

# GLOBAL WARMING

Reno, NV

June 25, 2009

# GLOBAL WARMING

- ✖ The Pleistocene epoch, over the past few million years when ice sheets cycled back and forth, was an unusual time in the Earth's history
- ✖ Glacial periods alternated with times of warmer climate, each cycle lasting many tens of thousands of years
- ✖ Much farther back in time there had been a few other relatively brief epochs of glaciation, revealed by very ancient ice-scraped rocks and gravel deposits
- ✖ The most common condition was long temperate epochs, like the balmy times of the dinosaurs. Much rarer were glacial epochs like our own, lasting a few millions of years, in which periods of glaciation alternated with warmer "interglacial" periods like the present.

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- ✖ Given that something had put the Earth into a state conducive to glaciation, what made the ice sheets grow and then retreat, over and over again?
- ✖ A few scientists in Sweden and elsewhere developed the study of ancient pollens ("palynology")
- ✖ One could dig up soil from lake beds or peat deposits, dissolve away in acids everything but the sturdy pollen, and after some hours at a microscope know what kinds of flowers, grasses or trees had lived in the neighborhood at the time the layer of lake-bed or peat was formed



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- ✖ Studying ancient pollens, scientists found again a sequence of colder and warmer spells, glacial and interglacial periods. The most recent ice age had ended ten thousand years or so ago. Other ingenious studies showed that a particularly warm period had followed.
- ✖ A 1933 study of ancient beach deposits showed that as the continental ice sheets formed and then melted, they had locked up and then released so much water that the oceans had dropped and risen many tens of meters
- ✖ It was believed a pattern, in which the warm interglacial periods were long was observed. Our own time seemed near to the preceding ice age, so it was concluded that the Earth ought to get warmer for a while before it cooled again

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- ✗ In the mid 19th century, calculations of how the gravitational pulls of the Sun, Moon, and planets subtly affect the Earth's motion and orientation were published. The inclination of the Earth's axis and the shape of its orbit around the Sun oscillate gently in cycles lasting tens of thousands or hundreds of thousands of years. During some periods the Northern Hemisphere would get slightly less sunlight during the winter than it would get during other centuries. Snow would accumulate. It was argued that this would change the pattern of trade winds, leading to the deflection of warming currents like the Gulf Stream, and finally a self-sustaining ice age

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- ✖ The timing of such changes could be calculated exactly using classical mechanics. It was believed that the timing of the astronomical cycles, tens to hundreds of thousands of years long, roughly matched the timing of ice ages
- ✖ Serbian engineer Milutin Milankovitch not only improved the tedious calculations of the varying distances and angles of the Sun's radiation, but also applied an important new idea. Suppose there was a particular season when the sunlight falling in a given hemisphere was so weak, even in the summer, that the snow that fell in high latitudes in winter did not all melt away?



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- ✘ It would build up, year after year. As others had pointed out, a covering of snow would reflect away enough sunlight to help keep a region cold, giving an amplifying feedback. Under such circumstances, a snowfield could grow over the centuries into a continental ice sheet
- ✘ The sensitive zone would lie between the latitudes of 55 and 65 degrees north where moraines marked the edge of past continental ice sheets
- ✘ Dating the varying episodes of the Pleistocene ice ages by correlating them with the Milankovitch radiation curve appealed to a number of workers

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- ✖ It was also encouraging that even the tiny changes in solar radiation that came with the eleven-year sunspot cycle had some effect on weather
- ✖ Each year the spring runoff laid down a thin layer of silt followed by a settling of finer particles. From bogs and outcrops where the beds of fossil lakes were exposed, or cores of slick clay drilled out of living lakes, researchers painstakingly counted and measured the layers. Some reported finding a 21,000-year cycle of changes. That approximately matched the timing for a wobbling of the Earth's axis which Milankovitch had calculated as a crucial element, namely, the precession of the equinoxes, in fact a combination of 19,000- and 23,000-year cycles



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- ✘ Most geologists dismissed the astronomical theory, for they could not fit Milankovitch's timing to the accepted sequence of four ice ages.
- ✘ A generation of geologists had laboriously constructed this sequence from studies around the world of surface features, such as the gravel deposits (moraines) that marked where glaciers had halted, and hillside terraces that showed the level of ancient rivers
- ✘ Another problem lay in the fact that ice sheets had spread at the same time in the Northern and Southern Hemispheres. The astronomical theory relied upon an increase in the sunlight falling on one hemisphere along with a decrease on the other hemisphere

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- ✖ Studies that had found correlations between sunspot cycles and weather had all turned out wrong, giving an air of unreliability to every connection between solar radiation variations and climate
- ✖ Radiocarbon dating could tell with surprising precision the age of features like a glacial moraine. You only needed to dig out fragments of trees or other organic material that had been buried thousands of years ago, and measure the fraction of the radioactive isotope carbon-14 in them
- ✖ Carbon-14 measurements could now assign accurate dates to the palynologists' tables of cool and warm periods in northern regions.

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- ✗ For example, dating of lake deposits in the Western United States showed surprisingly regular cycles of drought and flood — which seemed to match the 21,000-year cycle predicted by Milankovitch
- ✗ In 1947, a way to measure ancient temperatures was discovered. The key was the oxygen built into fossil shells pulled up from the sea floor. The amount of heavier or lighter oxygen isotopes that an organism took up from sea water varied according to the water's temperature at that time, so the ratio ( $O^{18}/O^{16}$ ) served as a proxy thermometer



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- ✖ Tracking the shells layer by layer in long cores of clay extracted from the seabed, a record of temperature variations was discovered
- ✖ Researchers tentatively identified the rises and dips of temperatures with the geologists' traditional chronology of the past three glacial periods, and suggesting 50,000 year cycles
- ✖ Carbon-14 could date the more recent layers in the deep-sea cores, pinning down the chronology of temperature changes with unprecedented precision
- ✖ It was reported that the last ice age had come to a surprisingly abrupt end, starting sometime around 15,000 years ago.

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- ✖ Looking farther back, hints of a roughly 40,000-year cycle were found, which sounded like the 41,000-year cycle that Milankovitch had computed for slight variations in the inclination of the Earth's axis.
- ✖ Fossil reefs gave witness to how sea level had risen and fallen as ice sheets built up on the continents and melted away. The coral could be dated by measuring their uranium and other radioactive isotopes. These isotopes decayed over millennia on a timescale that had been accurately measured in nuclear laboratories
- ✖ As a check, the sea level changes could be set alongside the oxygen-isotope temperature changes measured in deep-sea cores

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- ✘ People began to speculate on how the calculated changes in sunlight, although they seemed insignificantly small, might somehow trigger ice ages. That could happen if the climate system were so delicately balanced that a small push could prompt it to switch between different states.
- ✘ Some researchers used improved measurements, thanks to a fine set of cores that reached back more than 400,000 years. They could not make the data fit the traditional ice ages timetable and rejected the entire scheme of a Pleistocene epoch comprising four major glacial advances alternating with long and equable interglacial periods.



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- ✗ The interglacials had been briefer, and had been complicated by irregular rises and falls of temperature, making dozens of ice ages. They believed the sequence correlated rather well with the complex Milankovitch curve of summer sunlight at high northern latitude. Calculating how the cycle should continue in the future, they predicted that "a new glaciation will begin within a few thousand years generating widespread public concern about future cooling
- ✗ New evidence came from scientists who took a census of a particular species of foraminifera, recognizing that the assemblage of different species varied with the temperature of the water where the animals had lived.

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- ✖ The data confirmed that there had been dozens of major glaciations during the past couple of million years, not the four or so enshrined in textbooks
- ✖ On the island of Barbados, terraces of ancient coral covered much of the island, rising to hundreds of meters above the present sea level. The dates for when the coral reefs had been living (125,000, 105,000, and 82,000 years ago) closely matched dates from Milankovitch cycles for times when the ice sheets should have been melted and the seas at their highest (127,000, 106,000, and 82,000 years ago).
- ✖ Since the Milankovitch cycles could be computed directly from celestial mechanics, one could project them forward in time



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- ✘ In 1972, presenting more Caribbean cores, researchers advised that the present episode of amiable climate is coming to an end and we may soon be confronted with... a runaway glaciation. Greenhouse effect warming caused by human emissions might overwhelm the orbital shifts, so we might instead face a runaway deglaciation
- ✘ Geological and oceanographic studies had shown that over the course of millions of years, now and then the Earth's entire magnetic field flipped: the North magnetic pole became the South magnetic pole and vice-versa. These reverses were recorded where layers of sediment or volcanic lava had entombed the direction of the magnetic field at the time



# GLOBAL WARMING

- ✘ In 1972, a group of leading glacial-epoch experts met at Brown University to discuss how and when the present warm interglacial period might end. A large majority agreed that the natural end of our warm epoch is undoubtedly near
- ✘ The Greenland ice sheet is a daunting sight with colossal bare cliffs where unimaginable quantities of ice pour down to the sea in a slow-motion flood. The landscape rises and rises, over entire mountain ranges hidden under ice. A few geologists had dared to postulate the existence, in the distant past, of seas of solid ice kilometers thick. Then astonished explorers of Greenland found just such a thing

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- ✘ In the late 1950s, scientists came back to Greenland, hoping to find the key to the history of climate change
- ✘ At Camp Century, Greenland, workers drilled short cores from the ice to demonstrate that it could be done. An improved drill, brought onto the ice in 1961, produced cores 5 inches in diameter in segments several feet long
- ✘ With the U.S. Army's Cold Regions Research and Engineering Laboratory, the drill at Camp Century reached bedrock. The hole reached down some 1.4 kilometers (7/8 of a mile), bringing up ice as much as 100,000 years old
- ✘ In 1968, another long core of ancient ice was retrieved from a site even colder and more remote: Byrd Station in West Antarctica



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- ✘ Individual layers with a lot of acidic dust pointed to past volcanic eruptions. Individual eruptions could be assigned dates simply by counting the annual layers of ice. Known eruptions like the destruction of Pompeii in the year 79 gave a check on the counts.
- ✘ Farther down the layers became blurred, but approximate dates could still be assigned. Deep in the ice there were large amounts of mineral dust, evidence that during the last ice age the world had been windier, with storms carrying dust clear from China. Still better, ancient air had been trapped and preserved as bubbles in the ice, a million tiny time capsules packed with information about past climates.

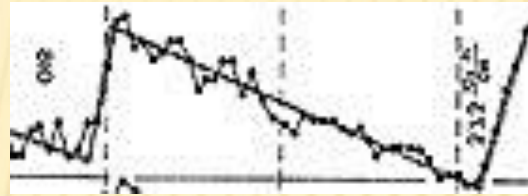


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- ✗ The ratio of oxygen isotopes ( $O_{18}/O_{16}$ ) in the ice measured the temperature of the clouds at the time the snow had fallen — the warmer the air, the more of the heavy isotope got into the ice crystals
- ✗ The preliminary study of the ice cores, published in 1969, showed variations that indicated changes of perhaps  $10^{\circ}\text{C}$  ( $18^{\circ}\text{F}$ ). Some cycles were tentatively identified, including one with a 13,000 year length. Comparison of the Greenland and Antarctic cores showed that the climate changes were truly global, coming at essentially the same time in both hemispheres

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- ✗ In each cycle, a spurt of rapid warming was followed by a more gradual, irregular descent back into the cold over tens of thousands of years



- ✗ The Greenland ice cores could say little about long-term cycles. They were too short to reach past a single glacial cycle. And the ice flowed like tar at great depths, confusing the record. In the 1970s, despite the arduous efforts of the ice drillers, the most reliable data were still coming from deep-sea cores.

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- ✘ In a few places, layers of silt had built up unusually swiftly and steadily and without disturbance
- ✘ Improved techniques for measuring the layers gave data good enough for thorough analysis
- ✘ The most prominent feature turned out to be a 100,000-year cycle — evidently a key to the entire climate puzzle
- ✘ According to the data, the prominent cycle seen earlier and attributed to the 41,000-year orbital shifts was actually the 100,000-year cycle. It seemed possible that Milankovitch cycles were real



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- ✘ In 1973, new magnetic-reversal dates established by radioactive potassium were determined in a deep-sea core (Vema 28-238). It reached back over a million years, and included the most recent reversal of the Earth's magnetic field, which geologists dated at a bit over 700,000 years ago. This calibrated the chronology for the entire core
- ✘ They were also able to extract and analyze the rare foraminifera that lived in the deep sea, which reflected basic oceanic changes independent of the fluctuating sea-surface temperatures. The deep-sea forams showed the same isotopic variations as surface ones, confirming that the variations gave a record of the withdrawal of water to form ice sheets

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- ✗ The core Vema 28-238 and a few others contained such a long run of consistent data that it was possible to analyze the numbers with a mathematically sophisticated "frequency-domain" calculation. Detailed measurements and numerical calculations found a set of favored frequencies, a spectrum of regular cycles visible amid the noise of random fluctuations. Researchers analyzed the oxygen-isotope record in selected cores from the Indian Ocean, and checked their curves against temperatures deduced from the assemblage of foraminifera species found in each layer.



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- ✖ The analysis showed cycles with lengths roughly 20,000 and 40,000 years, and especially the very strong cycle around 100,000 years, all in agreement with Milankovitch calculations. Extrapolating the curves ahead, the group predicted cooling for the next 20,000 years - the Earth was gradually — indeed, perhaps quite soon as geologists reckoned time — heading into a new ice age
- ✖ Confirmation came from other scientists who likewise found cycles near twenty and forty thousand years - they could even split the 20,000 year cycle into a close pair of cycles with lengths of 19,000 and 23,000 years — exactly what the best new astronomical calculations predicted. By the late 1970s, most scientists were convinced that orbital variations acted as a "pacemaker" to set the timing of ice age



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- ✗ The variation in the intensity of sunlight that was computed for the 100,000-year astronomical cycle came from a minor change in orbital eccentricity — a slight stretching of the Earth's path around the sun out of a perfect circle. It was a particularly tiny variation; the changes it caused should be trivial compared with the shorter-term and larger orbital shifts, not to mention all the other influences on climate. Yet it was the 100,000-year cycle that dominated the record

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- ✗ During the 1980s, ocean drilling pursued on an international scale, produced ever better cores. A project dedicated to "spectral mapping" yielded a spectrum of cycles that matched the astronomical calculations with gratifying precision going back hundreds of millennia. Five separate cores confirmed that variations in the Earth's orbit drove the coming and going of ice ages
- ✗ The prominent 100,000-year cycle (due to changes in the orbit's eccentricity) had dominated climate change only during the most recent million years. During a long earlier phase of the Pleistocene epoch, the rise and decay of ice sheets had followed the 41,000-year cycle (due to shifts in the inclination of the Earth's axis).

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- ✘ Milankovitch and his followers had originally expected that this cycle would have a much stronger effect than the feeble 100,000-year shifts
- ✘ The ice and seabed climate curves were found to go up and down in fine agreement, and researchers began to combine data from both sources in a single discussion. The most striking news from the ice was evidence that the level of CO<sub>2</sub> in the atmosphere had risen and fallen more or less in time with the temperature
- ✘ The outstanding record was extracted by a French-Soviet team at the Soviets' Vostok Station in Antarctica



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- ✗ While the Greenland record reached into the most recent ice age, by 1985 the Antarctic team had pulled up cores of ice stretching clear through the cold period and into the preceding warm period—a complete glacial cycle. During the cold period, the CO<sub>2</sub> level had been much lower than during the warm periods before and after. Indeed the curves of gas level and temperature tracked one another remarkably closely
- ✗ Measurements in ice cores of an even more potent greenhouse gas, methane, showed a similar rise and fall that matched the rise and fall of temperature

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- ✘ The Vostok team pointed out that the swings in greenhouse gas levels might be amplifying the effect of the orbital shifts. A small rise or fall in temperature seemed likely to cause a rise or fall in the gas levels (for example, when seawater got warmer it would evaporate some CO<sub>2</sub> into the atmosphere, whereas it would absorb the gas during a cooling period)
- ✘ More or less greenhouse gases in the atmosphere would make for further changes in temperature, which would in turn raise or lower the gas levels some more... and so on. It was the first truly plausible theory for how minor shifts of sunlight could make the entire planet's temperature lurch back and forth

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- ✗ Changes in atmospheric CO<sub>2</sub> and methane physically linked the two hemispheres, warming or cooling the planet as a whole
- ✗ By the late 1980s, most calculations had converged on the familiar prediction that the natural Milankovitch cycle should bring a mild but steady cooling over the next few thousand years
- ✗ Improved calculations said that the next ice age would not come naturally within the next ten thousand years or so. The calculations were backed up in 2004 by data from a new drilling effort in Antarctica that brought up ice spanning the past eight glacial cycles



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- ✘ In the Antarctic record, atmospheric CO<sub>2</sub> levels over the past 750,000 years had cycled between about 180 and 280 parts per million. The level in the late 20th century had now climbed above 370 and kept climbing
- ✘ Greenhouse warming and other human influences seemed strong enough to overwhelm any natural trend
- ✘ As emissions climbed exponentially, we might not only cancel the next ice age, but launch our planet into an altogether new climate regime
- ✘ Computer models were predicting for our future that a few degrees of warming would occur if the CO<sub>2</sub> level doubled

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- ✖ By the late 1980s, it did seem to be an established fact that ice ages were timed by orbital variations. The chief question that remained in the minds of most scientists was what kind of feedbacks amplified the effect
- ✖ The cycles, most scientists now agreed, involved not only orbital variations in solar irradiation, but also a variety of geological effects
- ✖ New evidence gave a particularly crucial role to changes in CO<sub>2</sub> and other greenhouse gases
- ✖ The faint variations of summer sunlight were effective only because the astronomical schedule somehow resonated with other factors — ice sheet and ocean dynamics, the bio-geochemical CO<sub>2</sub> system, and who knew what else

# GLOBAL WARMING

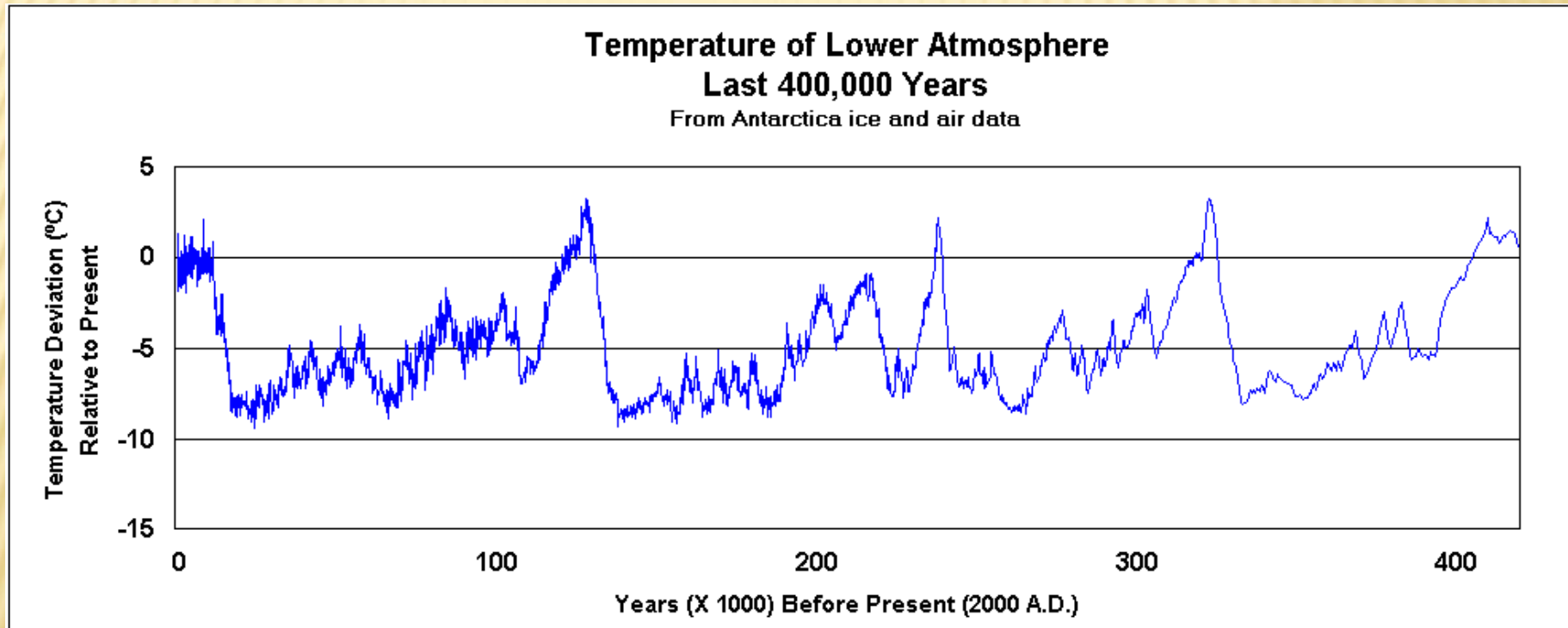
- ✖ An important clue came from some especially good ice core records that timed precisely the changes in the levels of CO<sub>2</sub> and methane. The levels apparently rose or fell a few centuries *after* a rise or fall in temperature
- ✖ The close of a glacial era came when a shift in sunlight caused a slight rise of temperature, and that raised the gas levels. The greenhouse effect then drove the planet's temperature a bit higher, which drove a further rise in the gas levels
- ✖ On the other hand, when the sunlight in key latitudes weakened, that would not only bring more ice and snow, but also a shift from emission to absorption of gases, causing a further fall in temperature



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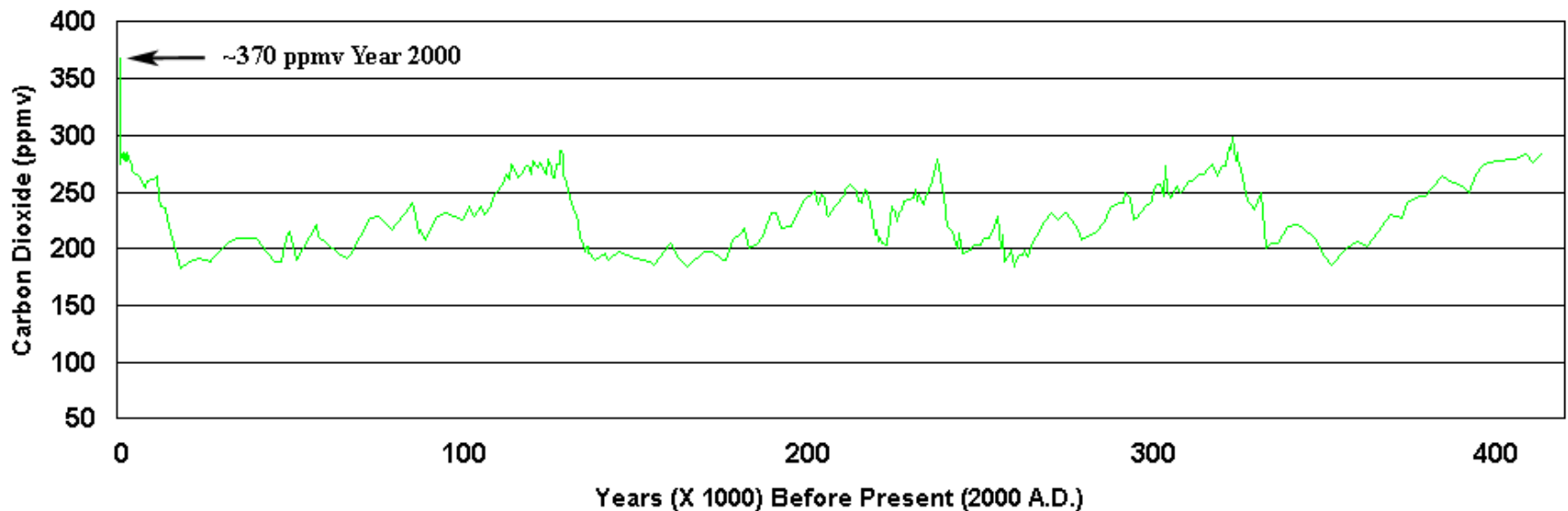
- ✗ Our current situation was altogether different. The warming was not started by a small shift of sunlight - our addition of gases to the atmosphere was initiating the process, with the temperature rise lagging behind the rise of gas levels
- ✗ Our emissions were climbing at a far swifter rate, and had already reached a far higher level, than anything in the Pleistocene record
- ✗ Drying forests and warmer seawater were getting less efficient at taking CO<sub>2</sub> out of the air, and methane was seen bubbling up from Arctic wetlands
- ✗ By the start of the 21st century, it was clear that the connection between global temperature and greenhouse gas levels was a major geological force

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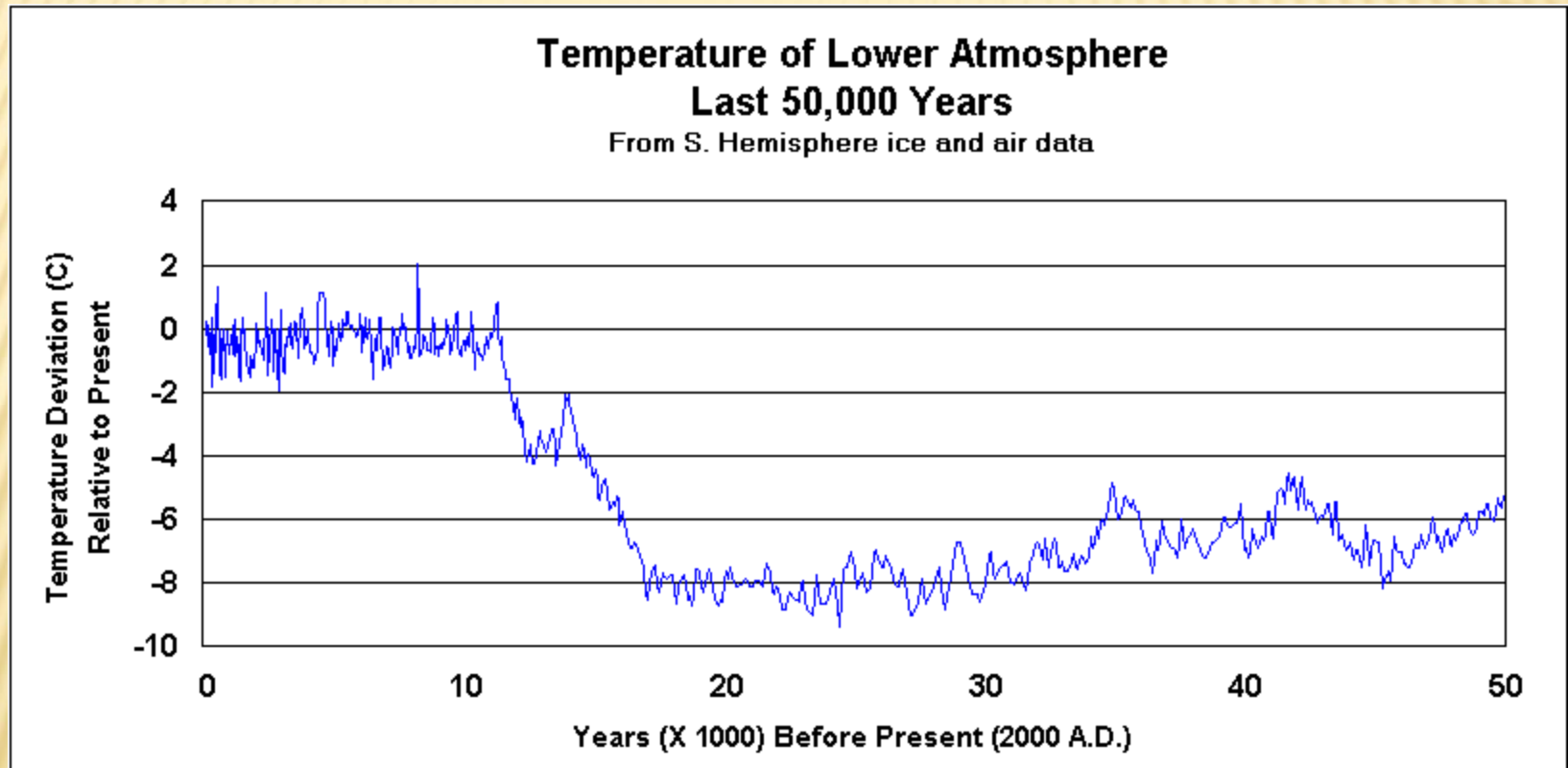
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**Atmospheric CO<sub>2</sub> Concentrations  
Last 400,000 Years**  
From Antarctica Ice and air data

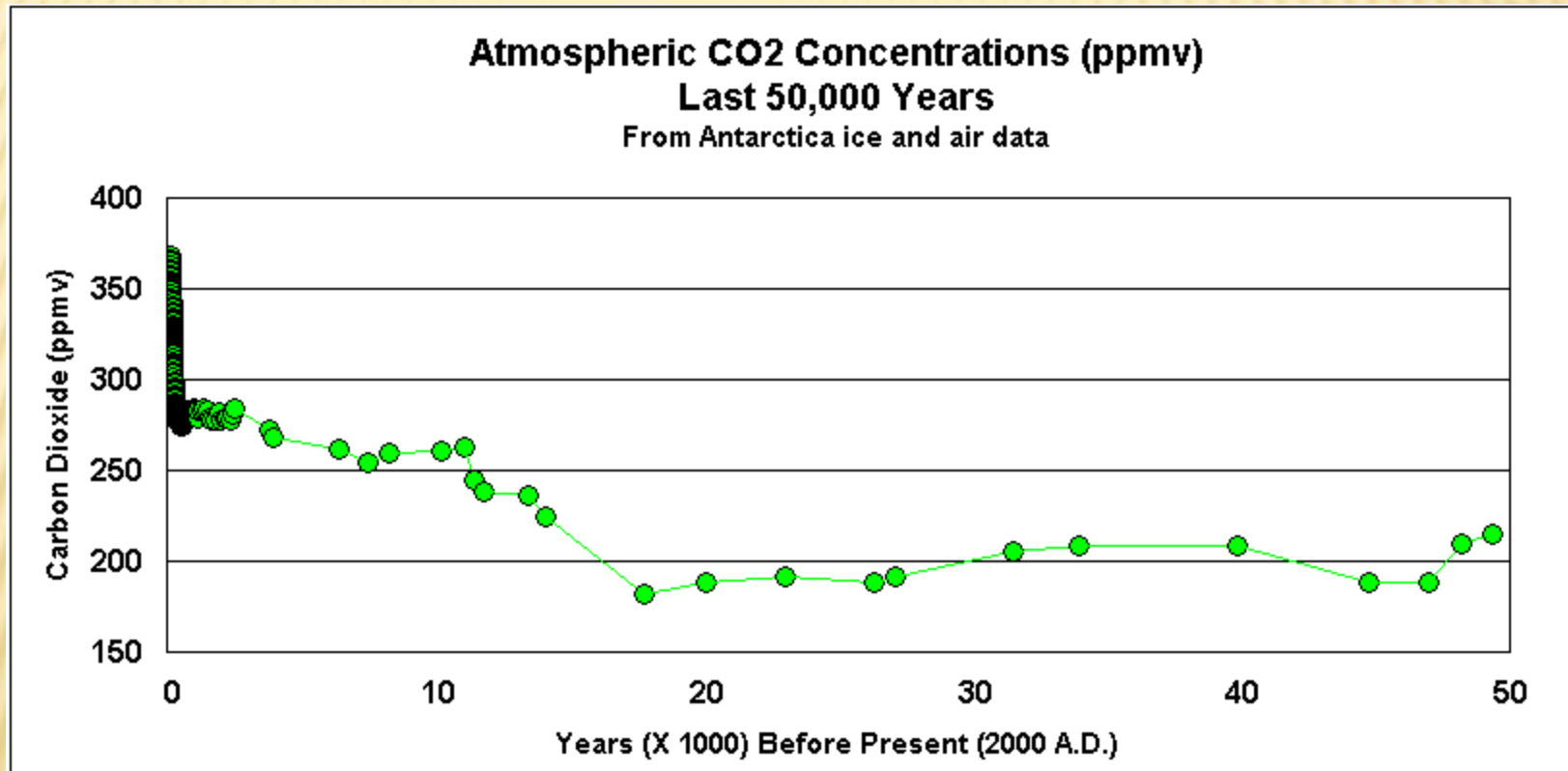




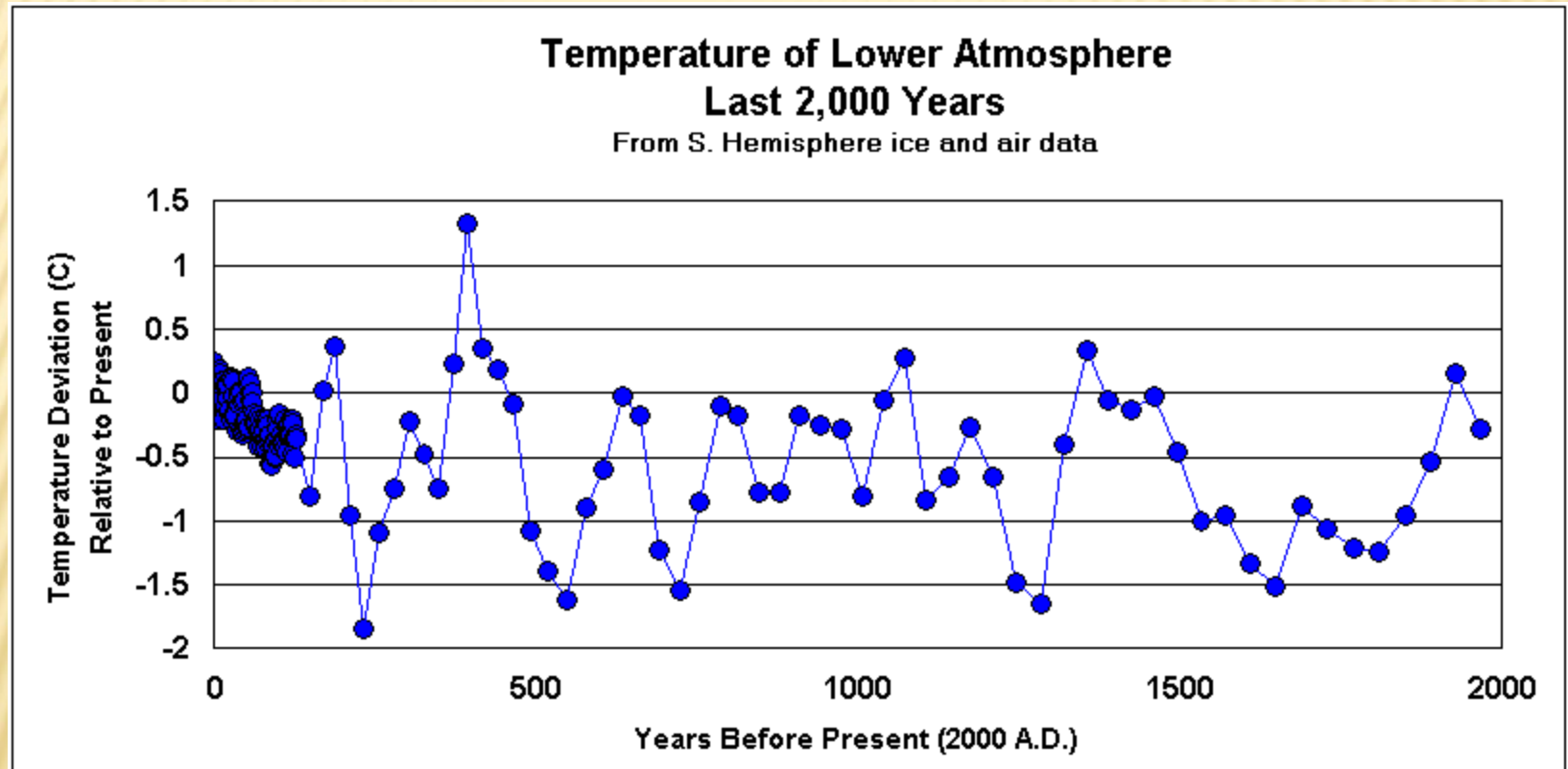
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