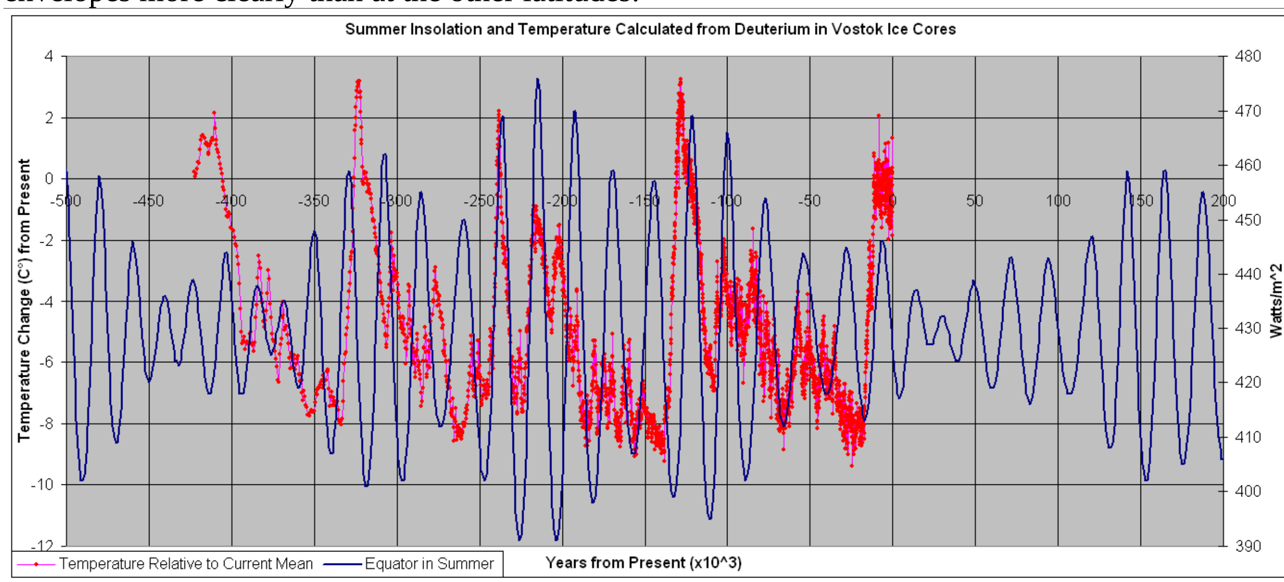
See below for correlation coefficients.

Finally, one could argue that the average summer insolation over all latitudes should be the driving force for climate. The following plot is the average summer insolation for 5 degree latitude intervals from the South Pole to the North Pole:



See below for correlations coefficients.

The insolation at the Equator in the summer shows the 100,000-years and 400,000-years periods envelopes more clearly than at the other latitudes:

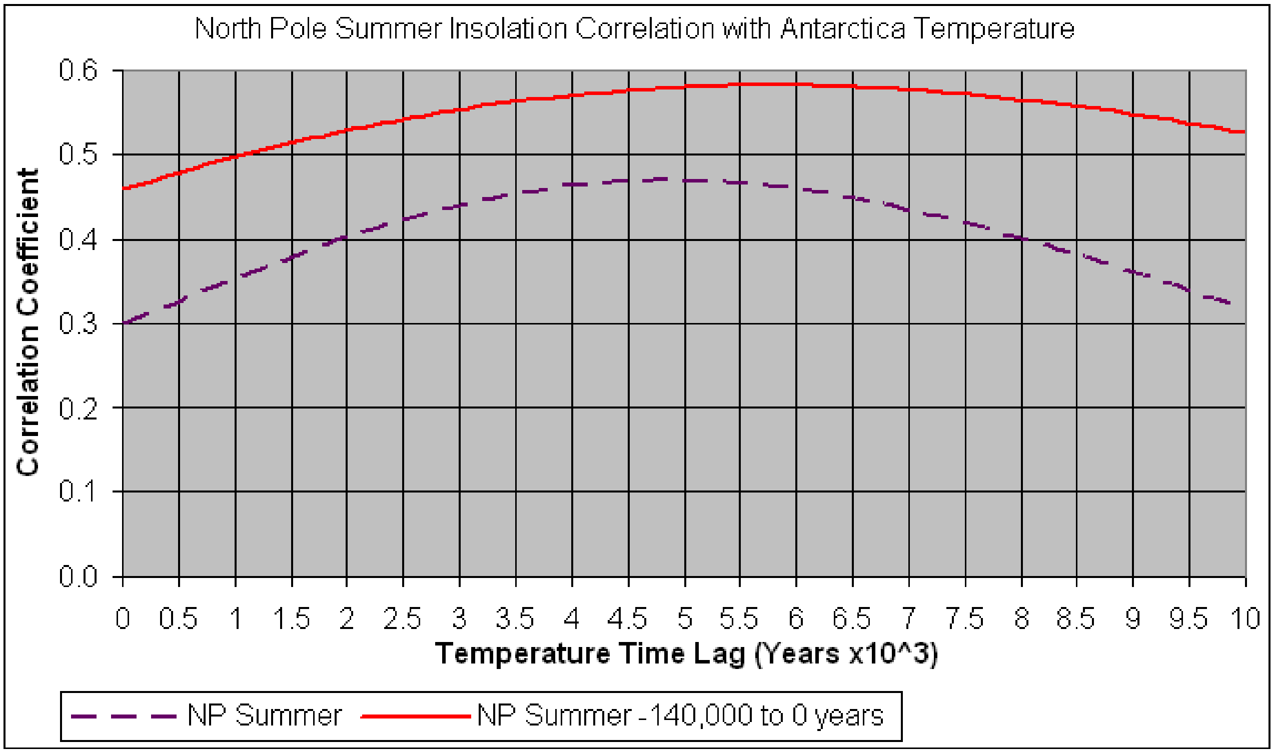


See below for correlations coefficients.

Note in all of these insolation-temperature graphs that, after a warm spike is triggered by an insolation peak, there is a latency period that prevents the next insolation peak from being so effective in creating another warm spike. This a common feature of nonlinear phenomena; it is part of the effect of the various feedbacks that are in effect. That is, it is what produces a sawtooth function.

I calculated the correlation coefficient for various insolation values with Antarctica temperatures for years from 0 to -422×10^3 ybp and got the highest correlation with the North Pole summer insolation. The highest correlations coefficient was 0.470 for a temperature time lag of about 5,000 years.

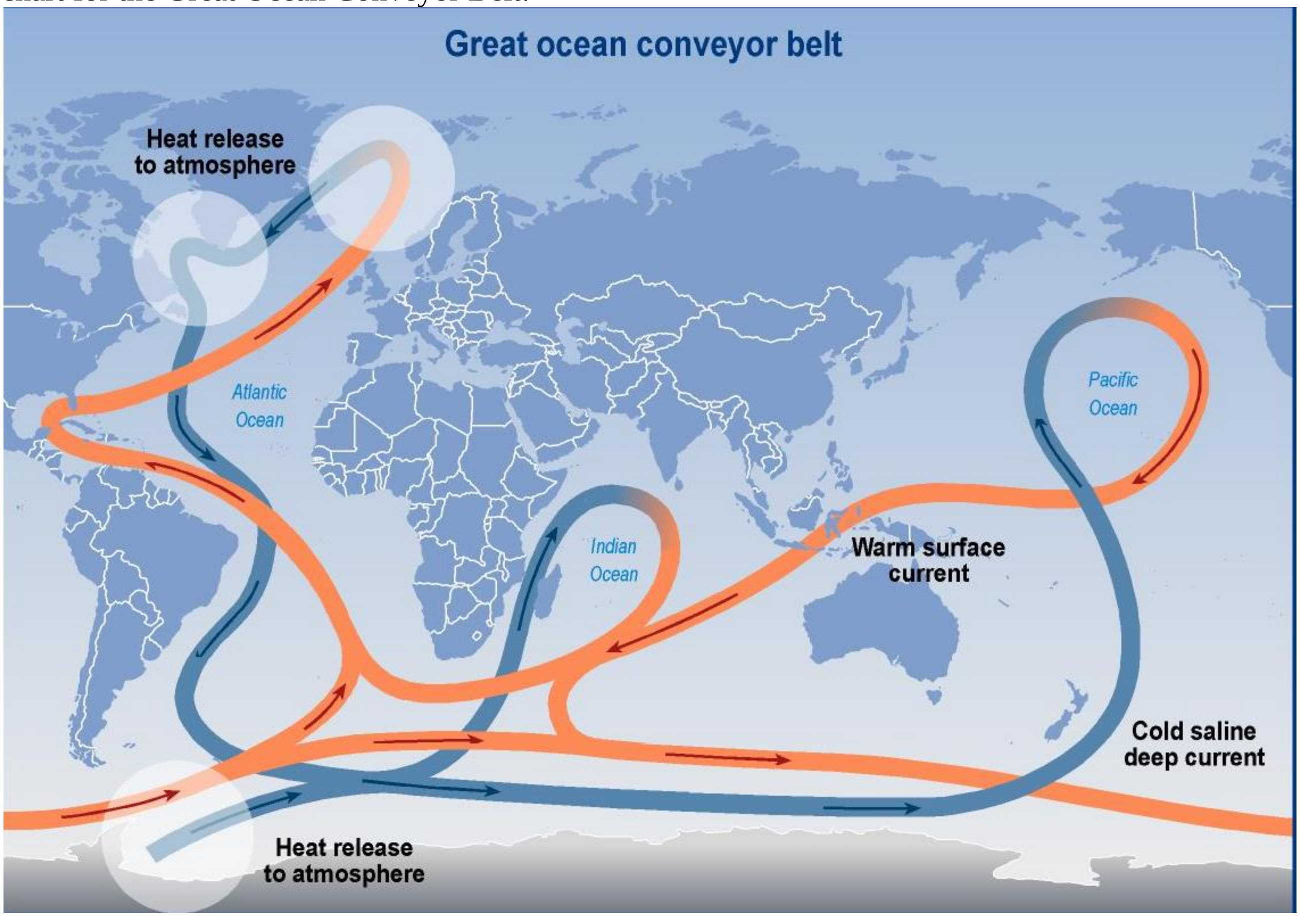
The correlation coefficient is shown as a function of temperature time lag in the following graph:



Why would the temperature lag the summer insolation averaged over all latitudes and lead the winter insolation averaged over all latitudes? Triggering can occur for both leads and lags, depending on the nature of the feedback agents. A threshold for enhanced temperature increase can be reached on the way up a peak in insolation and a threshold for enhanced temperature decrease can be reached on the way down a minimum in insolation, not necessarily at or after the peak or minimum. Also, a threshold for a rapid temperature decrease can occur if the temperature gets too high and a threshold for a rapid temperature increase can occur if the temperature gets too low. Since we know very little about all the components of climate-changing feedbacks, one should look for correlations for both leads and lags. It appears that a threshold exists causing rapidly increasing temperatures for increasing insolation, and a threshold exists causing rapidly decreasing temperatures when the temperature gets too high. The main candidate for these thresholds is the changing of large ocean currents (http://www.firstscience.com/site/articles/gribbin.asp). Also, CO_2 concentration in the atmosphere is also involved.

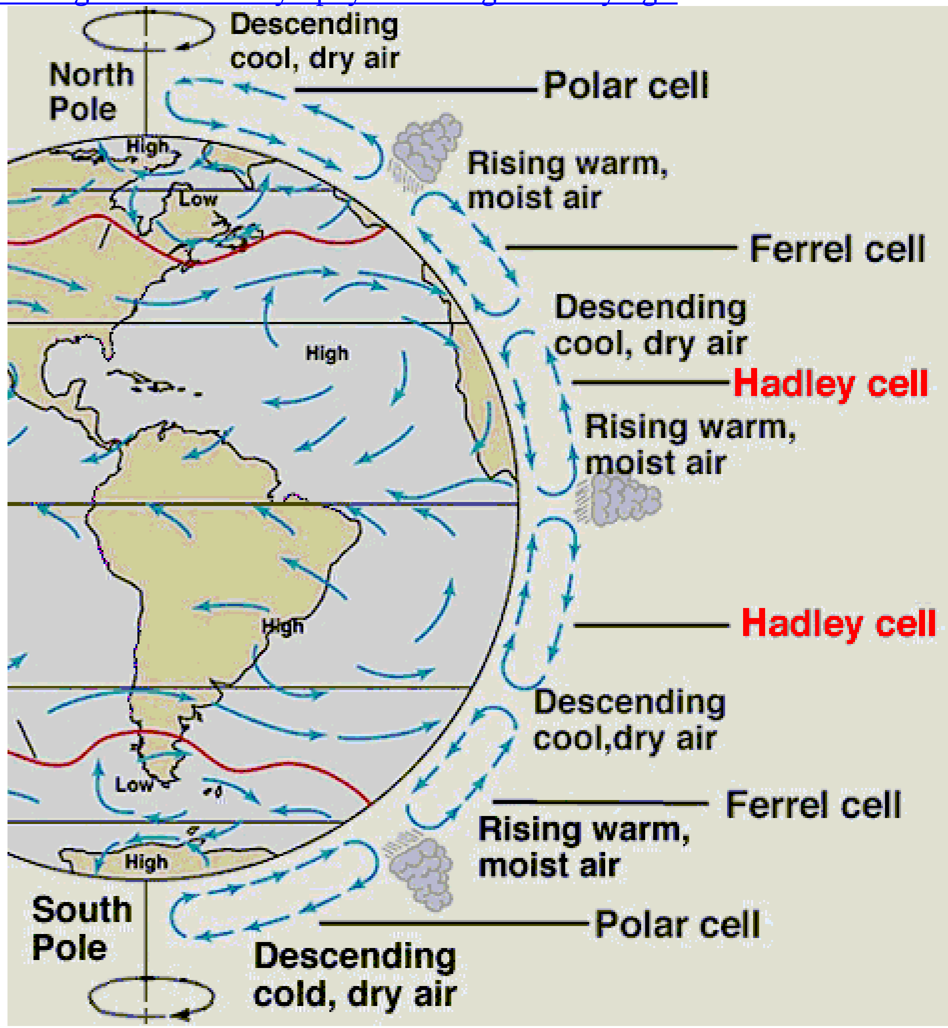
On the other hand, the temperatures for the Major Ice Ages before the most recent one (earlier than 150,000 years ago), may not be correctly determined.

After completing the correlation analysis above, I considered the known energy currents in the atmosphere and ocean. The 1991 Intergovernmental Panel on Climate Change give the following chart for the Great Ocean Conveyor Belt:



This made me think that perhaps the difference between the 60° and the -60° insolation values might be a possible driver of the climate.

Also, consider the Hadley, Ferrel and Polar cells description of atmospheric currents, as shown in http://hendrix.uoregon.edu/~dlivelyb/phys161/images/hadley0.gif:



This made me think that the insolation combination to consider as a driving force is (90°- 60°) - (60°-30°) + (30°-0°) = (90° - 2· 60° + 2· 30° - 0°). I call this cell-circulation insolation. (Note that the atmospheric circulation is not independent from the ocean circulation, as represented by the thunderheads at the junctions of the cells. Much heat is transferred between the atmosphere and the oceans.)

The correlation coefficients and lag times with the Antarctica temperatures over the last 150,000 years for these situations and some others discussed above are:

Item	**Correlation Coefficient**	**Temperature Lead (- for lag)**
North Pole Summer	**0.561**	-3000 years
Average Latitudes Summer	**0.510**	-1500 years
60° - (-60°)	**0.294**	-3000 years
90° - 2· 60° + 2· 30° - 0°	**0.145**	-7000 years

So, the ocean current and Hadley-Ferrel-Polar cells ideas do not work very well.

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