The Science Behind *The Ice-Breaker*

Or,
What Earth and Climate Science Tell Us About Past Global Climate Changes and the Catastrophic Climate Changes That We May Face in the Next Hundred Years

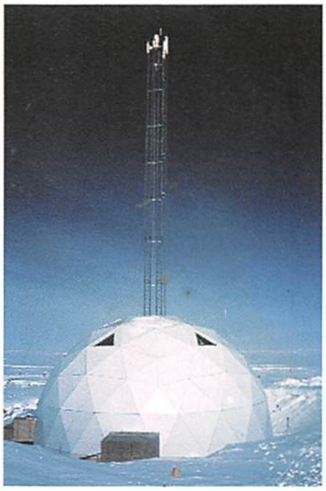
BY MONTE MARSHALL

One of the most important things that the plate tectonic revolution of the 1960s and 1970s in the earth sciences taught us is that the earth is constantly changing. Even the shape and location of such enormous features as continents and oceans were very different in the past than they are today. The only reason that such vast changes are not readily noticeable to us is that most geologic processes are so slow that differences are small in one human lifetime. Many of these movements are about as slow as the growth of our fingernails. Earth scientists have to play detective and infer from clues in the rock record what the past was like. Only now with the advent of satellites and very sensitive and expensive GPS instruments can we directly measure the movement of the continents and the rise of mountain tops over a single year.

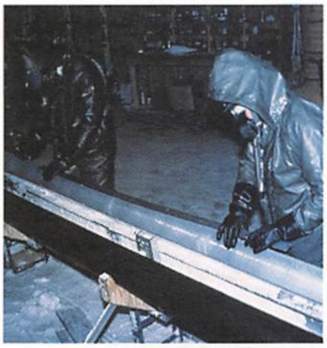
Geology, or the study of the earth, became a science only two hundred years ago and one of the first earth scientists, Louis Agassiz, began studying the movement of glaciers in the Swiss Alps. He became familiar with surface features known to be caused only by glaciers: the linear piles of loose rocks and the polished and grooved bedrock surfaces over which they had flowed. After observing these same features far north of the Alps, even up in Scandinavia and northern North America, he shocked the scientific world in 1837 by proclaiming that Alpine glaciers in the recent geological past had extended much lower and farther out and that a great ice sheet had covered much of northern Europe and North America, i.e., there had been a fairly recent "Ice Age."

Only relatively recently did geologists and paleontologists (half geologist—half biologist, they study fossils) realize the rock record can give us *detailed* information about these unusual past climates. In the last 30 years earth scientists discovered that things like stalactites in caves, deposits of ancient lake beds, cores of seafloor sediments, and mile-long cores drilled deep into ice caps could give them detailed records of local temperature and atmospheric composition going back hundreds of thousands of years! When they plotted these data, they and the meteorologists and climatologists quickly realized that the earth's past weather/climate was a lot more complicated than they had realized. Given the human tendency to assume the past was always like the present, people were astonished to discover that the earth at times was much warmer or colder than now—that there were jungles in the arctic and a time when the entire earth was possibly a giant snowball!

In order to help you more fully understand the terms and concepts in this play and their very great potential importance to our world, read on to learn how ice forms in glaciers and ice caps, some of the causes and effects of ice ages, the highly detailed information on climate changes during the past 400,000 years contained in ice cores, the central topic in this play, and how these data give us a much better background for understanding current global warming and what the future may bring.



The GISP2 Drill Dome.
Photo by Mark Twickler, GISP2 SMO, University of New Hampshire.



Scientists extrude the core from its barrel with the utmost care.
Photo by Kendrick Taylor, Desert Research Institute, University and Community College System of Nevada.

How Glaciers and Polar Ice Caps Form

At present, 70% of earth is covered by oceans and 10% of the remaining 30%, land, is covered with ice. Most of this ice occurs as very thick sheets in polar areas, like Greenland and Antarctica, and the rest as glaciers in high mountain ranges, like the Andes, Alps, and Himalayas. The water for most of this ice comes from the sea surface by evaporation. The water vapor condenses into rain drops or ice crystals in clouds, is carried by wind currents, and falls as rain or snow, depending on the air temperature.

The transformation of snow crystals into 'solid' ice takes place gradually on the surface of a glacier or ice cap. Freshly fallen snow consists of millions of tiny, elaborate, six-pronged ice crystals surrounded by air. As the flakes pile up, the crystals become blunted and compacted into loose, granular ice. With increasing depth the crystals become even more equant or granular and the pressure squeezes out most of the air and fuses the crystals into a solid mosaic of small grains with air bubbles. In order for an ice sheet or glacier to grow in thickness more ice must form in winter than melts in summer. At present the climate is sufficiently cool for ice buildup only at high latitudes or high elevations; hence ice only lasts near the poles and tops of high mountain ranges.

One special property of ice, considered by geologists to be a rock, is that it is plastic enough to flow at an almost visible rate. The solid

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ice actually flows by the stretching or elongation of each tiny crystal when it is under stress or pressure. The only other rock that is so plastic, rock salt, actually forms salt glaciers in the arid deserts of Iran! Since ice piles up thickest (10,000 feet thick) near the centers of Greenland and Antarctica, forming a dome-shape, gravity pulls the ice in giant frozen streams, tens of miles wide and hundreds of miles long, downwards and out to the coasts. Gravity likewise pulls the ice accumulating at mountain tops down into valleys and the ice flows slowly downstream like a frozen river. The action of the moving ice is to grind down any obstruction in its path, leveling hills and rounding V-shaped valleys into U-shaped ones, like Yosemite Valley. Since the ice often contains gravel and even boulders, the overridden bedrock surface is usually polished and grooved. In valley glaciers, rocks plucked from the sides and floor of the valley are left as linear rock piles along the edges of the glaciers (lateral moraines), or as giant rock dams at the glacier's terminus (terminal moraines). Where two valley glaciers merge into one, they are usually kept separate by a medial moraine.

Ice Ages—Some Causes and Effects

Ice ages are rare in the geologic record—only 4 others have been confirmed in the earth's 4.5 billion year history! The current ice age began in earnest about three million years ago and consisted of a series of glacial (ice advances) and interglacial (ice retreats) times, with each pair lasting about 100,000 years. Obviously the earth's surface has been too warm over most of geologic time for ice to last. Realizing that the vast majority of animals that have ever lived on our earth never saw sheets of ice covering vast continents or beautiful white and blue-green glaciers slowly flowing down high mountain valleys is surprising! And this knowledge leads us to ask what factors cause the average surface temperature to drop to the point when, at least near the poles and in high mountains, ice can form and last for millions of years?

Scientists currently think the most important factors controlling long-term climate are the position of the continents relative to each other and to the poles, the composition of our atmosphere, and the brightness/luminosity of our sun. Giant currents in the atmosphere and oceans distribute the excess heat in equatorial areas to the poles. The positions and elevations of the continents can interfere or help with this heat transfer/balancing. The surface temperature is also very much affected by the balance between the amount of incoming sunlight that is absorbed or transmitted by the atmosphere, which warms the surface, versus the amount that is reflected or re-radiated out into space. Certain atmospheric gases, like carbon dioxide, water vapor, and methane allow visible light to enter and leave the atmosphere, but 'reflect' the infrared (heat) light radiated by the earth's surface back to the surface and act just like the glass in a greenhouse—this is the famous greenhouse effect. Dust, volcanic ash, and other gases, like sulfur dioxide from volcanic eruptions, can reflect sunlight and lower surface temperatures. A NASA satellite showed that the 25 million tons of sulfur dioxide erupted from Mt. Pinatubo, in the Philippines in June 1991, formed sulfuric acid droplets that increased the reflectance of the atmosphere so much that global temperatures fell one degree F! Finally, since our sun is the source of essentially all the heat at the earth's surface, any changes in the amount of energy radiated by it will directly affect surface temperatures.

The times between the 5 known ice ages vary greatly, between 160 million and 1.8 billion years. So they are not cyclic or periodic, and therefore not obviously predictable. However, the climate fluctuations during a given ice age, like the one earth has been experiencing for about the last 3 million years, may well be predictable. As will be seen in the next section, the climatic variations during the last glacial and interglacial periods, i.e., the last 110,000 years, seem to be largely cyclic. The length of the cycles ranges from 100,000 to as short as 10 years. Some of the factors that are involved in these cycles are solar luminosity, oceanic currents, greenhouse gas concentrations, and the earth's orbital parameters. Of all of these, only the last is well understood and appears to be due to a combination of three astronomical cycles that have different periods. These three cycles were discovered by a Yugoslav mathematician and geophysicist, Milutin Milankovitch, in the 1920s and 30s. The shape of the earth's orbit changes from more circular to more elliptical and back every 100,000 years. The more elliptical the orbit, the greater percent of each year the earth spends far from the sun. The other two factors are variations in the tilt and wobble of the earth's axis of rotation, with periods of 40 and 20 thousand years, respectively. Both of these cyclic variations also affect the amount of sunlight received at a given place.

So, to put all of this together: the conditions, rarely met, needed for ice to accumulate on our earth, and in quantities sufficient to flow over continents and down valleys, are just the right combination of astronomical factors that vary like clockwork and complex processes in our earth's and sun's deep interior and atmosphere that we are just beginning to understand. But, as long as we live in an ice age, and to the extent that climate changes are cyclic and not due to random causes, we can hope that computer models based on lots of detailed climate records, like the ice cores, will someday predict future climates — just as they are beginning to predict hurricane tracks now.

Many of the effects on us and all the other forms of life of lowered surface temperatures are seen clearly when we think how plants and animals change going from tropical jungles to barren, wind-swept arctic or Antarctic regions. Less obvious is the effect of freezing so much of the evaporating sea water and locking it up as ice on the continents. At the peak of the last ice advance 120,000 years ago, some 30% of the land was covered by ice! The removal of sea water to form so many cubic miles of glacial and polar ice lowered sea level almost 400 feet worldwide! During ice maximums like this, aboriginal Asians were able to walk across the Bering Straits into parts of Alaska and eventually proceed south. Many of the traces of this migration, like their kitchen middens, are now submerged on the continental shelves. Conversely, should the ice in Greenland and Antarctica continue to melt completely, sea level is calculated to rise and flood all coastal areas in the world to a depth of about 200 feet! Most of the major cities in the U.S. would have to be evacuated. Thirteen of the 20 largest cities in the world are located in coastal areas at sea level. This range in sea level, from –400 to +200 feet, is what can be expected if our earth either cools or warms significantly from its present state.

The Search for a Detailed, Continuous, and Long-term Record of the Climate During the Recent Goelogical Past

If a geologist really has to know what is beneath the surface at a place devoid of road cuts, stream banks, or sea cliffs, the best way is to drill a hole there. The technology of drilling holes in the earth began with the search for salt water, highly valued as a source for the salt needed as a spice, a necessary dietary ingredient, and a food preservative (not many ice-boxes/fridges before 1800!). Of course, this technology has been tremendously advanced in the modern search for oil, gas, and minerals. Limited information about the subsurface can be gained by examining the loose sediments or rock chips brought to the surface. But you can learn a lot more, for ten times the cost, from cylindrical rock cores left by special bits with hollow centers while drilling through solid rock.

Plastic tubes pounded into the muds on the sea floor have long been used by oceanographers and marine scientists to obtain samples of the mineral grains and fossils deposited there. Since the sixties they have had the use of a ship-mounted drilling rig—the same kind used by petroleum companies to drill offshore wells (and used by the CIA to raise half of a Russian nuclear submarine from 15,000 feet deep in the mid-Pacific during the cold war!). In the seventies, they discovered that they could estimate both the paleotemperature of the oceans and the amount of ice on the earth's surface by measuring the oxygen isotope ratio in the shells of a species of marine, single-celled organisms called forams. Their shells are made of calcium carbonate, which they form from the calcium, carbon, and oxygen dissolved in the sea water. This is the same mineral that coral reefs, beach shells, pearls, limestone, and marble are made of. The main isotope of oxygen in sea water is O-16, but water molecules also have atoms of O-18, a slightly heavier atom. As the sea water temperature increases, the forams incorporate more O-16 into their shells than when the water is cold. Secondly, during evaporation of sea water, water molecules with the lighter oxygen atoms preferentially go up into the air, thus enriching the remaining sea water in O-18. If the climate is so cold that much of the water vapor is precipitated as snow and turns into 'permanent' ice, the lighter O-16 atoms remain in the ice caps and glaciers and are not returned by rivers to the sea. The sea water becomes progressively enriched in O-18, as do the foram shells. Thus, with proper sampling of the forams, the O-16/O-18 ratio in the shells becomes a semi-quantitative index of both oceanic temperature and how much sea water was lost to form 'permanent' continental or sea ice at the time the forams lived. This seemingly arcane data told us that ice caps/glaciers advanced and retreated 20 times during the present ice age... and would probably advance again! But, the story isn't over!

In their search for an even more complete, long-term record of climate changes, Russian scientists in the 1960s turned to the thick ice sheet under their Vostok base in Antarctica. People had known for years that sheets of ice consisted of alternating dark and light layers, where each pair recorded the difference between summer and winter ice, i.e., recorded a year just like tree rings! The oxygen isotope ratio in the ice would be useful for indicating paleotemperatures in Antarctica. They realized that the air bubbles frozen into the layers of ice would be good samples of the atmosphere at that place during the 20 years or so that the snow was converted into ice. Plus, the ice should also contain the ash of past eruptions, pollen, and, at the top, a record of modern pollution. By the 1970s the Russians had drilled ice cores to a depth of 3,000 feet and were getting interesting correlations between the ice formation temperature, as indicated by oxygen isotope ratios, and the carbon dioxide percent in the air bubbles.

Encouraged by the Russian results, a mile-deep ice core was drilled in 1966 in Greenland. Although the lower annual layers were obscured by ice flowage, scientists realized they had found a detailed, long-term paleoclimate recorder. Between 1989 and 1993 two drilling rigs were set up at an elevation of 10,519 feet on the very cold, wind-swept crest of the Greenland ice cap. Located only 20 miles apart, so they could test the reproducibility of each other's results, European and American teams drilled the now-famous GRIP (Greenland Ice Core Project) and GISP2 (Greenland Ice Sheet Project, 2) core holes, respectively.

Working 12 hours a day during the 4 summer months for 5 years, the American team drilled 10,018 feet of 5-inch-thick cores until they hit bedrock. The ice at the bottom was at least 250,000 years old and they had penetrated ice formed during the last two glacial and interglacial periods. Using the light and dark banding, caused by semi-annual differences in dust content and density, and aided by lasers and differences in electrical conductivity, scientists were able to confidently identify annual layers back to 110,000 years ago—back to the last, or Sangamon, interglacial. The cores were cut in half, with half going to the National Ice Core Repository in Denver, and the other half for sampling. Samples were taken every two years between 0 and 10,000 years, every 15 years between 10,000 and 45,000 years, and every 50 years between 45,000 and 110,000 years. Kept at −4 degrees F, the samples were sent to 25 research institutes in the U.S. for measurements of 50 different physical and chemical properties. This hole has the record for the longest, continuous ice core in the Northern Hemisphere (the Vostok hole was cored to a depth of 10,988 feet by a joint Russian/French/American team in 1997), and the best detail in the world. Analyzing the miles of 5 inch-thick cores, the scientists soon realized that they had drilled the best recorder of paleoclimates yet!

What Was Found in the Ice Cores?

The Vostok ice core showed that the last 4 glacial advances occurred about every 100,000 years. During this, the major climatic cycle, the glacial periods lasted about 90,000 years and ended with an interglacial period of about 10,000 years (Fig.1). Since our current interglacial has lasted about 11,000 years, under normal (pre-industrial age) conditions we should be entering an ice age soon. The temperature at the start of each glacial period decreased in a series of large, rapid oscillations. Even during interglacial times, the climate experienced rapid, but less extreme, temperature oscillations. Interestingly, the percent of carbon dioxide and methane tracked all these temperature variations fairly closely.

Some of the highly detailed climate changes found in the U.S. Greenland ice core, GISP2, are shown in Figure 2. Note how small the temperature changes during the last 110,000 years were thought to be before scientists had the ice core data. Even the temperature increase between the depth of the last glacial at 20,000 years ago and the

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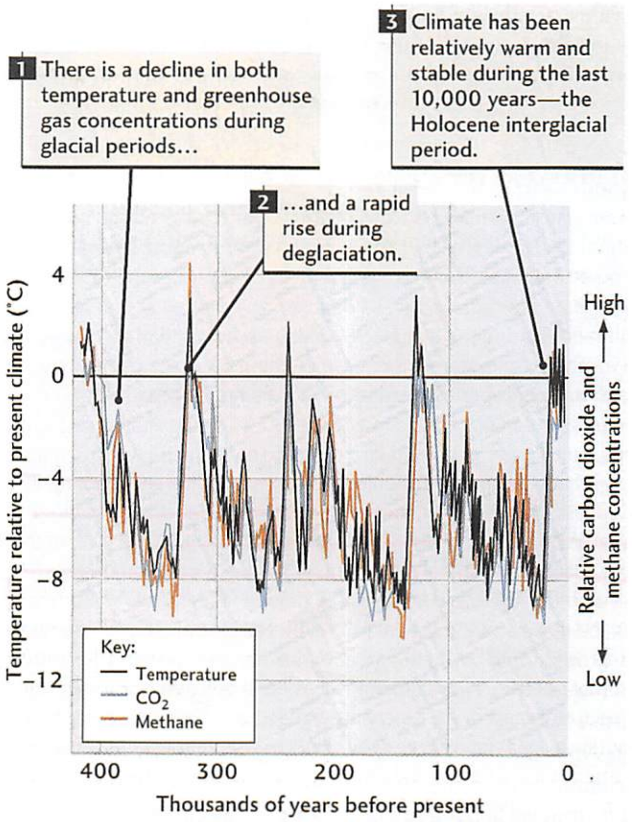
1 There is a decline in both temperature and greenhouse gas concentrations during glacial periods...

2 ...and a rapid rise during deglaciation.

3 Climate has been relatively warm and stable during the last 10,000 years—the Holocene interglacial period.

Figure 1. Relative temperature (dark line) and carbon dioxide and methane concentrations (light lines) measured in the Vostok ice core. Temperature variations based on oxygen isotope ratios in the ice, gas concentrations from air samples in the bubbles. (IPCC, Climate Change 2001: The Scientific Basis.)

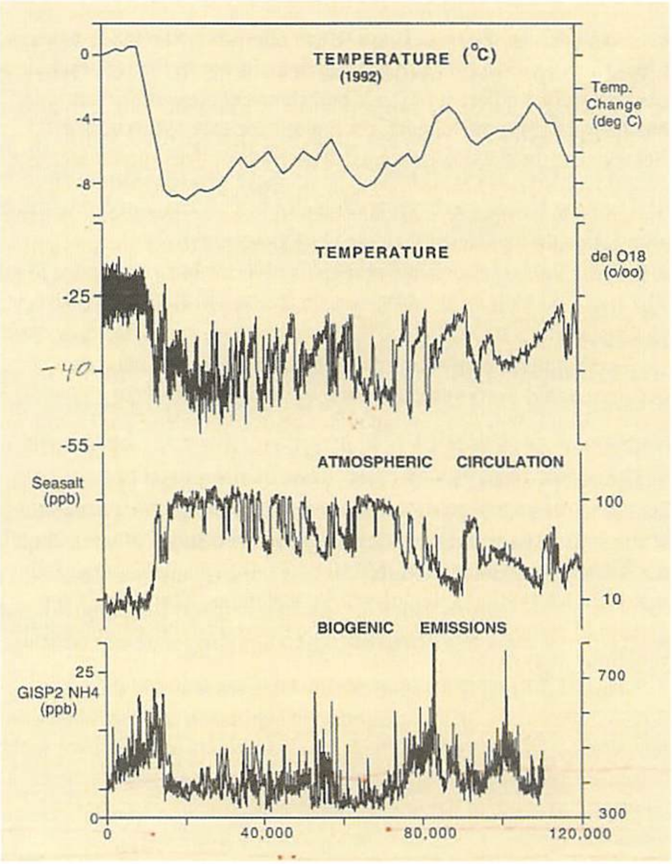

Figure 2. Top curve shows temperatures during the present interglacial/last glacial cycle as estimated by scientists in1992, before the data from the Greenland ice cores. The lower three curves show variations in temperature, and sea salt and ammonia concentrations as measured in GISP2. (From Mayewski and White, 2002, p. 83)

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present interglacial (11,000 Y to present) was thought to be only 8 degrees C (14 degrees F)! The second from top curve shows the temperature fluctuations as measured by oxygen isotope ratios in GISP2. Note the rapid, large, 15 degree C (27 degree F) temperature oscillations during the last glacial. Many of the oscillations are cyclic and involve a temperature decrease of about 6 degree C over a span of 10,000 to 15,000 years, preceded and followed by a large temperature change that took place in 10 to 30 years! The Milankovitch cycles cannot explain such large and rapid changes, so they may be due in great part to the variations in Greenhouse gases seen in Figure 1. Imagine our ancestors in caves in southern France experiencing an average annual temperature drop of 30 degrees F in their lifetimes! Were the tribes chased repeatedly away from and toward equatorial areas?! Note also the large, 20 degree C (36 degree F) increase in temperature from the depths of the glacial to the interglacial, and the 5 degree C (9 degree F) rapid oscillations in the present interglacial. The concentration of sea salt in glacial-period ice is ten times that in our interglacial period (third graph). As a measure of wind velocity and sea surface turbulence, this timid curve speaks of cold, violent winds whipping up the open North Atlantic and carrying salt into the atmosphere. The last/bottom curve shows, via the ammonia concentration in the ice, the terrestrial biomass. After a low at 20,000 years, the amount of continental plants increased rapidly at the beginning of our interglacial, then, strangely, decreased up to the present. Showing cycles within cycles, periodically the biomass within the last glacial time was equal to that at the beginning of our interglacial.

The resolution of the Greenland data is so good that the time scale can be expanded even more (Fig. 3). The last, and one of the fastest, oscillations during the last glacial is named the Younger Dryas. About 13,000 years ago the average temperature fell 20 degrees F during ten years and then shot up 20 degrees at about 11,500 years ago—the official beginning of our interglacial, or "Holocene epoch." Such quick and large temperature changes are now called RCCEs (Rapid Climate Change Events) and are found throughout the ice cores and in other records. Their causes are currently unknown, but are suspected to be, at least in part, due to changes in solar luminosity. Just the existence of such poorly-understood, large, and rapid climate changes is sufficient to give us pause before we radically alter our climate. And would a fairly rapid change of 'only' 5–10 degrees F in the average annual temperature during our interglacial affect our civilization? It would and has.

Human history has been influenced by climate changes much more often and to a greater extent than we realize. Our change from being hunter-gatherers to farmers, i.e., the beginning of civilization in the 'west' at about 10,000 years ago in Mesopotamia —at about the same time that the terrifying climate of the last glacial ended and the world entered a period of more or less sustained mild climate is probably not coincidental. And 6,000 years later when this civilization, called the Akkadian empire, collapsed there, detailed GISP2 records and cores in the eastern Mediterranean show that the climate in the Mediterranean and Mid-east was hot and dry. Another mystery, the end of the Mayan civilization between 750 and 900 AD, could well be due to the extreme dryness at that time across much of the northern hemisphere as evidenced by the ammonia levels in GISP2 and data from lake beds in Mexico. The disappearance of much of the North Atlantic sea ice pack during the Medieval Warming Period (200 to 1350 AD, Fig. 3), allowed the Vikings from Norway and Iceland to explore that area and found settlements on coastal Greenland and Canada about 1000 AD. When the Little Ice Age (LIA) began with a temperature drop of only 2.5 degrees F at about 1400 AD, the hearty Viking settlements collapsed as their grain and cattle died. More recently, such small temperature drops following large volcanic eruptions have caused famine and "years without summers" in Europe.

Most recently, scientists have wondered if the warming trend that began in about 1900 marks the natural end of the LIA, or if that cooling trend was prematurely ended by the increase of greenhouse gases, especially carbon dioxide, in our atmosphere. Increasing exponentially since 1850, the carbon dioxide percent in the atmosphere is now

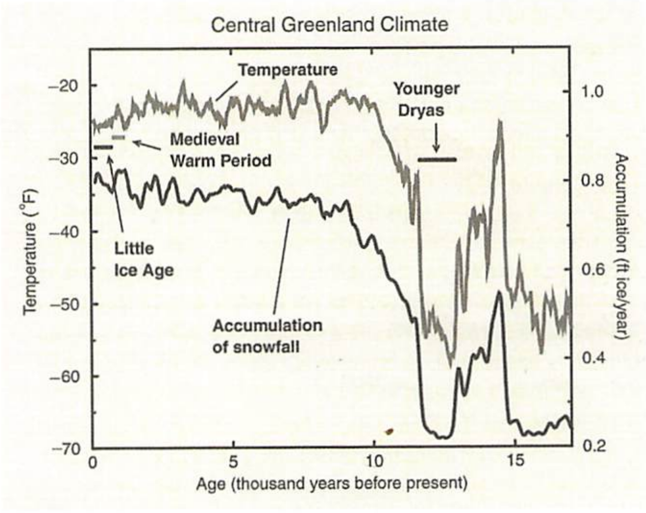

Figure 3. Expanded view of temperature and snowfall accumulation changes during the last 17,000 years, as measured in GISP2 ice core (From Allen, 2000, p. 9)

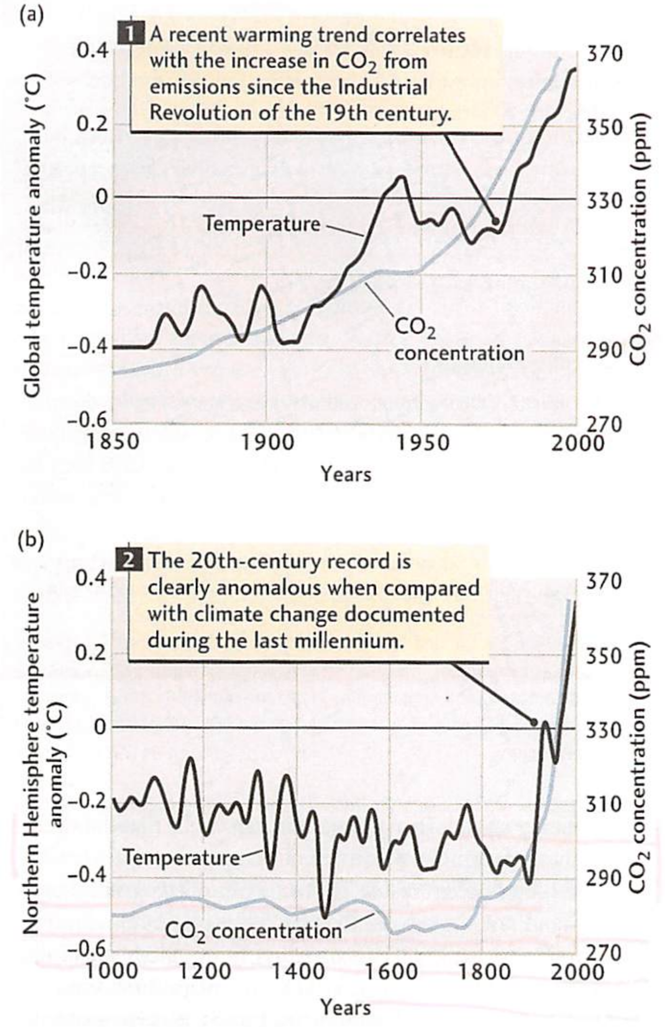

Figure 4. Change in average annual global surface temperature and carbon dioxide concentration since 1850 (a), changes in these same two properties, in the northern hemisphere since the year 1000. The most important point in these graphs is the exponential (very rapid) increase in these two properties since about 1850, the beginning of the industrial revolution. (IPCC, Climate Change 2001: The Scientific Basis.)

greater than at any time in the last 400,000 years (Fig. 4). Most experts now agree that this increase is largely caused by us, by our burning of the fossil fuels oil, coal, and natural gas. They also predict that it will increase the global average temperature by 1.4 to 5.8 degrees C (2.5 to 10 degrees F) by the end of this century. The 1.4 degree increase is twice that during the last century! The fact that the ten hottest years during the last 100 years were all in the last 15 years should not be too surprising. At this point few people are unaware that the arctic sea ice is melting so fast that it is expected to disappear before the end of the century, or that the warming of the oceans and atmosphere will increase the number and violence of wind and rain storms and hurricanes. Some of the low islands in the tropics are already threatened with inundation. Melting of the Greenland and Antarctic ice caps, as mentioned earlier, will wreak havoc as sea level rises 200 feet.

The Future and Us

The recent trend in climate research among earth scientists is to search the world and look for any geological process, whether it's the slow annual growth of stalactites and stalagmites in caves, thick sections of lake beds, large tuffa (calcite) mounds at hot springs—any rock that contains datable layers with climate proxies that sample the climate over a lengthy and continuous interval. Current emphasis is on equatorial and mid-latitude records, so we can compare that data with the polar records to know how extensive the climate changes are and how they vary with latitude. The more we know about the world's natural, pre-1800 climate changes, the better we can detect and understand the man-made changes. Climate scientists, for their part, are trying to incorporate all this new data into their computer models, so they can understand all the variables/factors that influence climate and their relative importance. Hopefully this will lead to more accurate and exact predictions of future climate changes.

Clearly, no one wants terrible climate changes to happen to us and our children/grandchildren. No scientists know at this point exactly how much the global temperature will increase as we continue to pour carbon dioxide into the atmosphere, and at what point our climate system may go through another RCCE, which could dwarf the effects in the section above. But, many people now realize that the price of doing nothing is most likely much greater than the price of reducing our carbon dioxide emissions. Many believe that we can reduce carbon dioxide levels to 1970 levels with current technology and reasonable efforts by a majority of people. Since most of our electricity, transportation, and other energy needs are met by burning fossil fuels, the world needs to become more efficient in these areas. Our national government has been negligent in this regard, but fortunately our state and many city governments are beginning to find ways of reducing energy use and encouraging recycling. The current average daily U.S. carbon dioxide emission is 122 pounds per person. The worldwide average is 'only' 24 pounds. Not surprisingly, the biggest single source of emissions for the average American is driving: 22 pounds of carbon dioxide per day. The second largest sources are air-conditioning and electric clothes dryers: 4 pounds per person per day. The average American lives very well, at least materially, compared to the average Viking on the coast of Greenland. When the Vikings died cold and hungry in their huts in 1400, the local Eskimos continued to live, because of their better adaptation to the environment and simpler lifestyle. This time even the Eskimos may not survive.

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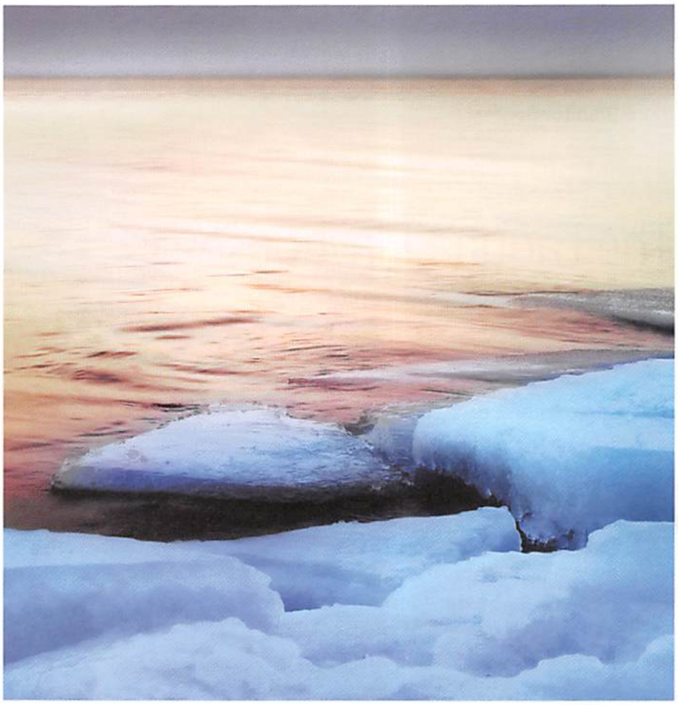

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Postlogue

The audience may well wonder if Lawrence, the character in David Rambo's *The Ice-Breaker,* had abandoned his career in earth science because he was ostracized from the scientific world for promoting theories that were considered too radical for the time, or because of personality conflict with his department chair/colleague, or largely because of his own personality. Was he like Alfred Wegener, the German Meteorologist who publicized continental drift—a theory that was anathema to most of the geologic and, especially, geophysical establishment prior to the discovery of plate tectonics in the sixties?

The current scientific culture, especially that of earth scientists, is much more open to radical ideas after living through/learning about the great turn-around in the sixties! As told by Mayewski and White (2002), the funding of the Greenland ice core project in 1988 involved such large amounts of money that it involved scientists at the highest levels of the National Science Foundation and high-level support of the federal government. So, at least by 1988 the earth science community realized the importance of getting more data on past climate changes. As an involved earth scientist since 1970, the author of this article knows of no "sacred" global climate theories. As mentioned above, earth scientists since 1968 have been pretty humble and open to new theories! As also mentioned above, the tremendous amount of new data that came out of the ice cores in the early nineties revolutionized our ideas about past climate changes almost as much as the flood of new data on sea floor magnetic anomalies revolutionized our thinking about continental drift in 1968!

Certainly, "personality conflicts" have led scientists to move from one university to another, but not to give up their work or ideas.

More likely, Lawrence, if he were real and worked for some federal science agencies, could well have run into 'doctrinal' problems. But any doctrinal hurdles to his research and its publication would have been political and involve big lobbies, like that of the oil and other energy companies. The author has read, both in the scientific and regular press, about assistants to President George W. Bush hobbling the dissemination of and radically editing the global climate reports of government scientists. The author would not be surprised to learn of such 'editing' during the previous Bush and Reagan administrations as well. Understandably, an honest and professional government scientist encountering such unscientific treatment might well have become so frustrated that he/she would abandon their work. But, as you will see in *The Ice-Breaker,* Lawrence's spirit is troubled by much more than that!

Dr. Monte Marshall: Ph.D., Stanford U., 1971. Researcher at the United States Geological Survey, Menlo Park, CA. 1971–1975, Professor at SDSU 1975–2004. Guest Professor, University of Rennes, France, 1985–1986; University of St. Petersburg, Russia, 1993: Charles University, Prague, Czech Republic, 1998. Research areas: History of the earth's magnetic field; using the past direction of the earth's magnetic field, as frozen in rocks, to help understand the plate tectonic history of Alta and Baja California; using the earth's present gravity and magnetic fields for locating and studying active faults in metropolitan San Diego and the Salton Sea area.

Recommended Reading

Press F., R. Siever, J. Grotzinger, and T. Jordan, 2003, *Understanding Earth,* 4th Edition, W.H. Freeman and Company, New York.

Tarbuck, E. and F. Lutgens, 2005, *Earth,* Eighth Edition, Pearson: Prentice Hall, New Jersey.

These two introductions to physical geology are the best written, best illustrated, and most accurate of beginning geology texts. They are highly recommended starts for any inquiry into earth science. Press et al. also has good references and web sites listed at the end of every chapter—like the chapters on glaciers and the earth's environment. They can be purchased for about $25 (used) and $50 (new) on amazon.com. Freeman has just come out with a 5th edition of "Understanding Earth," which has Grotzinger as the first author and may be slightly more costly.

Climate Change 2001: The Scientific Basis. Report of the Intergovernmental Panel on Climate Change. 2001. Cambridge University Press, Cambridge.

Alley, R., 2000, *The Two-Mile Time Machine,* Princeton University Press, Princeton, N.J. Written by one of the scientists involved in the Greenland core-hole project, this is an interesting and concise account of the scientific results.

Mayewski, P. and F. White, 2002, *The Ice Chronicles—The Quest to Understand Global Climate Change,* University Press of New England, Hanover, NH. Written by the Chief Scientist, Paul Mayewski, and noted writer Frank White, this book is an interesting account of the science, logistics, and mechanics of drilling the ice core on Greenland and a detailed account of the scientific results and their bearing on future climates.

Gore, Al, 2005, *An Inconvenient Truth,* Paramount Studios. Some may find this movie a bit too personal or political, but it is an excellent account of the science, economics, and politics of global warming. Scientifically accurate and full of very good graphics, he makes a very good case for our need to limit carbon dioxide emissions.

The Laguna Playhouse
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