Major Ice Ages, Ocean Currents and Global Warming

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Much discussion has occurred about the relationships of ocean currents in the Atlantic Ocean with climate change and global warming. It is well known that there is a complicated set of currents in the Atlantic and Pacific Oceans involving surface and deep water (Colling, 2002) and that those ocean currents, particularly the North Atlantic currents, are intimately involved in the Earth's climate (Houghton, 2001). It is speculated that global warming could decrease or cut off the North Atlantic Ocean currents "soon" (time scale of decades to millennia) and thereby cause "sudden" changes in climate leading into the Next Major Ice Age. (See below for definitions of terms.)

A recent movie *The Day After Tomorrow* is based on the theory that global warming could cause an Atlantic ocean current to turn off sooner than normal and hasten the inevitable entry of the Earth into the Next Major Ice Age, although with an unrealistic time scale of weeks to months. The time scale is more likely to be at least decades or centuries.

Major Ice Ages and Major Interglacials

In this article a "Major Ice Age" is defined as the period of about 115 kiloyears between two Major Interglacials surrounding the Major Ice Age. (See Figure 1.) The "Major Interglacials" are of about 5-15 kiloyears duration and are the times when the Earth's temperature is at a high maximum at the edges of a Major Ice Age period. The temperature differential between the low point (Glacial Maximum) of a Major Ice Age and the Major Interglacial that follows it is about 9-12 degrees Celsius. The Earth left the Last Major Ice Age to enter the Present Major Interglacial about 10 kiloyears ago and is on the verge of entering the Next Major Ice Age. That is, the Earth is on the high-time edge of the Present Major Interglacial. The Last Glacial Maximum was about 20 kiloyears ago. There have been eight Major Ice Ages of varying severity and variability over the last 900 kiloyears (Alley, 2001; Wilson, 2000). The Last Major Interglacial is called the Eemian Interglacial.

In Figure 1 it is seen that, in addition to the two large temperature peaks (the Last and Present Interglacials) there are eight peaks that stand above the other temperatures at-106, -102, -84, -57, -51, -42, -35, and -14 kiloyears ago. These large peaks appear to be highly correlated with the maxima of the North-Pole summer insolation (solar energy per area at the top of the atmosphere) (Berger, 1991), which is also shown in Figure 1. These peaks are called Stadials and the large valleys between them Interstadials. The author prefers the more descriptive terms Minor Ice Ages and Minor Interglacials. The even smaller valleys are called Heinrich Events (Wilson, 2000). The author prefers the more descriptive terms Little Ice Ages and Little Interglacials for the even smaller peaks and valleys between the eight small (compared to the two Major Interglacials) peaks.

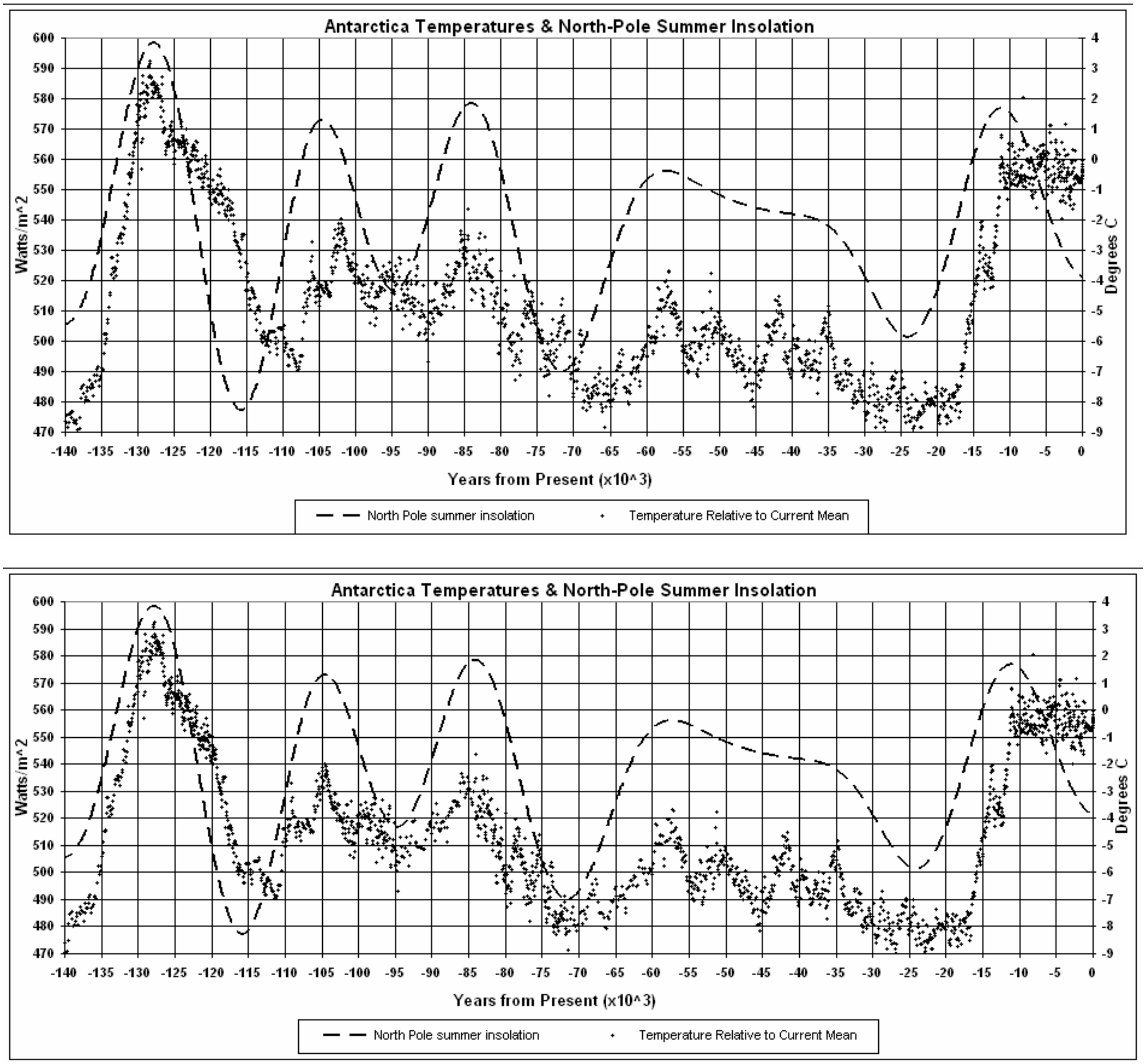

Figure 1. The top graph shows the Antarctica temperature data (relative to present temperature; scale on right) (Pettit, 1999) determined from hydrogen content of ice cores and it also shows the calculated North-Pole summer insolation (Berger, 1991) (scale on left). Note the visually obvious high, but far from perfect, correlation between the Antarctic temperatures and the North-Pole summer insolation. The bottom graph shows the "tuned" Antarctica temperature data. See the text for information about tuning.

Ocean Currents and Major Interglacials

A first step in understanding the relationship of ocean currents to climate is to try to model conceptually and mathematically how past climate might be related to ocean currents.

This article proposes a theory of how the turning on and off of Atlantic Ocean currents is related to Major Ice Ages. The theory was arrived at by fitting Antarctica atmospheric temperature data for the Last Major Ice Age (and three earlier Major Ice Ages) with a mathematical function that represent the turning on and off of Earth states and a correlation with North-Pole summer insolation (solar energy per area entering the top of the atmosphere). A possible interpretation of the Earth states is as components of the Atlantic Thermohaline Current (ATC) (Colling, 2002). (The Pacific Ocean also has ocean currents connected to the Atlantic Ocean currents, but they do not have much effect on the heat balance in the North Polar region which, as will be described below, is the location of most importance in climate change. (Colling, 2002; Calvin, 2002))

Four different types of fits to Antarctica temperature data for the last 140 kiloyears will be described:

1. A fit involving the North-Pole summer insolation (solar energy per area at the top of the atmosphere). Although some major oscillatory features of the temperature data are represented, the fit is very poor in the time region of the Major Interglacials.

2. A fit involving the North-Pole summer insolation plus one component of the Atlantic Thermohaline Current (ATC) turning on and off near the Last Major Interglacial about 127 kiloyears ago and again near the Present Major Interglacial. This is a reasonably good fit to the data, except for short-term Earth states (e.g., volcano eruptions, asteroid/comet impacts or ATC fluctuations) turning on and off with a duration time of about 5 kiloyears.

3. A fit involving the North-Pole summer insolation plus two components of the ATC turning on and off near the Last Major Interglacial about 127 kiloyears ago and again near the Present Major Interglacial. This is a better fit to the data, but does not account for short-term Earth states (e.g., volcano eruptions, asteroid/comet impacts or ATC fluctuations) turning on and off with a duration time of about 5 kiloyears.

4. A fit involving the North-Pole summer insolation plus turning on and off of three components of the ATC in the vicinity of the Last Major Interglacial and two components of the ATC plus a brief cutoff of one of them (the Younger Dryas) at about 12 kiloyears ago for the Present Major Interglacial. This is a better fit to the data, but does not account for short-term Earth states (e.g., volcano eruptions, asteroid/comet impacts or ATC fluctuations) turning on and off with a duration time of about 5 kiloyears.

5. A fit involving the North-Pole summer insolation plus turning on and off of three components of the ATC in the vicinity of the Last Major Interglacial and two components of the ATC plus a brief cutoff of one of them (the Younger Dryas) at about 12 kiloyears ago for the Present Major Interglacial plus fourteen other transient Earth states (e.g., volcano eruptions, asteroid/comet impacts or ATC fluctuations) with a duration time of about 5 kiloyears. This, of course, is the best fit to the data.

It is possible that the some of the Earth states that are turned on and off in the vicinity of Major Interglacials are some other Earth events besides ATC. For example, they could be a switch in atmospheric circulation to the North-Polar region or due to the 100-kiloyears period of the Earth orbit moving into and out of the invariant Solar system plane (essentially the orbit plane of Jupiter) (Muller, 1997).

Antarctica Temperature Data for the Last Major Ice Age

Measured Antarctica temperatures for the Last Major Ice Age are shown in Figure 1 (Pettit, 1999). These temperature data were calculated from the concentration of deuterium in ice cores. The Earth is now at 0 time at the extreme right of the graph, near the end of the Present Major Interglacial. Note the extreme low-temperature minima near the end of the Last Major Ice Age (Last Glacial Maximum) at about 20 kiloyears ago and at the end of the Penultimate Major Ice Age (Penultimate Glacial Maximum) at about 140 kiloyears ago.

Also shown in Figure 1 is the calculated solar energy per area at the top of the atmosphere (insolation) for 21 June (summer) at the North Pole (Berger, 1991). A visually obvious correlation exists between the Antarctica temperature data and the North-Pole summer insolation. The top graph in Figure 1 is for the original data and the bottom graph is for “tuned” data. There are errors in the determination of the timing of yearly ice layers since, unlike tree rings, ice layers can be obliterated or obfuscated by weather action and glacial movement (Alley, 2001). Therefore, fitting to the ice-core temperature data is done with both the original data and with “tuned” data, for which the temperature data maxima and minima are aligned more with the North-Pole summer insolation maxima and minima. Some subjective decisions were made about the “maxima” and “minima” of the temperature data to be tuned to the maxima and minima of the insolation. (Roper, 2004)

A time lag between the calculated North-Pole summer insolation and the Antarctica temperature data is not visually obvious in the top graph of Figure 1. Correlation studies have shown that the highest positive correlation coefficients occur for time lags of 3 to 6 kiloyears. The correlation studies also show that North-Pole summer insolation has higher correlation with Antarctica temperatures than does insolation at other Earth locations and other seasons of the year. (Roper, 2004)

Rather than trying to account for a specific time lag in the fits described here, the original data were fitted and data tuned to the maximum and minima of the calculated North-Pole summer insolation were fitted, so that the two cases can be compared. Since the tuned data presumably eliminate any time lag, comparing the two fits should give an approximate picture of the case for a time lag. The results of the fits are qualitatively similar for the original and the tuned temperature data. The fit to tuned data is considered by the author to be the more accurate fit, with the understanding that there may be a time lag of a few thousand years between the insolation and the temperatures and between the ATC and the temperatures.

Fits to the Antarctica Temperature Data for the Last Major Ice Age

The temperature data points in Figure 1 are from ice-core measurement in Antarctica, which are the best temperature data available for the Last four Major Ice Ages. Data for Antarctica temperatures, relative to the present temperature, for the last 423 kiloyears (the period of the last four Major Ice Ages) have been calculated from measurements of deuterium concentration in ice cores (Petit, 1999).

There are many indications that the temperature variation with time in Antarctica is similar to that of the rest of the Earth. For example, the well-known Younger-Dryas dip at about 12 kiloyears ago (Alley, 2001) seen in Figure 1 is present in many other world-wide temperature data sets.

The North-Pole summer insolation is the appropriate solar entity to use in the fits since much more land mass exists in the vicinity of the North Pole than near the South Pole and summer is the time that determines whether ice melts in the North-Polar region (Wilson, 2000). Land mass can accumulate ice much more readily than oceans can. Insolation can be very accurately calculated from the effects of the other planets' orbits and the moon's orbit on the Earth's orbit and spin orientation (Berger, 1991).

The temperature data for the last 1000 years (Houghton, 2001) were excluded in the fits to the temperature data because of the effects on temperature of the recent rapid population rise and the attendant rapid rise in carbon-energy use (global warming). However, including those few data has little effect on the fits.

Fits Using only North-Pole Summer Insolation

Fits to the original and tuned Antarctica temperature data were done using the equation:

$$T(t) = C + F \cdot I(t) = \text{ temperature in degrees Celsius,}$$

$$\text{where } I(t) = \text{calculated summer North-Pole insolation at time } t \text{ in } \frac{Watts}{m^2}\ .$$

The factor F multiplies the summer North-Pole insolation, which provides correlation with the summer North-Pole insolation. And there is a constant C, which is related to internal Earth energy (e.g., radioactivity) heating the atmosphere.

The results of the fits are shown in Figure 2 and the fits' parameters are given in Table 1.

The fits are very poor, especially in the vicinity of the Major Interglacials; although the larger oscillatory features of the temperature data are accounted for in the fit. Some other transient term is needed in the equation to account for the large temperature rise into a Major Interglacial and fall after a Major Interglacial.

Most climate theories indicate that the major climate-change agent at the Major Interglacials is the Atlantic Thermohaline Current (ATC) (Wilson, 2000; Houghton, 2001). So, in all that follows the assumption will be made that the large transient Earth state changes around the two Major Interglacials are components of the ATC..

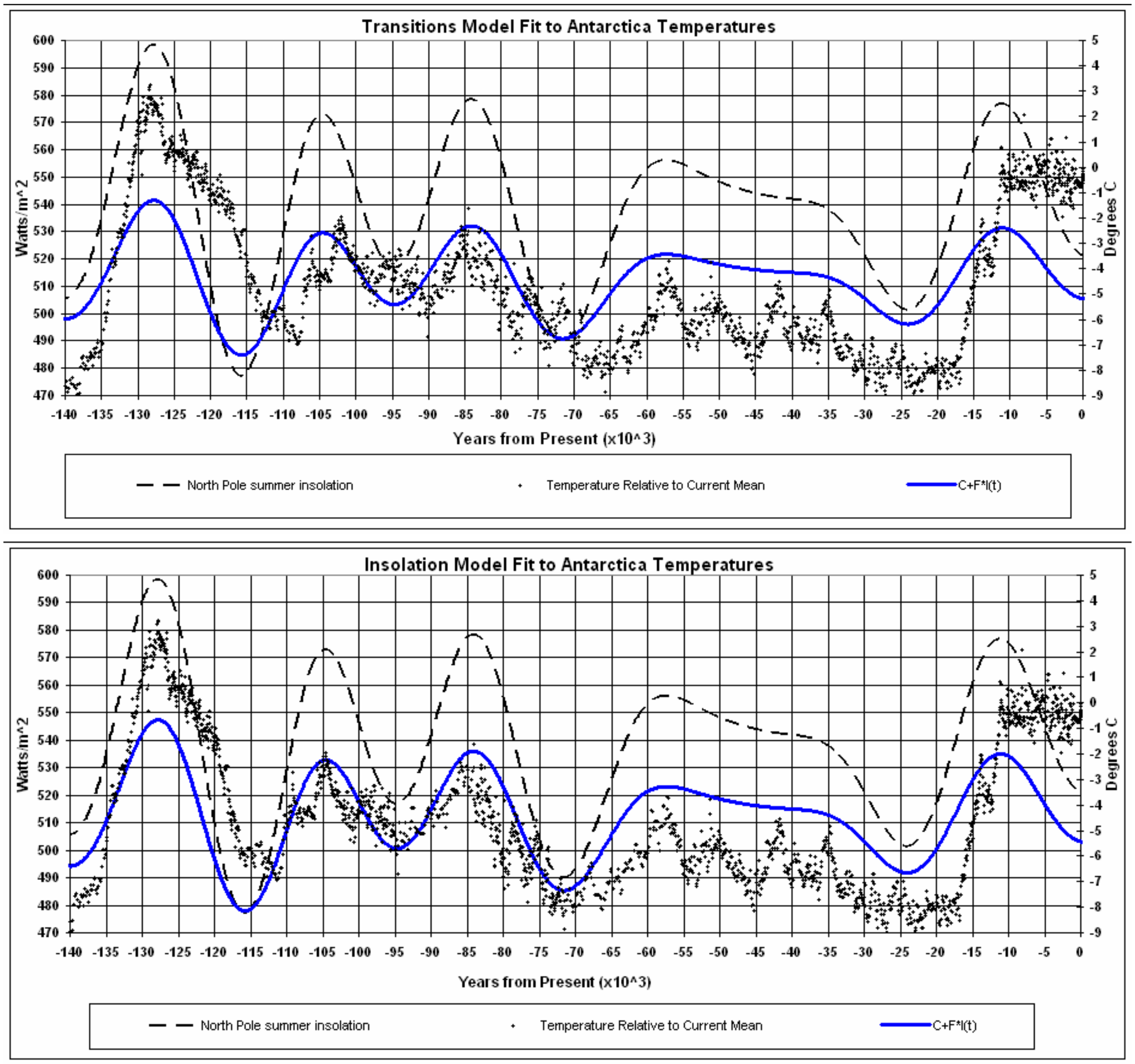

Figure 2. Fits of the $T(t) = C + F \cdot I(t)$ equation to the Antarctica temperature data (scale on right). The top graph is for the fit to the original data and the bottom graph is for the fit to the tuned data. The North-Pole summer insolation is also shown (dashed curve with scale on left).

Table 1. The parameters of the fits to the Antarctica temperature data using the equation $T(t) = C + F \cdot I(t)$. The top row in a table cell is for the original-data fit and the bottom row is for the tuned-data fit.

$T(t) = C + F \cdot I(t)$ Fit	
F [(degrees Celsius)/(Watts/m^2))	0.05035 0.06168
C (degrees Celsius)	-31.4278 -37.5758
No. of data	1936
No. of parameters	2
Chi Square:	12,586* 10,450

*No errors are given for the Antarctica temperature data; so no statistical significance can be assigned to the Chi Square.

Fits Using Insolation and One ATC Component for Each Major Interglacial

One can mathematically represent the turning on and off of a transient Earth state, such as a component of the Atlantic Thermohaline Current (ATC), by a double-hyperbolic-tangent function (DHTF) (also called a double-sigmoid function):

$$\frac{1}{2}\left[\tanh\left(\frac{t-c_1}{w_i}\right) - \tanh\left(\frac{t-c_2}{w_2}\right)\right],$$

where c_n = position (kyr), w_n = width (kyr).

The first hyperbolic tangent turns on the transient state and the second one turns the state off. The DHTF behaves as follows:

- Starts from an asymptote of 0 at $t = -\infty$.
- Then goes through a smooth transition region of width w_1 centered at c_1 to a value of 1.
- Maintains the value of 1 for a finite region determined by the values of the two positions.
- Then goes through a second smooth transition region of width w_2 centered at c_2.
- Then approaches an asymptote of 0 at $t = +\infty$.

Different widths for the turn on and the turn off allow for asymmetry. The DHTF could be called a rectangular wave with rounded edges, the amount of rounding of the edges determined by the two width parameters. However, if one or more of the widths is about the same size as or larger than the difference between the two positions $(c_{12} - c_1)$, a quite different behavior occurs. In extreme cases the function starts from asymptotic 0 and then goes to a positive or negative peak, then through 0 to a negative or positive peak and then asymptotically to 0 again.

The original and tuned Antarctica temperature data were fitted to the equation:

$$T\left(t\right)=C+F\cdot I\left(t\right)+\sum_{i=1}^{N}s_i\,\frac{1}{2}\left[\tanh\left(\frac{t-c_{1i}}{w_{1i}}\right)-\tanh\left(\frac{t-c_{2i}}{w_{2i}}\right)\right] \qquad \text{Eq. 1}$$

= temperature in degrees Celsius,

where $I\left(t\right)$ = calculated summer North-Pole insolation at time t in $\frac{Watts}{m^2}$;

DHTF parameters: $s_i =$ strength, c_{ni} = position, w_{ni} = width;

and N = number of DHTFs used in the fit.

The factor F multiplies the summer North-Pole insolation, which provides correlation with the insolation. And there is a constant C, which is related to internal Earth energy (e.g., radioactivity) heating the atmosphere. The DHTF sum term can provide as many transient states as needed to fit data. For this fit N=2 to allow for one DHTF for each of the two Major Interglacials. That is, one term in the sum is used to represent one transient Earth state turning on and then off in the vicinity of each of the two Major Interglacials. The parameters of the fits shown in Figure 3 are given in Table 2.

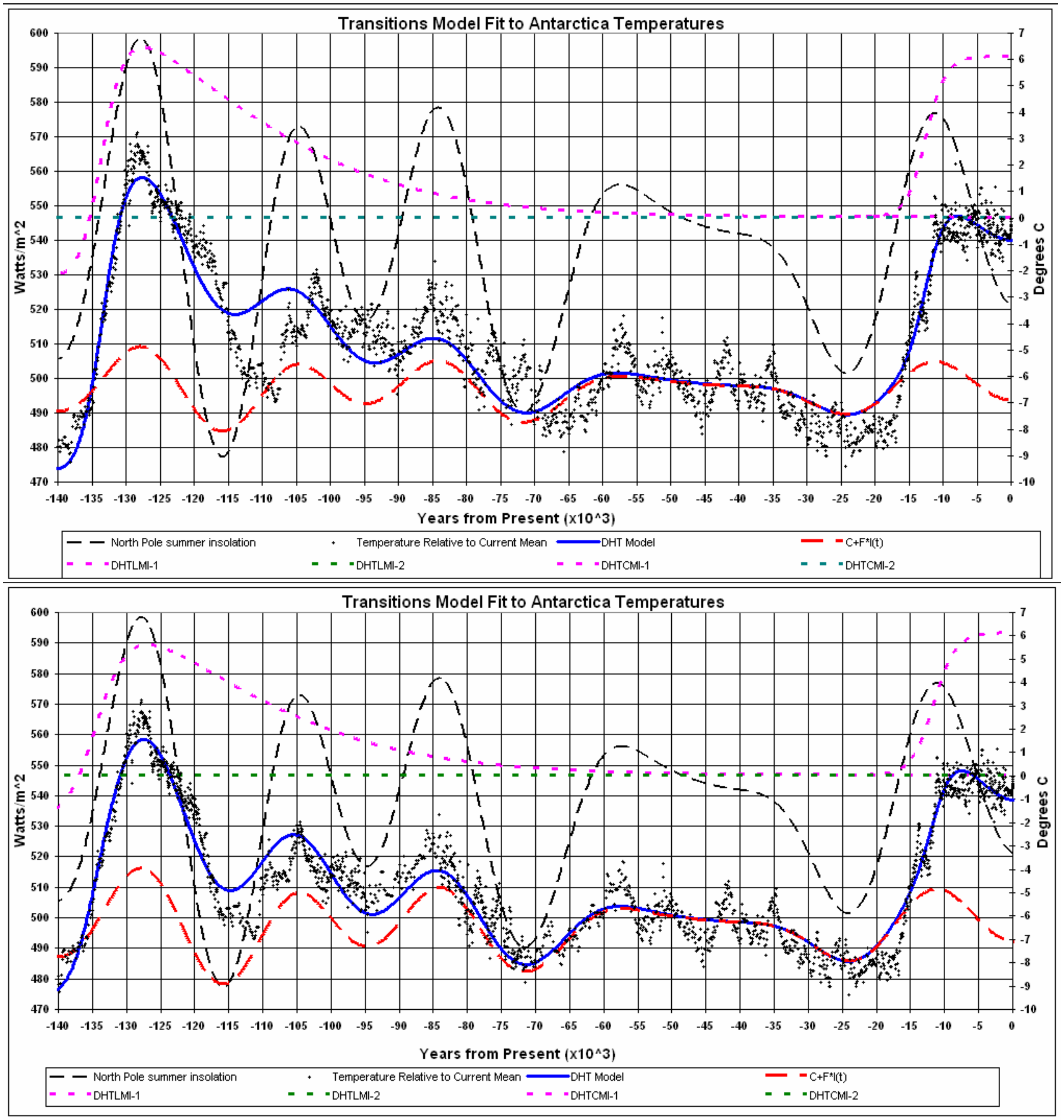

Figure 3. The top graph shows the best fit to the Antarctica temperature data (relative to present temperature; temperature scale on right) and also shows the North-Pole summer insolation (dashed black curve with scale on left). The bottom graph shows the fit to tuned Antarctica temperatures. The components of the fits are a constant term plus a term proportional to the North Pole summer insolation (dashed red curve) plus a single double hyperbolic tangent for each of the two Major Interglacials.

Table 2. The parameters of the fits using one double hyperbolic tangent for each of the two Major Interglacials at the edges of the Last Major Ice Age. (LMI=Last Major Interglacial; CMI=Present Major Interglacial) The top row in a table cell is for the original-data fit and the bottom row is for the tuned-data fit.

Major Ice Age	**s1 (degrees Celsius)**	**c11 (kiloyears)**	**w11 (kiloyears)**	**c12 (kiloyears)**	**w12 (kiloyears)**	**F [(degrees Celsius)/(Watts/m2)]**
LMI	11.109 10.119	-133.518 -134.379	3.4737 4.774	-120.854 -121.325	29.7210 29.503	0.02639 0.04081
CMI	6.0831 6.102	-12.382 -11.506	2.8727 3.213	? (>0) ? (>0)	? ?	**C (degrees Celsius)**
Chi Square :	2264* 1478	No. of Data:	1936	Variable Parameters:	10	-20.694 -28.411

* No errors are given for the Antarctica temperature data; so no statistical significance can be assigned to the Chi Square. The ? marks for the turn-off parameters for the Present Major Interglacial indicate that the values are indeterminate because of lack of future data.

The general large oscillatory features of the temperature data are present in the fits, especially for the tuned data. However, the fit is not nearly as good as for fits using two components of the ATC for each Major Interglacial that are described below. (Chi Square of 2264 compared to 1287 for the two-components fit to the original data and Chi Square of 1478 compared to 940 for the two-components fit to the tuned data.)

There is another better-fit solution that has a large reversal of the single ATC component in between the two Major Interglacials. This solution, although it has a lower Chi Square than the solution described above (1125 versus 1478 for tuned data and 1678 versus 2264 for the original data), is not consistent with a uni-directional (south to north surface current) ATC model. Because of its better agreement with the more accurate fits described below, the fit of Figure 3 and Table 2 is the preferred solution for this case of only one ATC for each Major Interglacial.

The blue solid curve in Figures 3 is the fit to the data. The black dashed curve is the calculated North Pole summer insolation (Berger, 1991) and is connected with the scale on the left. The red dashed lowest curve is the contribution to the Earth's temperature due to the North Pole summer insolation plus a negative constant in the fit to the temperature data. The dotted curve at the top is possibly a component of the Atlantic Thermohaline Current (ATC) being turned on and off. The sum of the red dashed curve and the dotted ATC curve yields the blue solid curve.

Combining the North-Pole summer insolation and one component of the ATC turning on and then off for each Major Interglacial does a fairly good job of fitting the main features of the temperature data, especially for the tuned data. (Below will be described a much better fit obtained by using two components of the ATC for each of the two Major Interglacials.)

The turn off of the ATC for the Present Major Interglacial cannot be determined very accurately because of the lack of data for the future; this is represented by the ? marks for the turn-off parameters in Table 2. Nevertheless, what can be determined of the ATC curve for the Present Major Interglacial is similar to the ATC curve for the Last Major Interglacial about 127 kiloyears ago.

Fits Using Insolation and Two ATC Components for Each Major Interglacial

In Figure 3 there is much fine structure in the two Major Interglacials that might be amenable to being fitted by one more ATC component. Here four terms in the sum of double-hyperbolic-tangents in Eq. 1 (N = 4) are used to fit the original and tuned Antarctica temperature data for the Last Major Ice Age, two terms for each of the two Major Interglacials. The parameters of the fits shown in Figures 4 are given in Table 3.

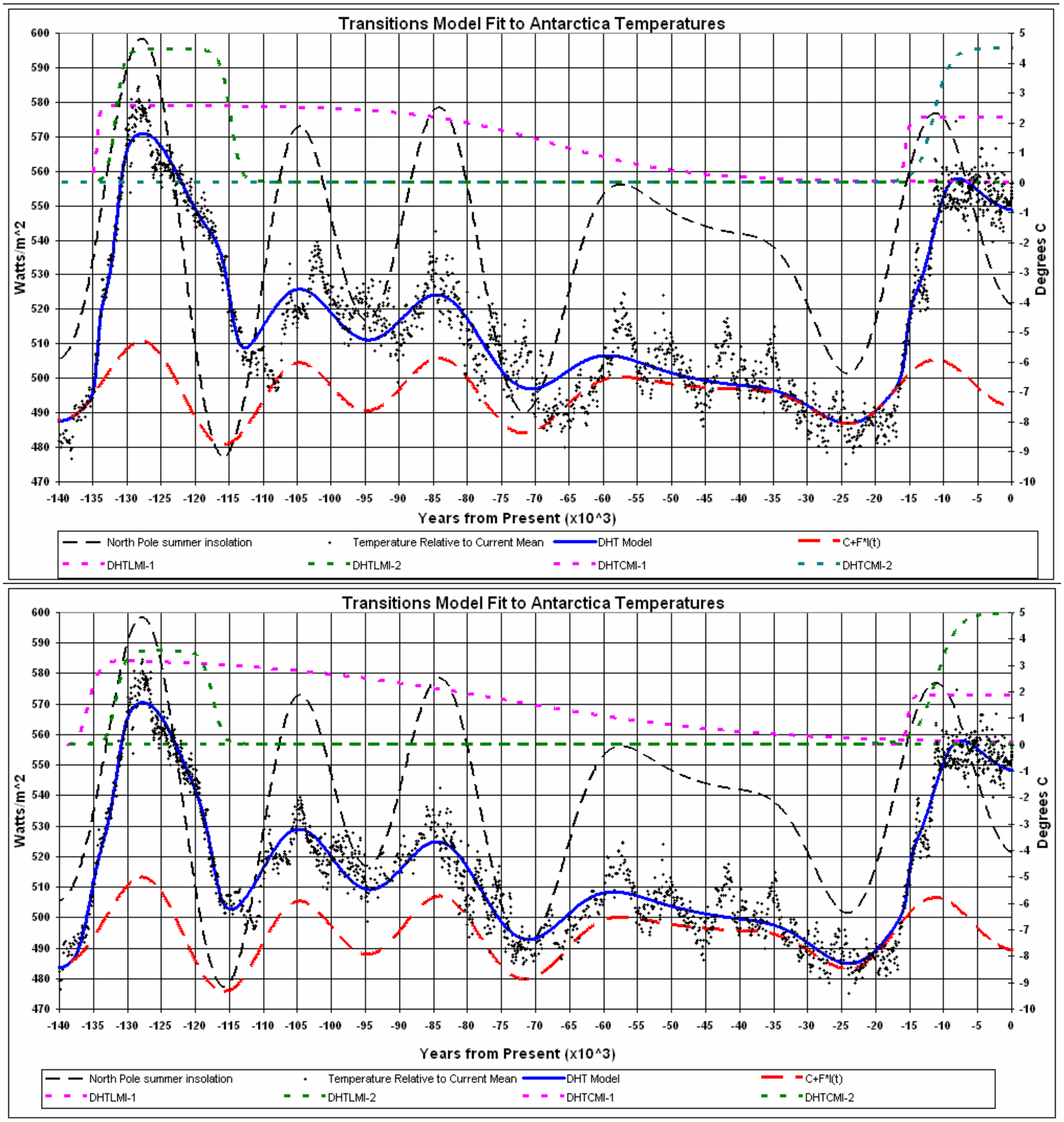

Figure 4. The top graph shows the fit to the Antarctica temperature data (relative to present temperature; temperature scale on right) and it also shows the calculated North-Pole summer insolation (dashed black curve with scale on left). The bottom graph shows the fit to tuned Antarctica temperatures. The components of the fit include a constant term plus a term proportional to the North Pole summer insolation (dashed red curve near the bottom). The four terms of double hyperbolic tangents represent the turning on and off of two components of the Atlantic Thermohaline Current in the vicinity of each of the two Major Interglacials (dashed curves near the top).

Table 3. The parameters of the fits using two double hyperbolic tangents for each of the two Major Interglacials at the edges of the Last Major Ice Age. (LMI=Last Major Interglacial; CMI=Present Major Interglacial) The top row in a table cell is for the original-data fit and the bottom row is for the tuned-data fit.

Major Ice Age	**s_1 (degrees Celsius)**	**c_{11} (kiloyears)**	**w_{11} (kiloyears)**	**c_{12} (kiloyears)**	**w_{12} (kiloyears)**	**F [(degrees Celsius)/(Watts/m^2)]**
LMI-1	2.556 3.311	-134.339 -135.597	0.496 1.607	-67.328 -74.215	20.423 37.837	0.02838 0.03557
LMI-2	4.435 3.522	-131.534 -131.518	1.209 1.305	-114.825 -117.444	1.488 1.512	**C (degrees Celsius)**
CMI-1	2.147 1.843	-15.487 -15.206	0.627 0.584	? (>0) ? (>0)	? ?	-22.31 -26.33
CMI-2	4.463 4.933	-11.333 -10.975	2.366 2.962	? (>0) ? (>0)	? ?	
Chi Square :	1287* 940	No. of Data:	1936	Variable Parameters:	18	

* No errors are given for the Antarctica temperature data; so no statistical significance can be assigned to the Chi Square. The ? marks for the turn-off parameters for the Present Major Interglacial indicate that the values are indeterminate because of lack of future data.

The North-Pole summer insolation and two components of the ATC for each of the two Major Interglacials do a rather good job of fitting the main features of the temperature data, especially for the tuned data. (Below will be shown a better fit that includes four short-term Earth events, three for each of the two Major Interglacials.)

There is another slightly-better-fit solution that has a small reversal of the single ATC around the last Glacial Maximum. This solution, although it has a slightly lower Chi Square than the solution of Table 3 (913 versus 940 for tuned data and 1181 versus 1287 for the original data), is slightly inconsistent with a uni-directional ATC model. Because of its better agreement with the more accurate fits described below, the fit of Figure 4 and Table 3 is the preferred solution for this case of two ATC components for each Major Interglacial.

The blue solid curve in Figure 4 is the fit to the data. The black dashed curve is the calculated North Pole summer insolation and is connected with the scale on the left. The red dashed lowest curve is the contribution to the Earth's temperature due to the North Pole summer insolation plus a negative constant in the fit to the temperature data. The dashed and dotted four curves at the top are possibly Atlantic Thermohaline Current (ATC) components being turned on and off. The sum of the red dashed curve and the four ATC curves yields the blue solid curve.

In these fits there are apparently two components of the ATC that turn on and off separately for each Major Interglacial; a long-term component and a short-term component. In the Last Major Interglacial the short-term ATC component lasted about 15 kiloyears. It is well known that there are at least two places where cold and salty ocean water sinks in the North Atlantic, one north-east of Iceland and one near Greenland (Colling, 2000), which is consistent with these fits to the Antarctica temperature data. It is possible that the some of the Earth states that are turned on and off in the vicinity of Major Interglacials are some other Earth events besides ATC. For example, they could be a switch in atmospheric circulation to the North-Polar region or to the 100-kiloyears period of the Earth orbit moving into and out of the invariant Solar system plane (essentially the orbit plane of Jupiter) (Muller, 1997).

The turn offs of the two ATC components for the Present Major Interglacial cannot be determined very accurately because of the lack of data for the future; this is represented by ? marks for the turn-off parameters in Table 3. Nevertheless, what can be determined of the two ATC curves for the Present Major Interglacial are somewhat similar to those for the Last Major Interglacial about 127 kiloyears ago.

Fits Using Insolation and Three ATC Components for Each Major Interglacial

In Figure 4 there is still some fine structure in the region of the two Major Interglacials that might be amenable to being fitted by yet another ATC component, making three for each of the two Major Interglacials. Here six terms in the sum of double-hyperbolic-tangents in Eq. 1 (N = 6) are used to fit the original and tuned Antarctica temperature data for the Last Major Ice Age, three terms for each of the two Major Interglacials. The parameters of the fits shown in Figures 5 are given in Table 4.

Actually, there are three ATC components for the Last Major Interglacial and two ATC components with a brief cutoff (the Younger Dryas event) of one of them, which cutoff is represented by a negative DHTF.

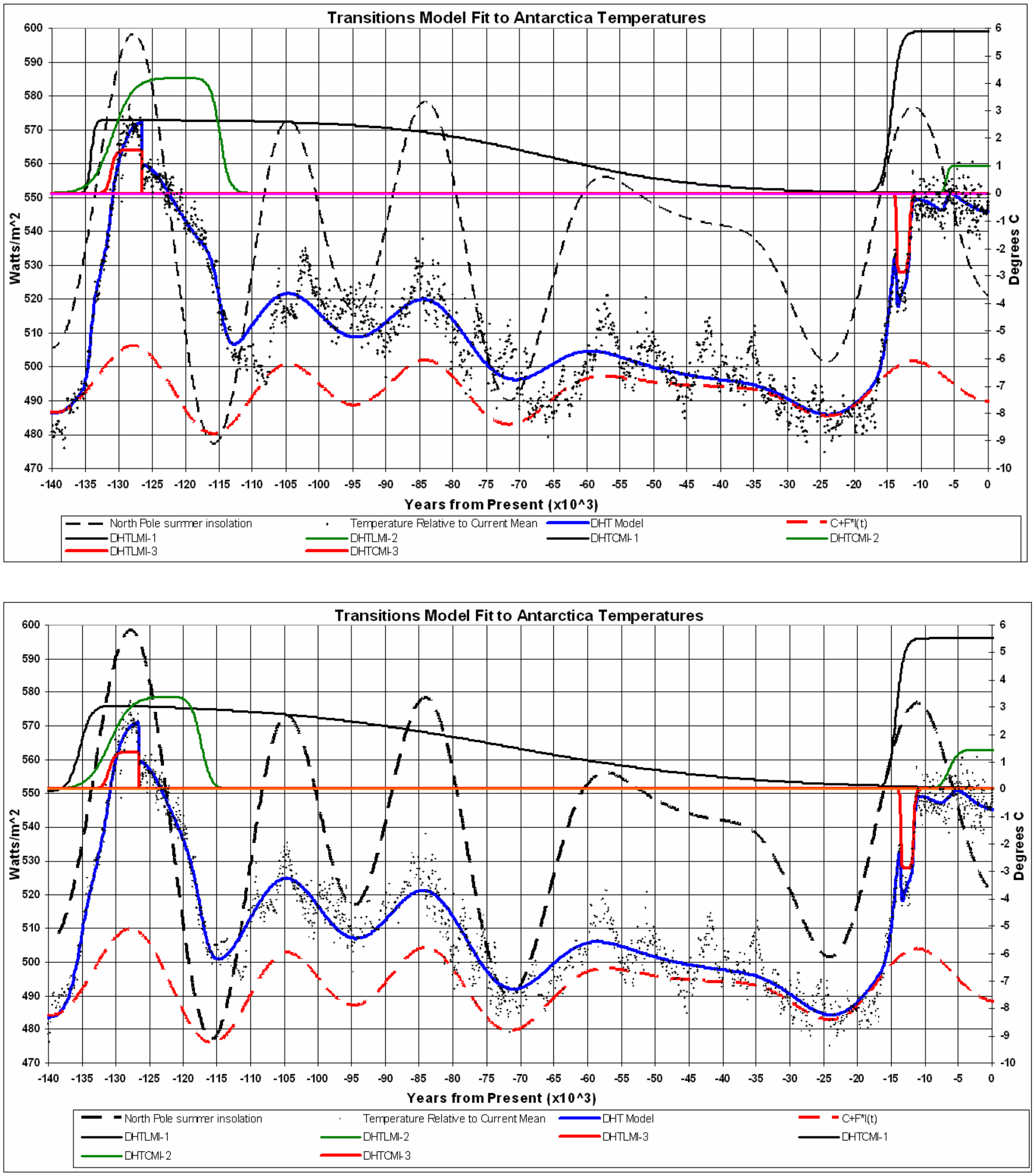

Figure 5. The top graph shows the fit to the Antarctica temperature data (relative to present temperature; temperature scale on right) and it also shows the calculated North-Pole summer insolation (dashed black curve with scale on left). The bottom graph shows the fit to tuned Antarctica temperatures. The components of the fit include a constant term plus a term proportional to the North Pole summer insolation (dashed red curve near the bottom). Six terms of double hyperbolic tangents represent the turning on and off of three components of the ATC in the vicinity of the Last Major Interglacial and two components of the ATC plus a brief cutoff of one of them (the Younger Dryas event) at about 12 kiloyears ago for the Present Major Interglacial (curves at the top).

Table 4. The parameters of the fits using three double hyperbolic tangents for each of the two Major Interglacials at the edges of the Last Major Ice Age. (LMI=Last Major Interglacial; CMI=Present Major Interglacial) An extra negative-temperature transient Earth state was necessary for the early part of the rise into the Present Major Interglacial; its parameters are not given here.) The top row in a table cell is for the original-data fit and the bottom row is for the tuned-data fit.

Major Ice Age	**s_1 (degrees Celsius)**	**c_{11} (kiloyears)**	**w_{11} (kiloyears)**	**c_{12} (kiloyears)**	**w_{12} (kiloyears)**	**F [(degrees Celsius)/(Watts/m^2)]**
LMI-1	2.687 3.186	-134.149 -135.354	0.576 1.673	-65.826 -72.610	23.433 35.918	0.02642 0.03430
LMI-2	4.218 3.404	-130.934 -130.931	3.049 3.112	-114.830 -117.382	1.411 1.473	**C (degrees Celsius)**
LMI-3	1.561 1.373	-131.134 -131.013	0.654 0.893	-126.553 -126.525	0.0001 0.048	-21.36 -25.64
CMI-1	5.899 5.508	-14.439 -14.254	1.279 1.146	? (>0) ? (>0)	? ?	
CMI-2	1.004 1.450	-6.242 -6.402	0.449 1.321	? (>0) ? (>0)	? ?	
CMI-3	-2.862 -2.884	-13.655 -13.542	0.148 0.142	-11.649 -11.953	0.297 0.291	(Note the negative **s_1** .)
Chi Square :	1185 822	No. of Data:	1936	Variable Parameters:	28	

* No errors are given for the Antarctica temperature data; so no statistical significance can be assigned to the Chi Square. The ? marks for the turn-off parameters for the Present Major Interglacial indicate that the values are indeterminate because of lack of future data.

The North-Pole summer insolation and three components of the ATC for each of the two Major Interglacials do an excellent job of fitting the main features of the temperature data in the Major Interglacials and a reasonable job of fitting the data in between them. (Below will be shown a much better fit that includes many other short-term Earth transient events, such as volcano eruptions, asteroid/comet impacts or transient fluctuations in the ATC.)

The blue solid curve in Figure 5 is the fit to the data. The black dashed curve is the calculated North Pole summer insolation and is connected with the scale on the left. The red dashed lowest curve is the contribution to the Earth's temperature due to the North Pole summer insolation plus a negative constant in the fit to the temperature data. The six curves at the top are possibly Atlantic Thermohaline Current (ATC) components being turned on and off. The sum of the red dashed curve and the six ATC curves yields the blue solid curve.

In these fits there are apparently three components to the ATC, or some other Earth state, that turned on and off for the Last Major Interglacial and two components of the ATC plus a brief cutoff at the Younger Dryas (at about 12 kiloyear ago) for the Present Major Interglacial. The short-term ATC component for the Last Major Interglacials lasted about 5 kiloyears. The medium-term component for the Last Major Interglacial lasted about 15 Kiloyears. It is well known that there are at least two places where cold and salty ocean water sinks in the North Atlantic, one north-east of Iceland and one near Greenland (Colling, 2000), which is consistent with two of the three events. Perhaps one of the short-term ATC components is in the South-Polar region or the North-Polar Pacific instead of the North-Polar region. Or perhaps one or more are some other Earth events; e.g., a switch in atmospheric circulation to the North-Polar region or the 100-kiloyears period of the Earth orbit moving into and out of the invariant Solar system plane (essentially the orbit plane of Jupiter) (Muller, 1997).

Figure 6 contains a closer look at the two Major Interglacials for the fit of Table 4 to the tuned data.

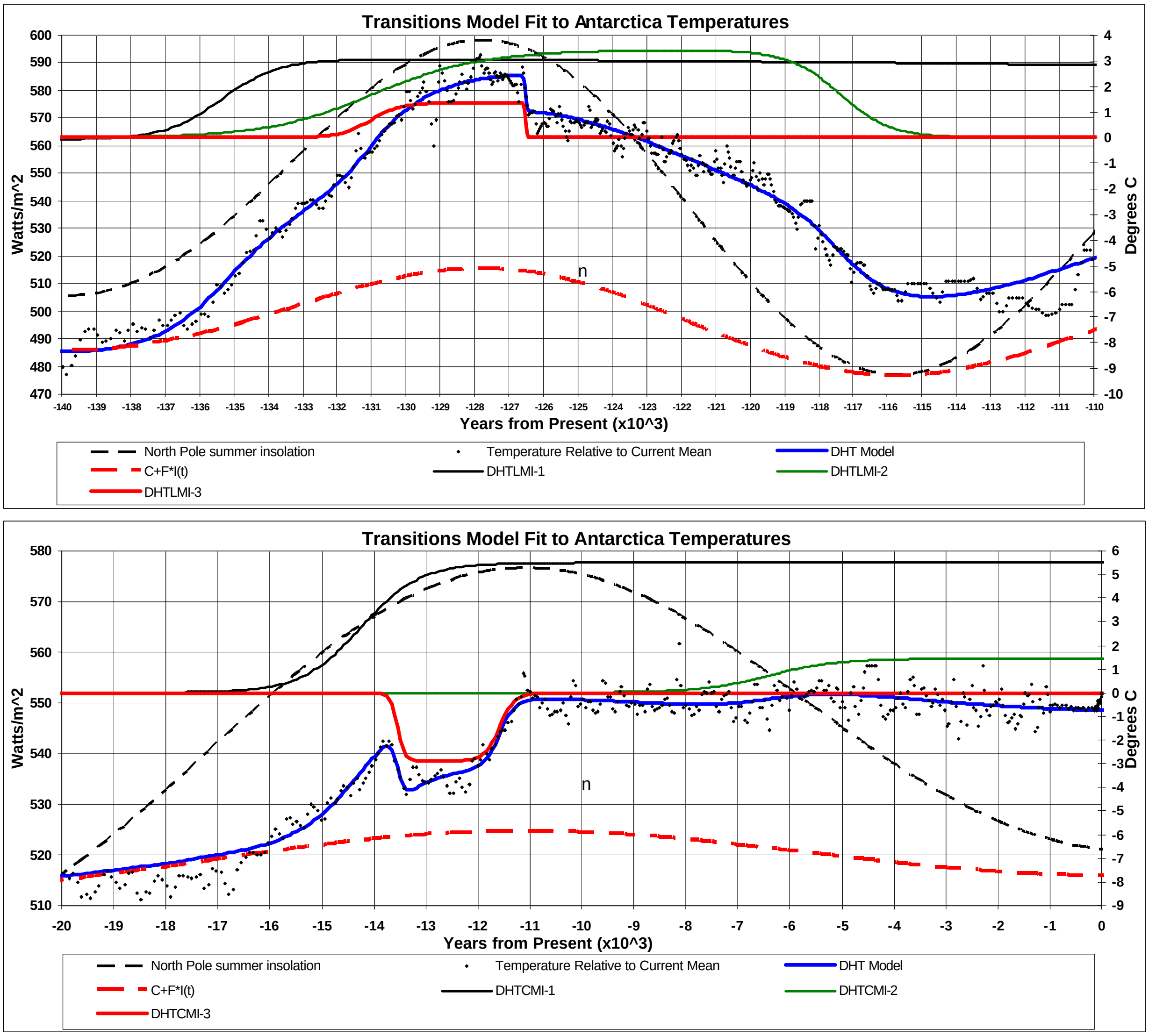

Figure 6. The three-DHTF fit to the tuned data in the regions of the Last Major Interglacial and the Present Major Interglacial.

The Younger Dryas event at 14-11 kiloyears ago is well represented by a cutoff (negative) DHTF. The temperature minimum at 8-7 kiloyears ago is due to the combined effects of the falling insolation and the turning on of an Earth state. The hump at 132-127 kiloyears ago is due to the turning on and then off of an Earth state adding to the effect of falling insolation. The rapid temperature fall at 116-113 kiloyears ago is due to the turning off of an Earth state. The North-Pole summer insolation is the main forcer of the Antarctica temperature at the Last and Penultimate Glacial Maxima; that is, none of the Earth states used in this fit were in effect then.

Fits Using Many Earth States

In Figure 5 there are obviously some transient semi-periodic Earth states at the lower maxima of the North-Pole summer insolation away from the two Major Interglacials. One can fit the Antarctica temperature data much more accurately by including the turning on and off of twenty Earth processes represented by DTHFs, as shown in Figure 7. There are, of course, many different ways to achieve such a fit. Only one of the possible fits is described here, but different ones for the original data and the tuned data to show that there are different ones possible. However, the six largest DTHFs do not differ much among the possible fits. The fit parameters for the six largest DTHFs, three for each Major Interglacial, are given in Table 5.

Note that, particularly for the tuned-data fit, another ATC component appears possible beginning a few kiloyears before the Younger Dryas event and turning off over the next 15 kiloyears.

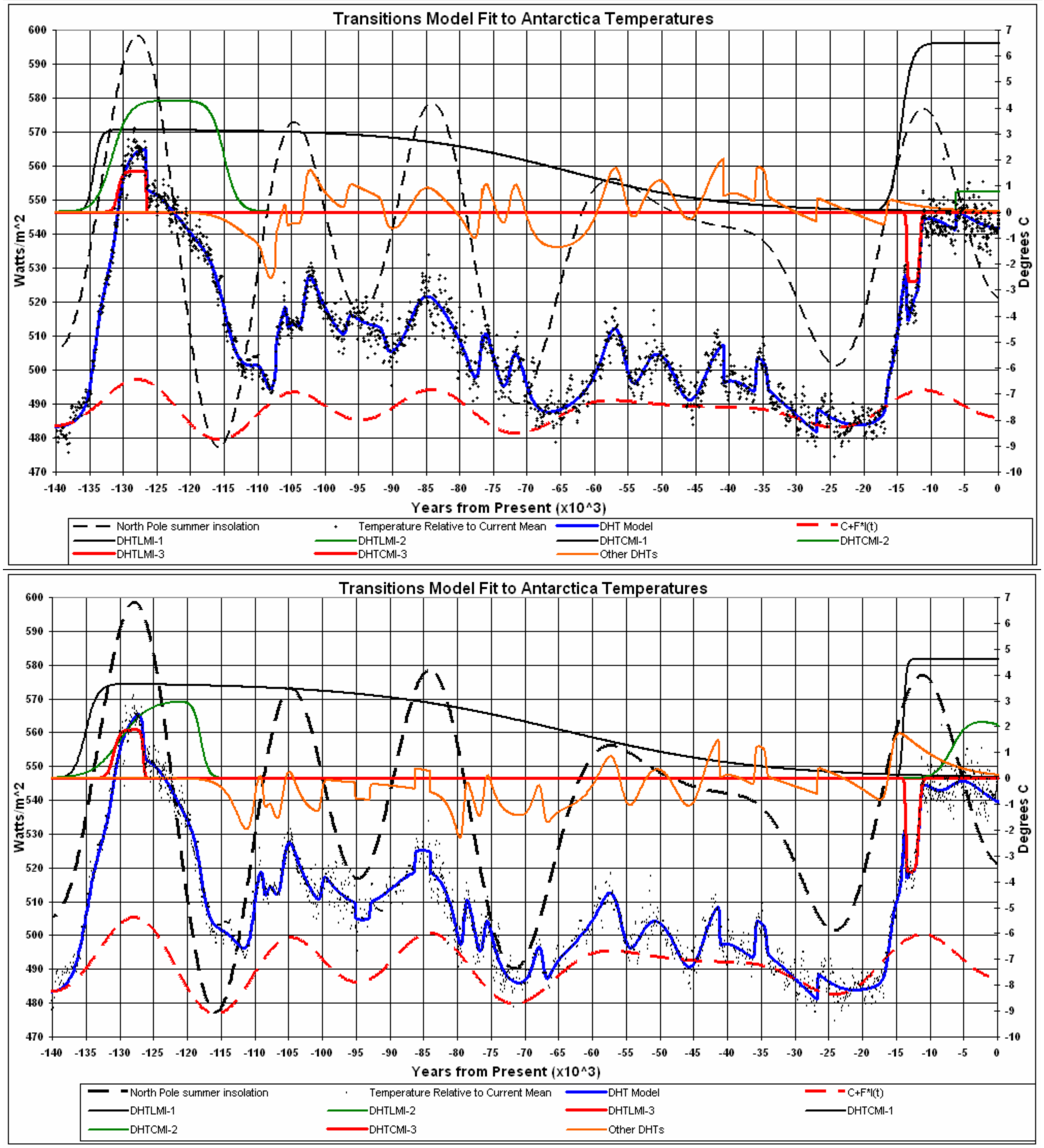

Figure 7. The top graph shows the fit to the Antarctica temperature data (relative to present temperature; temperature scale on right) and also shows the calculated North-Pole summer insolation (dashed-black curve with scale on left). The bottom graph shows the fit to tuned Antarctica temperatures. Six terms of double hyperbolic tangents represent the turning on and off of three components of the Atlantic Thermohaline Current in the vicinity of the Last Major Interglacial and two components of the ATC plus a brief cutoff of one of them (the Younger Dryas event) at about 12 kiloyears ago for the Present Major Interglacial (curves at the top). Fourteen other terms of double-hyperbolic-tangents represent the turning on and off of other Earth states (e.g., volcano eruptions, asteroid/comet impacts or other

transient components of the ATC); their sum is the solid rapidly-varying curve in the middle of the graphs.

Table 5. The parameters of the fits using three double hyperbolic tangents for each of the two Major Interglacials at the edges of the Last Major Ice Age and fourteen other double hyperbolic tangents for short-term Earth transient states during the Last Major Ice Age. (LMI=Last Major Interglacial; CMI=Present Major Interglacial) The top row in a table cell is for the original-data fit and the bottom row is for the tuned-data fit. The parameters for the other sixteen transient states can be obtained from the author.

Major Ice Age	**s_1 (degrees Celsius)**	**c_{11} (kiloyears)**	**w_{11} (kiloyears)**	**c_{12} (kiloyears)**	**w_{12} (kiloyears)**	**F [(degrees Celsius)/(Watts/m^2)]**
LMI-1	3.166 3.692	-134.343 -135.032	1.013 1.727	-64.278 -64.393	23.581 29.998	0.0308 0.0405
LMI-2	4.282 3.006	-131.607 -129.920	2.480 4.047	-114.934 -117.936	2.002 1.109	**C (degrees Celsius)**
LMI-3	1.566 1.885	-130.804 -130.935	0.659 0.887	-126.553 -126.554	0.0001 0.271	-17.92 -23.80
CMI-1	6.493 4.662	-14.419 -13.878	1.592 0.450	? (>0) ? (>0)	? ?	
CMI-2	0.791 2.409	-6.325 -6.766	0.014 2.346	? (>0) 6.827	? 7.407	
CMI-3	-2.678 -3.637	-13.636 -13.602	0.140 0.146	-11.634 -11.642	0.275 0.377	
Chi Square :	409* 389	No. of Data:	1936	Variable Parameters:	98 100	

* No errors are given for the Antarctica temperature data; so no statistical significance can be assigned to the Chi Square. The ? marks for the turn-off parameters for the Present Major Interglacial indicate that the values are indeterminate because of lack of future data.

It is interesting to note in Figure 7 that, for the fit to the tuned data, most of the fourteen small transient Earth states contribute mostly negatively to the temperature. That is consistent with those negative events being volcano eruptions, asteroid/comet impacts or transient turn offs of the ATC.

Some recognizable Earth transient events in Figure 6 are:

- The Younger-Dryas temperature dip at about 12 kiloyears ago, which is thought to be an ATC component turning off for a few kiloyears (Alley, 2001).

- The eruption of volcano Mt. Taupo in New Zealand about 26 kiloyears ago, one of the largest known volcano eruptions (Winchester, 2003).

- A huge meteor struck Arizona about 50 kiloyears ago. Perhaps it was one of many large meteors that struck all around the world at that time period or a fragment of a much larger asteroid/comet that also struck the Earth.

- The eruption of volcano Mt. Toba in Sumatra about 75 kiloyears ago, one of the largest known volcano eruptions (Winchester, 2003).

- An apparent rapid turn off of an ATC component, or some other Earth state, at about 127 kiloyears ago during the very high temperature Last Major Interglacial. This rapid turn off supports the theory that global warming could cause a similar rapid turn off in the near future. AT that time Antarctica temperature was almost $3C^\circ$ higher than now. The sudden drop was almost $2C^\circ$ in about a century.

Perhaps some of the other transient events shown in Figure 7 can be correlated with other known Earth events, such as volcano eruptions and asteroid/comet impacts. Some of the transient "events" for the tuned-data fit may be artifacts of incorrect choices for the "maxima" and "minima" of the temperature data to be tuned to the maxima and minima of the North-Pole summer insolation.

Residual temperatures obtained by subtracting the calculated temperatures from the measured temperatures are given in Figure 8 for tuned Antarctica temperatures. This graph gives a visual measure of the goodness of the fit.

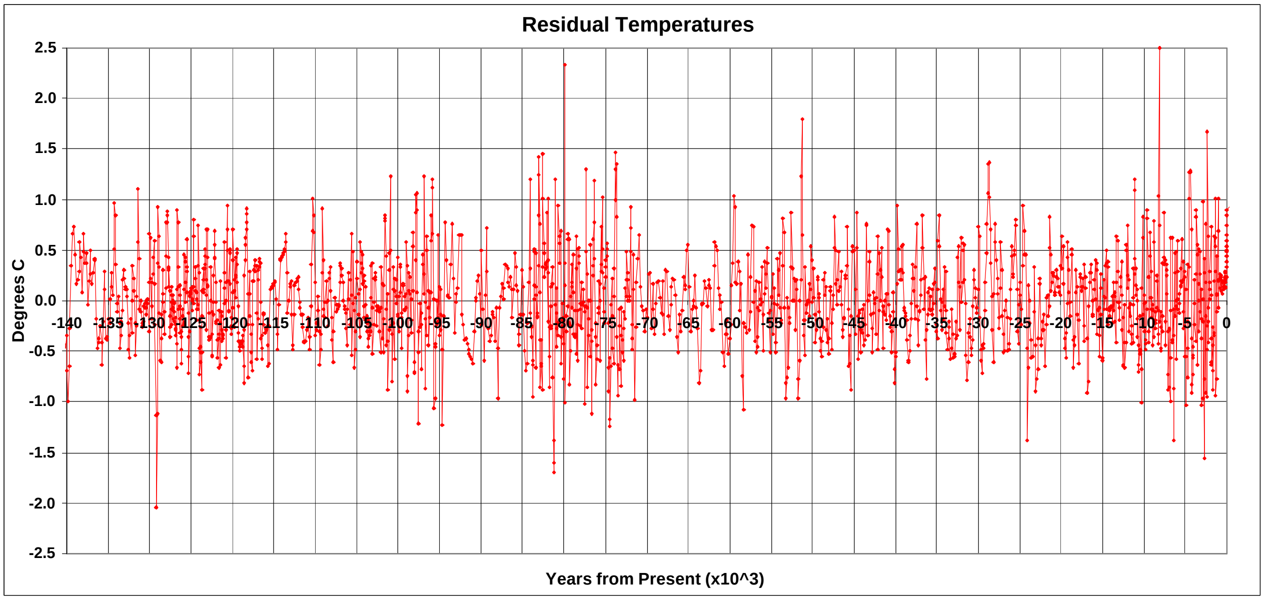

Figure 8. Residual temperatures obtained by subtracting the calculated temperatures from the tuned Antarctica temperatures.

What causes the Atlantic Thermohaline Current to turn on and off?

Start at the extreme low-temperature minimum of the Penultimate Major Ice Age in Figure 7 (the Penultimate Glacial Maximum) about 140 kiloyears ago. All components of the Atlantic Thermohaline Current (ATC) were off. Huge amounts of the present ocean water were frozen into ice, mostly on land around the North-Polar region, so ocean levels were very low (about 120 meters below the current level (Houghton, 2001)). The remaining Atlantic Ocean had a high surface salinity because of the smaller volume and absence of the ATC to carry the salt to the ocean bottom. The North-Atlantic water was very cold. Cold and salty water is much heavier than warm and less-salty water. At some point the combination of cold and high-salinity surface water caused the water near the North Pole to sink (probably northeast of Iceland), which is the switch that turns on the long-term ATC component. The cold salty water then travels along the bottom of the Atlantic to the South Atlantic and on into the Central Pacific (with possible side branches), where it rises and travels back to the North Atlantic to complete the circuit. A few kiloyears later similar conditions at another location in the North Atlantic (probably near Greenland) caused a shorter-term ATC component to turn on more slowly. About 5 kiloyears later an even shorter-term ATC component turned on for about 5 kiloyears duration, causing the hump in the Last Major Interglacial. (Colling, 2002; Houghton, 2001; Wilson, 2000)

The ATC brings warm surface water from the South Atlantic to the North Atlantic, making western Europe and eastern North America warm. This warm water causes much northern ice to melt, thus decreasing the amount of solar energy that is reflected back into space by the ice. Thus, the Earth's atmospheric temperature begins to rise. The cycling summer insolation at the North Pole enhances the temperature rise at just the right time, so a rapid rise in temperature occurs from the positive combination of increasing insolation and the ATC components causing more of the insolation to be absorbed by the Earth.

Note that the melting of huge amounts of ice in an atmospheric temperature rise into a Major Interglacial absorbs a large amount of energy, so the extra energy supplied by the action of ATC components and the insolation must be very large to cause the atmospheric temperature to rise so much anyway.

Some positive feedback mechanisms that contribute to the rapid rise in temperature are:

- As the northern ice melts more solar energy is absorbed by the Earth instead of being reflected by the ice back into space.

- As the temperature rises, more CO_2 and CH_4 and other gases are released from the Earth, especially from the oceans, into the upper atmosphere, where they serve as a greenhouse layer to prevent energy from escaping from the Earth.

- As the temperature rises more evaporation occurs, putting water vapor into the atmosphere, which contributes to the greenhouse effect. (There is a delicate energy balance among the amount of energy required to vaporize water, the amount of greenhouse effect of water vapor and the amount of solar energy reflected by clouds.)

Now for the second part of the question: **What causes the ocean current to turn off?:**

The ATC brings warm surface water from the lower Atlantic to the North Atlantic and ice around the North Pole begins to melt, providing fresh water to the North Atlantic. The ocean level rises. Also, the atmospheric-transport system moves water vapor to the North Atlantic, whose precipitation supplies more fresh water.

At some point the warmness and less salinity of the surface water cause the sinking near the North Pole to reduce and finally to stop and thus reduce and finally stop a component of the ATC. This happens relatively quickly for the two short-term components of the ATC and much more slowly for the long-term component (gradually over the entire course of the Major Ice Age). North Pole summer insolation also trends downward into a Major Ice Age on average with oscillations. The combination of the turning off of the short-term ATC component and the average decline of insolation takes the Earth into the next Major Ice Age, which is then gradually enhanced by the gradual turn off of the long-term ATC component.

Note that the freezing of huge amounts of ice as the atmospheric temperature dips into a Major Ice Age releases a large amount of energy, so the energy no longer available from the action of the ATC components and the insolation must be very large to cause the atmospheric temperature to fall so much anyway.

As the temperature falls due to the turning off of ATC components, the same positive feedback mechanisms described above apply:

- As northern ice increases more solar energy is reflected into space.

- As the temperature falls, less CO_2 and CH_4 and other gases are released from the Earth, so that their greenhouse effect is decreased.

- As the temperature falls, less evaporation occurs, putting less water vapor into the atmosphere, which reduces its greenhouse effect.

Concerns about Global Warming

There was a rapid rise in temperature in recent years (global warming), after $\pm 2^{\circ}C$ fluctuations during the last 10 kiloyears (Pettit, 1999; Houghton, 2001). (See the right side of Figure 1.) The temperature data for the last 200 years (Houghton, 2001) are shown in Figure 7, which also shows the population rise. Figure 9 shows convincingly that global warming is occurring, and that a major factor in its occurrence is population growth. The steep temperature rise in the last 30 years is due to increased per capita use of carbon fuels as well as population increase.

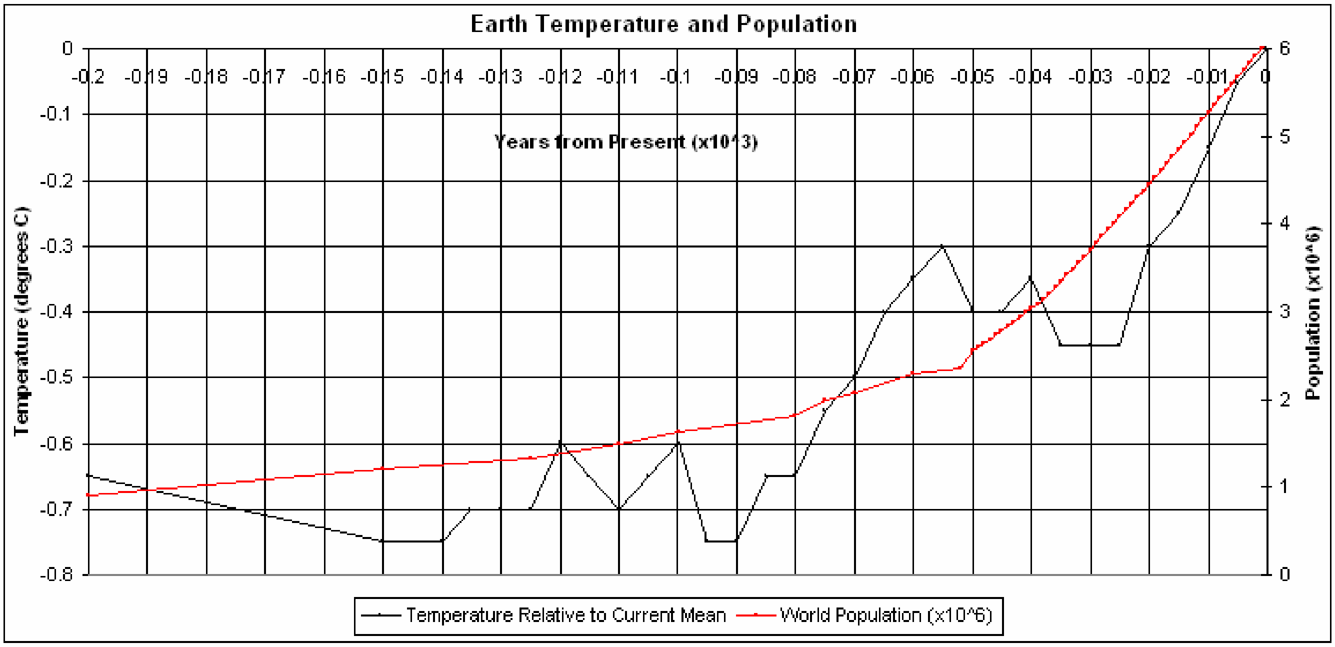

Figure 9. This graph shows how the Earth's Human population and temperature have risen together in the last 200 years (Houghton, 2001).

The big worry about global warming, besides the drastic short-term (of about 1000 years, the time it will take humans to exhaust extant carbon fuels) effects it will have on heating the environment, is that it may cause one or more components of the ATC to turn off much sooner than it/they would have if Humans were not causing global warming. If that happened the Earth would plunge into the Next Major Ice Age much sooner than it would without the help of Humans. As an example of how fast such a rapid temperature drop can happen, notice the temperature drops at about 127 kiloyears ago and at about 12 kiloyears ago in Figure 1.

Thus, there is the non-intuitive possibility that global warming may cause the Next Major Ice Age to start much sooner than it would have without global warming (Wilson, 2000; Houghton, 2001). (That is the plot of the movie *The Day After Tomorrow*, although the time scale in the movie was weeks and months instead of the more likely decades, centuries or millennia.

Conclusion

It has been shown that the main features of the Antarctica temperature data for the last 140 kiloyears (Last Major Ice Age with the two Major Interglacials on its edges) can be fitted quite well with North-Pole summer insolation and two components of the Atlantic Thermohaline Current (ATC) represented by the double-hyperbolic-tangent function, and that an excellent fit can be obtained by assuming many other transient Earth states (e.g., volcano eruptions, asteroid/comet impacts or ATC fluctuations) represented by the double-hyperbolic-tangent function.

The best fit using twenty double-hyperbolic-tangent functions contains three major components of the ATC for the Last Major Interglacials and at least two for the Present Major Interglacial.

The four largest transient Earth states for both the original and the tuned Antarctica temperature data fits of Figure 7 are shown in Figure 10. One could consider the two curves for the original and tuned fits for a given ATC component as defining a range for that ATC component. The curves for the tuned-data fit are probably the most accurate, except for existence of a possible time lag of a few thousand years between the ATC components and the temperatures.

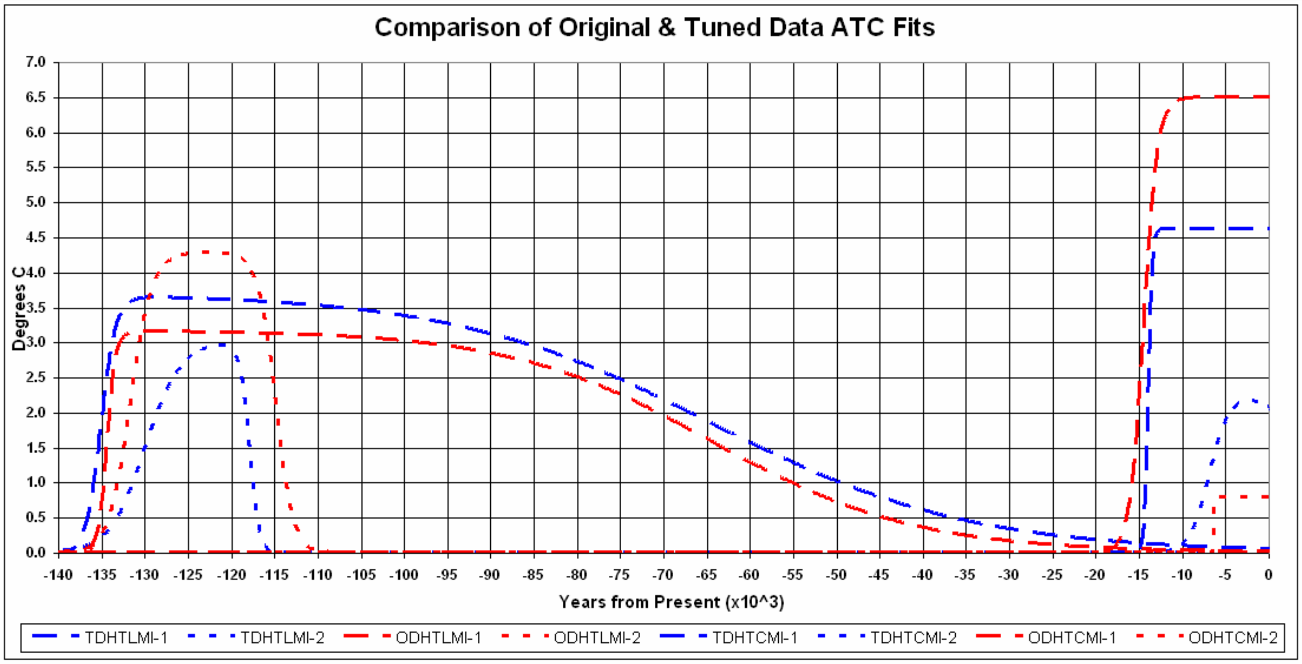

Figure 10. Comparison of the four largest transient Earth (possibly ATC) states for the fits to the original Antarctica temperature data (solid curves) and the tuned data (dashed curves) of Figure 7. (O = original data, T = tuned data, DHT = double hyperbolic tangent, LMI = Last Major Interglacial, CMI = Present Major Interglacial)

Similarly good fits have been obtained to the Penultimate, 2nd Penultimate and 3rd Penultimate Major Ice Ages. (Roper, 2004) The Antarctica atmospheric temperature data (Pettit, 1999) for these earlier Major Ice Ages are shown in Figure 11 along with the calculated North-Pole summer insolation (Berger, 1991).

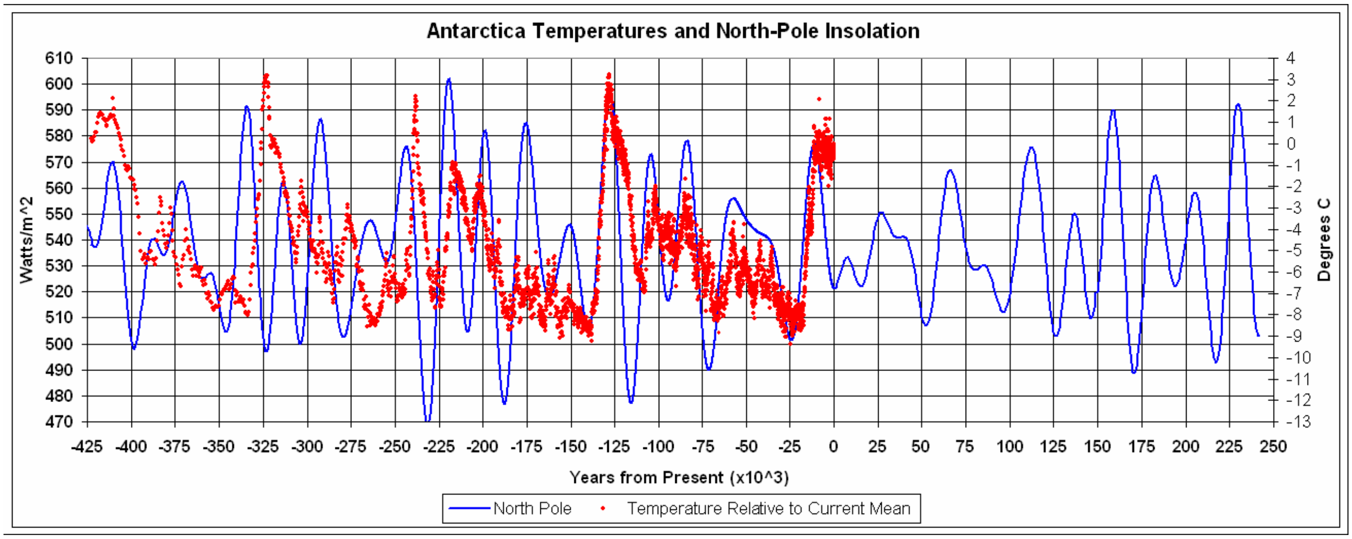

Figure 11. Antarctica atmospheric temperature data (relative to present temperature; scale on right) (Pettit, 1999) for the last four Major Ice Ages and North-Pole summer insolation (scale on left) (Berger, 1991) for the last four and the next two Major Ice Ages.

Fits also were made to the last four Major Ice Ages with common fit parameters for all four, assuming that this gives a reasonably good representation of any Major Ice Age. The DHTF parameters are assumed to be the same for all Major Ice Ages, except that there is a variable time-shift parameter for each Major Ice Age. Then the fit parameters were used to “predict” the next two Major Ice Ages, as shown in Figure 12 for four different fits to the tuned data. Note that the measured temperatures are higher than the predicted temperatures for recent years. This gives one more reason to suspect that global warming may quickly (decades or longer) plunge the Earth into the Next Major Ice Age.

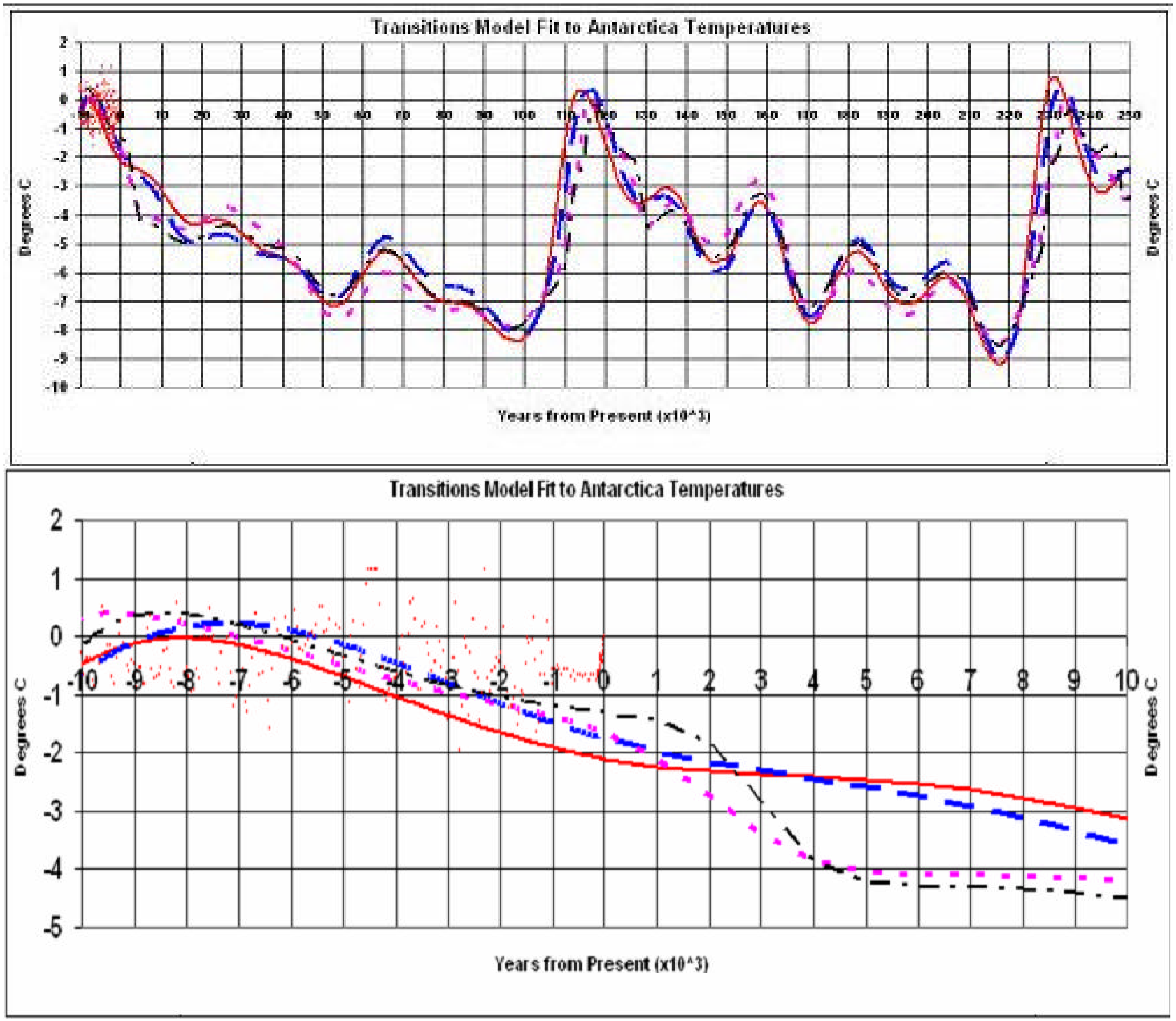

Figure 12. Predictions for the next two Major Ice Ages as projections from four common fits to the last four Major Ice Ages. The bottom graph shows the past 10 kiloyears Antarctica temperature data and "prediction" for the next 10 kiloyears. The solid red and dashed blue curves are for fits using only one DHTF for each Major Interglacial and the dotted purple and dash-dot black curves are for fits using two DHTFs for each Major Interglacial.

Note in Figures 10 and 11 that the insolation variations for the Next Major Ice Age, and thus the "predicted" temperature variations, are small compared to data for the Last Major Ice Age and the "predictions" for the Second Next Major Ice Age. Since wide temperature variations during a Major Ice Age are thought to be agents of biological evolutionary change, evolutionary change may be less during the Next Major Ice Age than it was during the Last Major Ice Age and than it will be during the Second Next Major Ice Age. (Macdougall, 1994 ; Calvin, 2002)

Some interesting anthropological observations about the Last Major Ice Age are (Wells, 2002; Klein, 2002; Wilson, 2000):

- Humans probably evolved as a separate branch of the Hominid family during the rapid temperature rise into the Last Major Interglacial (about 127 kiloyears ago) or during the rapid temperature fall out of the Last Major Interglacial.

- The number of Humans was greatly reduced about 70 kiloyears ago at a very low temperature time. Neanderthals occupied Europe from about 70-25 kiloyears ago. Some estimates are that only about 10,000 Humans survived that time of the Last Major Ice Age (Macdougall, 1994).

- About 60-50 kiloyears ago Humans migrated out of western Africa into Asia and then quickly into all parts of the Earth, finally reaching Europe about 35-30 kiloyears ago by a "scenic route" through north-central Asia. Africa was very dry because so much water was locked into Arctic ice.

- At about the Last Glacial Maximum (about 20 kiloyears ago) Humans migrated across the Bering Land Bridge into North America from northeast Asia. Surviving European Humans were forced by the low temperatures and glaciers into more temperate small refugia areas on the southern fringes of Europe, surely greatly reduced in number. There must have been similar Asian refugia.

- During the rapid rise into the Present Major Interglacial Humans moved back into central and western Europe proper from the refugia, probably in the largest numbers after 12 kiloyears ago.

- About 8 kiloyears ago more Humans migrated into Europe from the Middle East, bringing agriculture practices with them.

Surely, prior to the Next Glacial Maximum about 100 kiloyears in the future surviving Humans will migrate to European, Asian and also American refugia. (See Figure 12.) Surviving North Americans will probably migrate to Central America. A glance at Figure 12 should convince that an exodus to refugia could happen as early as 50, or even 20, kiloyears in the future.

With the Human development of weapons of mass and indiscriminant destruction and demonstrated willingness to use them when challenged by other Humans, it is likely that Humans will contribute to their own die offs as they struggle for survival as the Next Major Ice Age begins to take its Human toll. It is not clear that Humans will survive all of the three predicted coldest periods of the Next Major Ice Age. (See Figure 12.) The first and mildest, at about 20 kiloyears in the future, is probably the most dangerous, as there may be still enough of the destructive technology around then.

The qualitative science seems quite good concerning the possible turning off of one or more components of the Atlantic Thermohaline Current by global warming and the subsequent plunge into the next Major Ice Age; although the quantitative science is far from maturity. No accurate quantitative prediction can be made yet about the amount and timing of temperature fall that will occur given a specific amount of global warming. Figure 12 may be the best that one can do in "predicting" the onset of the Next Major Ice Age at the present time, with the possibility that global warming could cause a more rapid drop in temperature than the curves of Figure 12 show.

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