WHAT DO OUR PROXIES RECORD?

PROXY	TEMP.	PRECIP.	ICE VOLUME
EQUIL. SNOWLINE ELEV.	X	(X)	
TREE RING THICKNESS	X	X	
^{18}O TO ^{16}O IN ICE	X		
^{18}O TO ^{16}O IN SHELL $CaCO_3$	X		X
^{18}O TO ^{16}O IN CAVE $CaCO_3$	X	X	
Mg TO Ca IN SHELL $CaCO_3$	X		

Sidebar #1

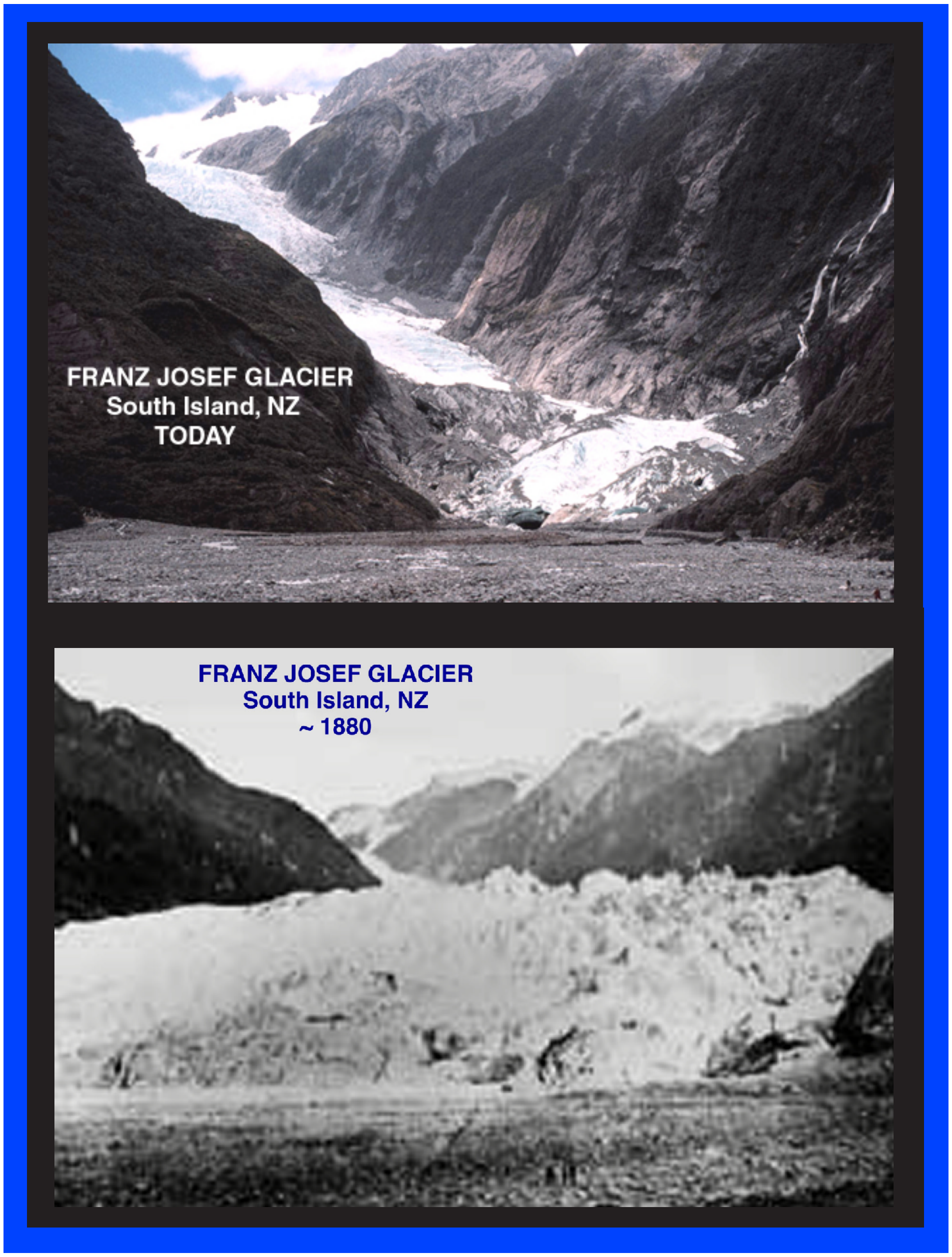

FRANZ JOSEF GLACIER
South Island, NZ
TODAY
FRANZ JOSEF GLACIER
South Island, NZ
~ 1880

Figure 12

go the colder it gets. Hence mountain tops are often so cold that even in the summer no melting occurs. The equilibrium snowline marks the boundary between the higher elevation portion of the glacier where, averaged over the whole year, accumulation of snow exceeds loss by melting. Below this boundary the opposite is true, melting exceeds accumulation.

It turns out that, as a rule of thumb, two thirds of a mountain glacier s surface lies above the equilibrium snowline and one third below it. This relationship turns out to be a handy one because it allows the equilibrium snowline for the glaciers which existed in the mid-1800s to be reconstructed. Based on geomorphic features created by these glaciers, it is possible to reconstruct their outlines. In the Swiss Alps, this has been done for hundreds of glaciers and the finding is that since 1850 the equilibrium snowline has risen about 100 meters. Based on the atmospheric lapse rate (i.e., the extent of cooling per 100-meter rise in elevation) this corresponds to a 0.6°C warming. After correction is made for the increases in snowfall which has accompanied this warming, the magnitude of the warming (~0.8°C) recorded by the Alpine glaciers agrees quite well with the extent of warming directly measured with thermometers.

In most parts of the world only the maximum in glacial extent of the mid-1800s is well documented. However, in the Swiss Alps, paintings and historical accounts document a second maximum in the 1600s (see Figure 13). An even earlier event in the 1300s is recorded by the stumps of trees knocked over by advancing ice. Taken together, these three periods when glaciers achieved a size comparable to that in 1850 are known as the Little Ice Age (see Figure 14). In Iceland a very long record has been kept of the number of months during each year when sea ice prevented the operation of the fishing

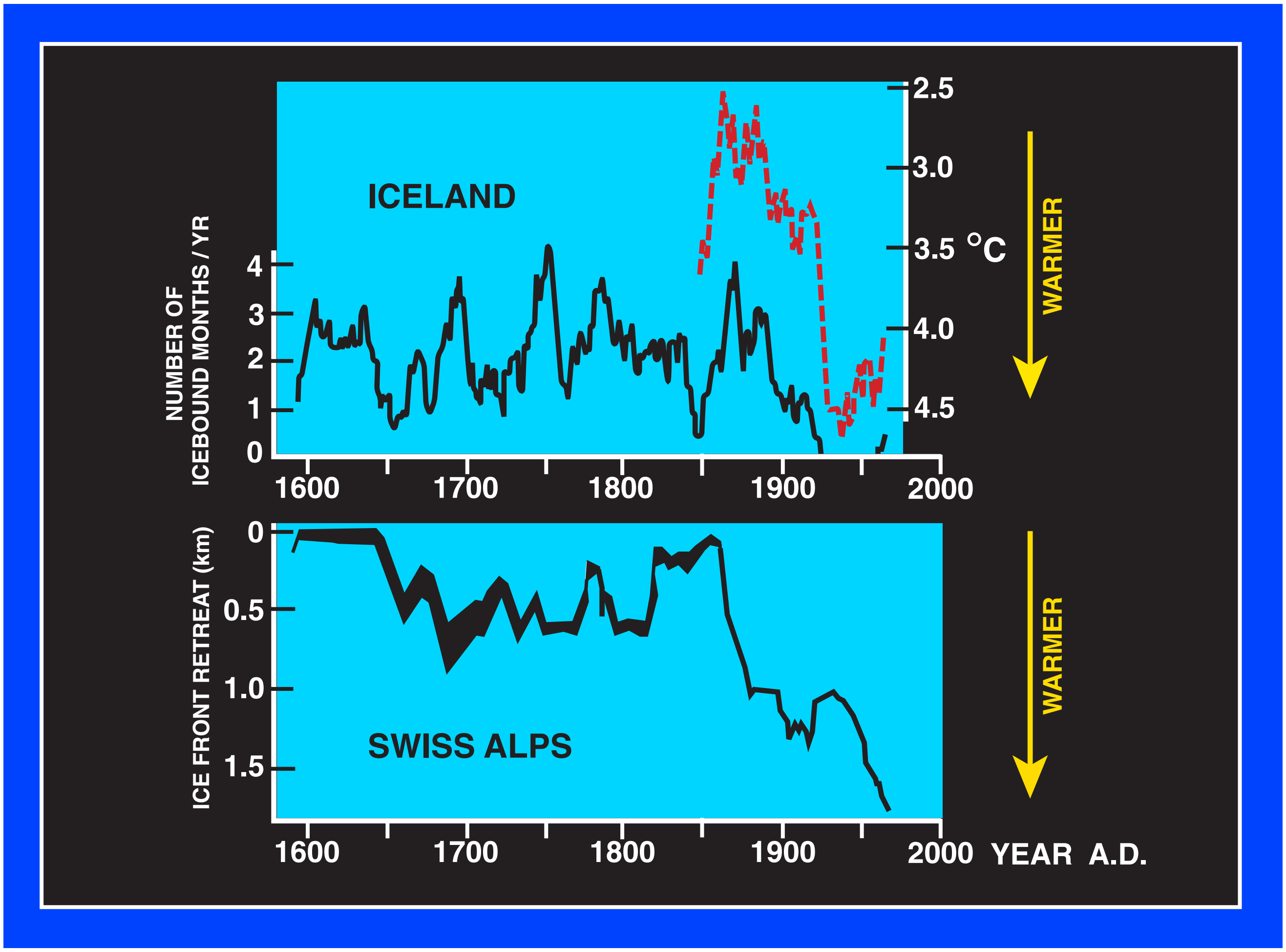

ICELAND
NUMBER OF ICEBOUND MONTHS / YR
0
1
2
3
4
2.5
3.0
3.5 °C
4.0
4.5
WARMER
1600
1700
1800
1900
2000
SWISS ALPS
ICE FRONT RETREAT (km)
0
0.5
1.0
1.5
WARMER
1600
1700
1800
1900
2000 YEAR A.D.

Figure 13

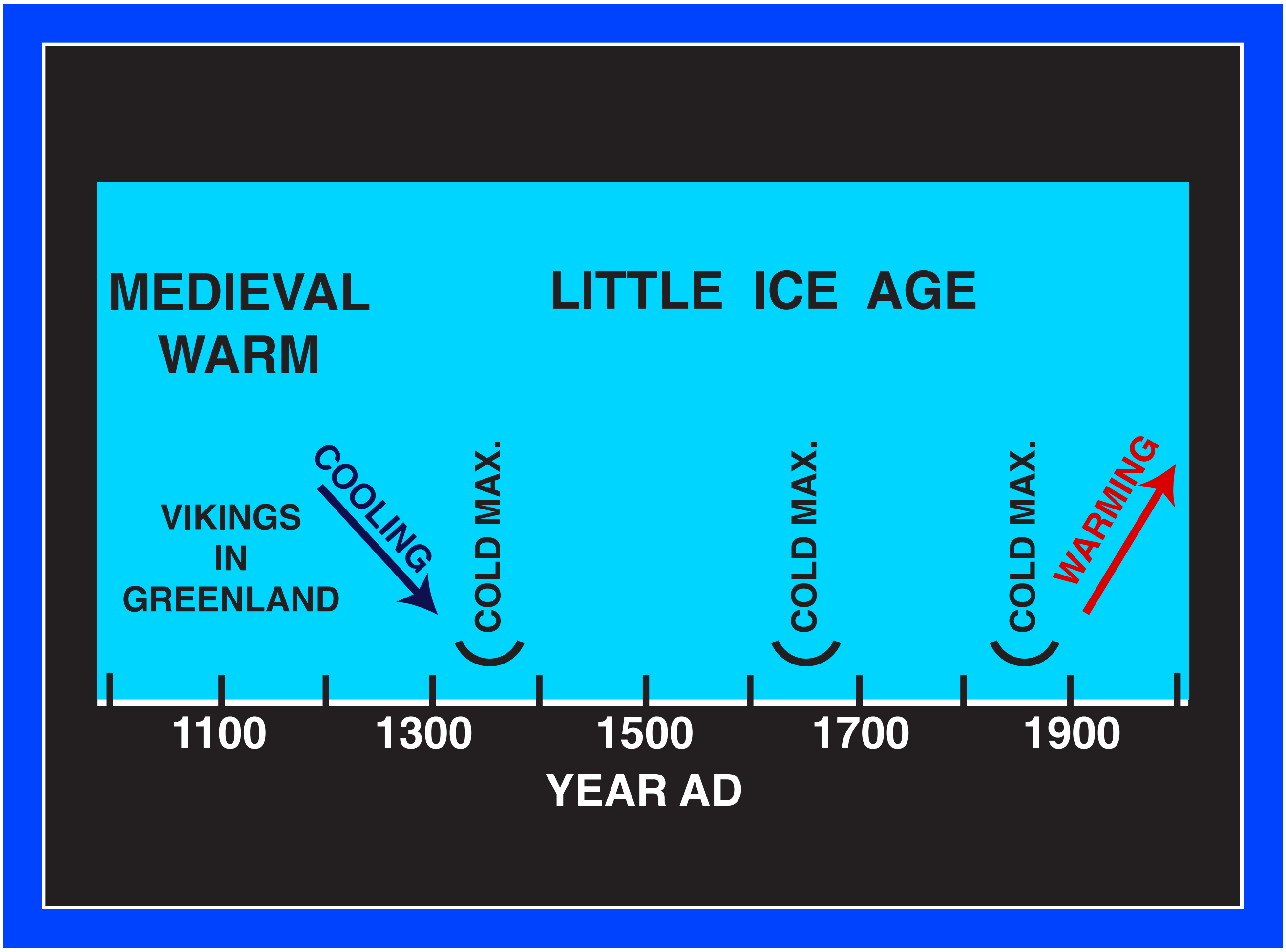

MEDIEVAL WARM
LITTLE ICE AGE
VIKINGS IN GREENLAND
COOLING
COLD MAX.
COLD MAX.
COLD MAX.
WARMING
1100
1300
1500
1700
1900
YEAR AD

Figure 14

fleet. It provides a basis for extending back in time the instrumental record of mean annual air temperature initiated in 1850 (red curve in Figure 13).

The Medieval Warm Period

We all learned in our childhood that Eric the Red led his band of Vikings to Greenland where they established a colony. It lasted several hundred years and achieved a maximum population of roughly 5000. Initially the Viking s diet was 80 percent mutton supplemented by 20 percent seafood. As time went on, the summers appear to have shortened and ever less grass was available to feed their sheep. In order to compensate, seafood became an ever more important part of the Viking diet reaching as much as 80 percent. This shift in food source is recorded by the ratio of heavy carbon (^{13}C) to light carbon (^{12}C) in Viking bones. In the early 1300s the colony disappeared. Archeologists have uncovered evidence that in desperation the starving colonists were forced to eat their dogs.

The Viking saga has led to the idea that the Little Ice Age was preceded by a warmer time. Less ice existed in the northern Atlantic thus facilitating passage for the Vikings ships. Summers were warmer and longer allowing grass to flourish in the ice-free valleys of southern Greenland. However, as with the snouts of glaciers, this gives us only a qualitative picture of climate. We need a means to quantify this warming. Glaciers would be great but while it is possible to map their perimeters when they were larger than now, it is not possible to do so if the boundaries have been obliterated by a subsequent advance.

One way to do this is through measurements of the thickness of tree rings. At high altitude (or at high latitudes), tree growth is very sensitive to temperature. This is why mountain tops are often treeless. The winters are too cold. The same is true on the lands surrounding the Arctic. Beyond the northern tree line, the landscape is free of trees. It s too cold for them to survive.

By comparing the records of ring thickness with records of air temperature, it has been shown that for trees growing near their northern limit, the colder the air temperature, the thinner the annual ring. When the ring thicknesses for many, many trees are averaged for any given year, the correlation becomes reasonably good, thus providing a paleotemperature proxy.

Jon Esper, a young dendrochronologist (i.e., tree-ring scientist), put together ring-thickness records for 1800 temperature-sensitive trees from Siberia, Scandinavia and Canada. As shown in Figure 15, his conclusion from this record is that there was indeed an extended period of warmth a millennium ago. Further, temperatures during this interval were comparable to those for the last decade. This record also documents that during the Little Ice Age temperatures were as much as 1°C colder than during the Medieval Warm. This result is, of course, music to the ears of the detractors. They would like to believe that the present warmth is just a repeat of that which occurred 1000 years ago. But wait! The plot will thicken.

Whereas I would like to think that the Medieval Warm Period was global in extent, as our proxies are not up to the task, we don t know whether or not this is the case. However, as the last of the three Little Ice Age cold maxima (i.e., that at 1850 AD) has been shown to be global, it is my opinion that the Medieval Warm Period will prove to be as well.

In one region, i.e., California s Sierra Nevada mountains, the impacts of the Medieval Warm are spectacular. Scott Stine, a professor at the University of California, Hayward, has documented that a profound drought lasting almost 200 years hit that

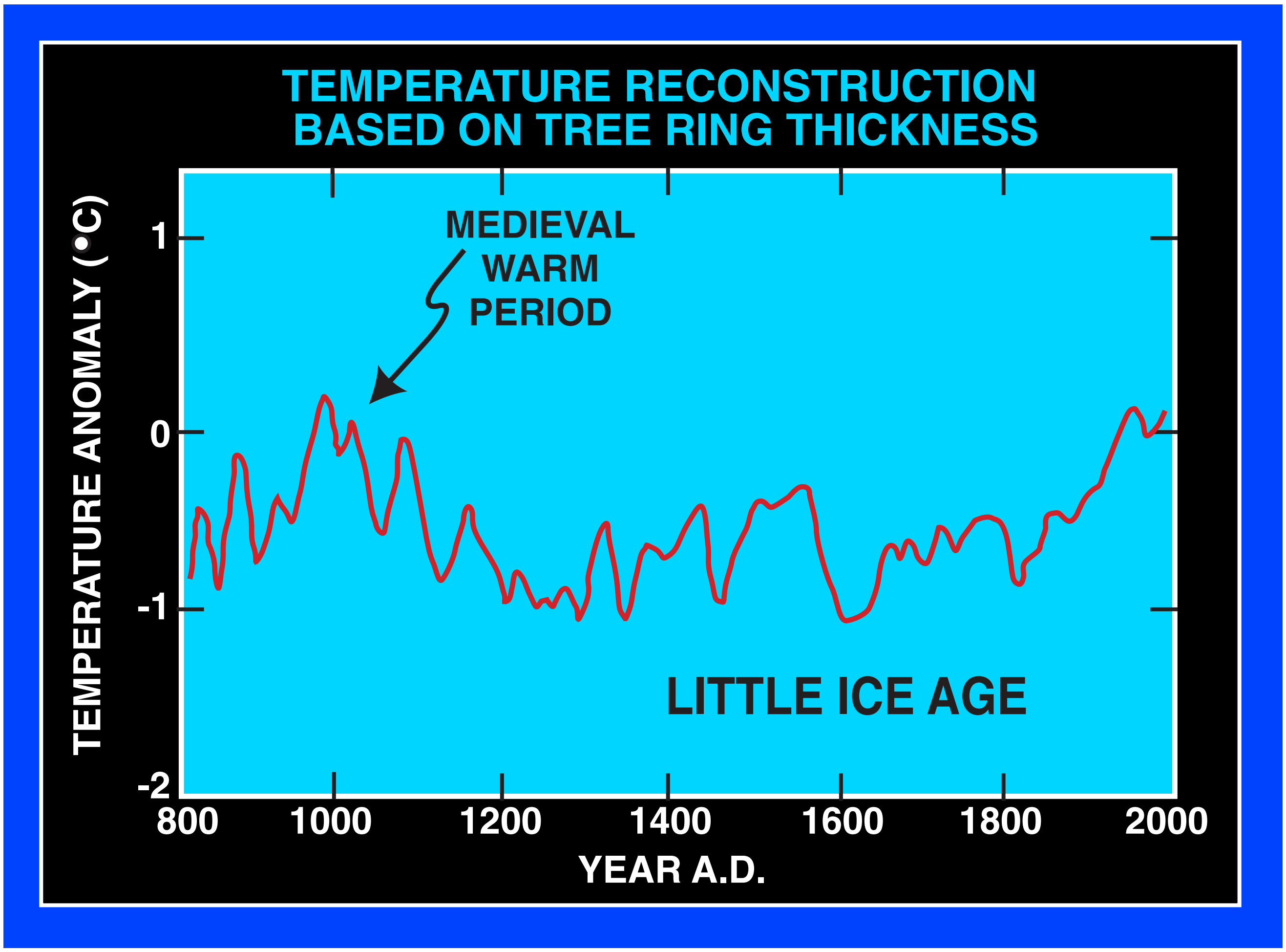

TEMPERATURE RECONSTRUCTION
BASED ON TREE RING THICKNESS
MEDIEVAL
WARM
PERIOD
LITTLE ICE AGE
TEMPERATURE ANOMALY (•C)
1
0
-1
-2
800
1000
1200
1400
1600
1800
2000
YEAR A.D.

Figure 15

region late in the Medieval Warm Period. At four separate sites, he found dead trees in growth position in places which are currently flooded with water. One set of these trees grew on the bottom of what is now high-Sierra Lake Tenaya. As this lake is 30 meters deep and has overflowed during all but one late spring melt period during the last century, for trees with 180 annual rings to have grown on the lake bed bears witness to an intense drought of long duration. A similar set of stumps appears in the channel of the West Walker River which heads in the high Sierra (see Figure 16). During the 100 or so years these trees grew, the river must have been largely dry. Similarly, woody plants of the same age are found growing from the bottom of Mono Lake which, until the streams feeding it were diverted into the Los Angeles water supply, was fed by streams draining the adjacent Sierra Nevada. During late Medieval Warm time, the level of this salty desert lake must have been at an all time low. This drought episode suggests that relatively small regional climate changes can have profound impacts on regional water availability, especially in semi-arid zones.

Extending the record back in time

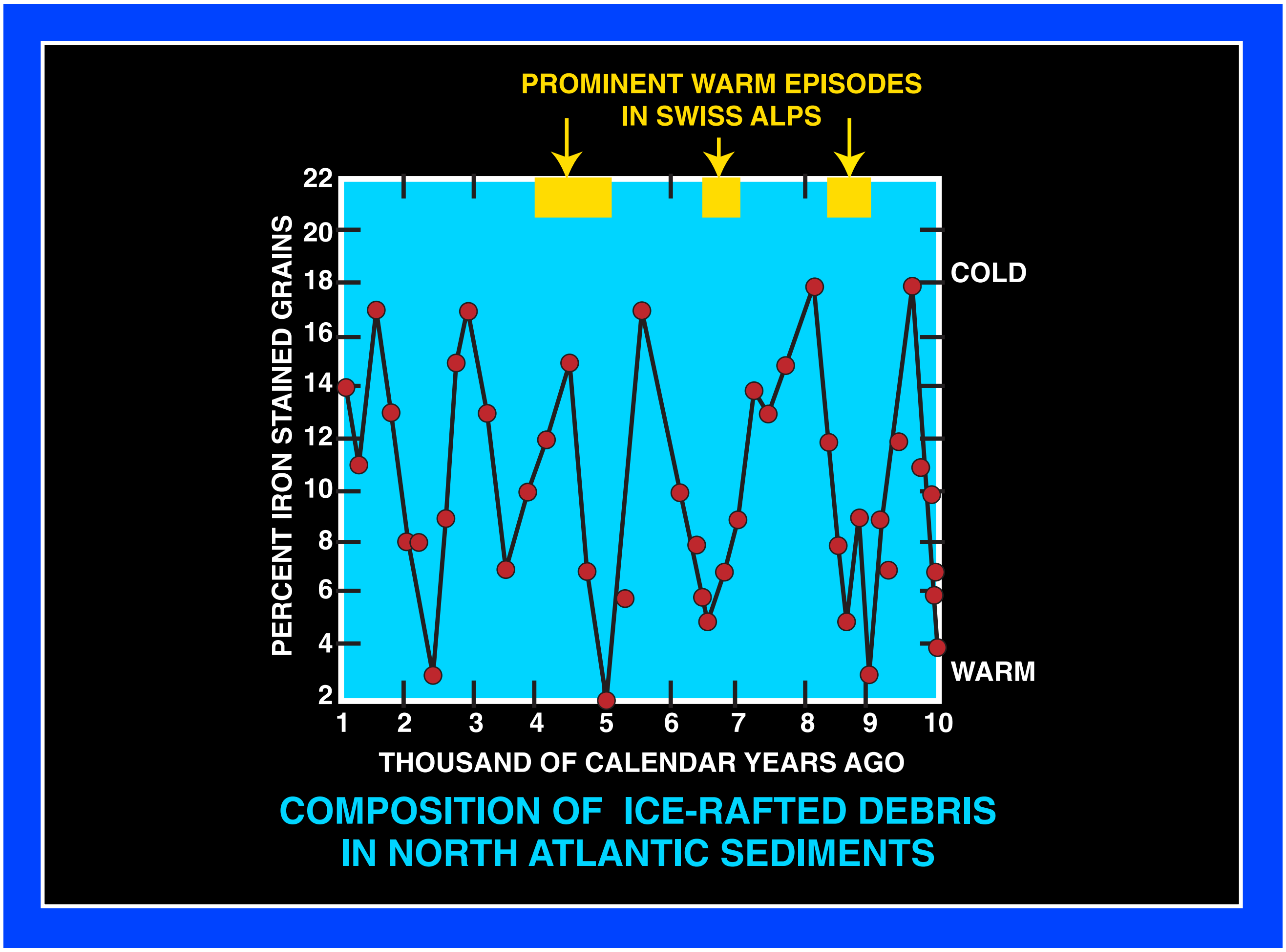
Having documented that during the Medieval Warm thermal maximum, the Earth was perhaps 1°C warmer than during the Little Ice Age, the question naturally comes to mind as to whether similar swings have characterized the last 12,000 years of warm and fairly stable climate. Gerard Bond, a scientist at Columbia s Lamont-Doherty Earth Observatory, made a startling discovery. Bond made his entry into marine geology by studying the distribution in deep-sea sediments of rock fragments carried southward in the northern Atlantic imbedded in the abundant floating ice of glacial time. Upon melting, this ice dropped its debris to the sea floor thereby creating a record of iceberg activity. At one point, Bond decided to extend his study from times of glaciation to the

West Walker River, California (recent photo)
Trees which grew during the Medieval Mega-Drought

Figure 16

last 12,000 years when ice was relatively scarce. In each sediment sample, he not only noted the abundance and average size of the rock fragments, he also looked for grains which might tell him where the ice had picked up its debris. In particular, he noted that some of the grains had a red hematite stain while others did not. Further, he was struck by a curious cycle in the abundance of these grains. As shown in Figure 17, it swung back and forth from a low of a few percent of the total grains to a high ranging from 15 to 20 percent of the total grains. By obtaining radiocarbon ages (see Sidebar #2) on shell material from various depths in these cores, Bond was able to place a time scale on this record. Note that in this and all the other geological records to be shown, time increases from left to right rather than from right to left as was the case for the historical and tree-ring records. The duration of a single cycle averages about 1500 years. Based on the geologic distribution of hematite-coated sandstones and on the composition of grains caught in sediment traps deployed beneath the ice-clogged water which flows southward along Greenland s east coast, Bond convinced himself that the source was ice which formed in the coastal waters of Canada s northern archipelago. He reasons that layers in the sediment rich in red-coated grains correspond to times when the northern reaches of the Atlantic were colder than today, thus allowing the ice bearing these grains to survive long enough to reach the sites of his sediment cores before melting. In other cores Bond was able to show that the most recent of these red-grain rich zones correspond to the Little Ice Age.

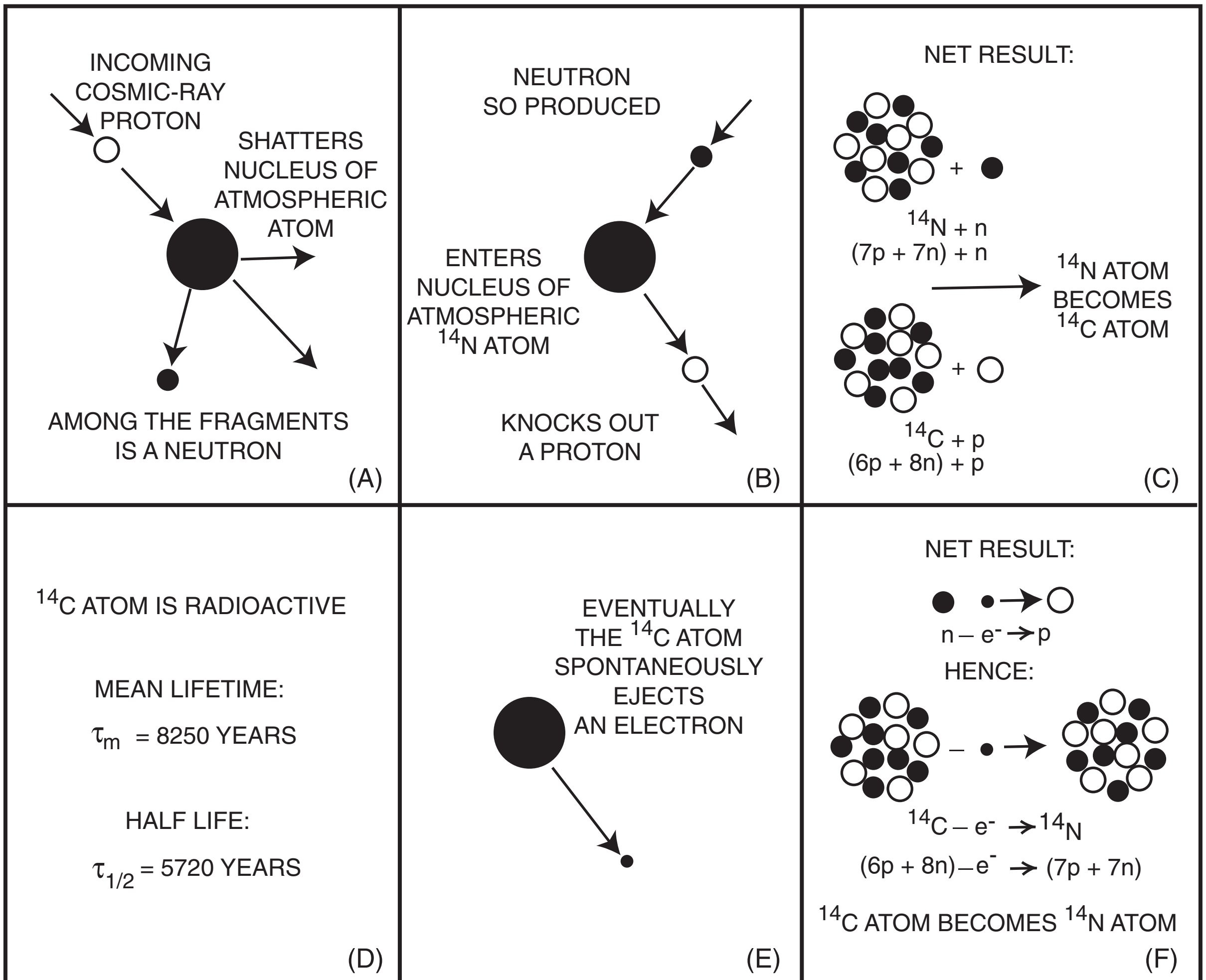
Evidence that Bond s red-grain cycles were indeed related to temperature swings was obtained by radiocarbon dating pieces of wood and peat swept out from under the snouts of glaciers in the Swiss Alps during periods of summer melting. As the forests in which these trees grew and the bogs in which the peat formed are now covered by ice,



PROMINENT WARM EPISODES
IN SWISS ALPS
PERCENT IRON STAINED GRAINS
22
20
18
16
14
12
10
8
6
4
2
COLD
WARM
1
2
3
4
5
6
7
8
9
10
THOUSAND OF CALENDAR YEARS AGO
COMPOSITION OF ICE-RAFTED DEBRIS
IN NORTH ATLANTIC SEDIMENTS

Figure 17

THE LIFE CYCLE OF RADIOCARBON ATOMS



$$\text{RADIOCARBON AGE} = 8250 \ln \frac{{}^{14}C/C)_{1850}}{{}^{14}C/C_{SAMPLE}}$$

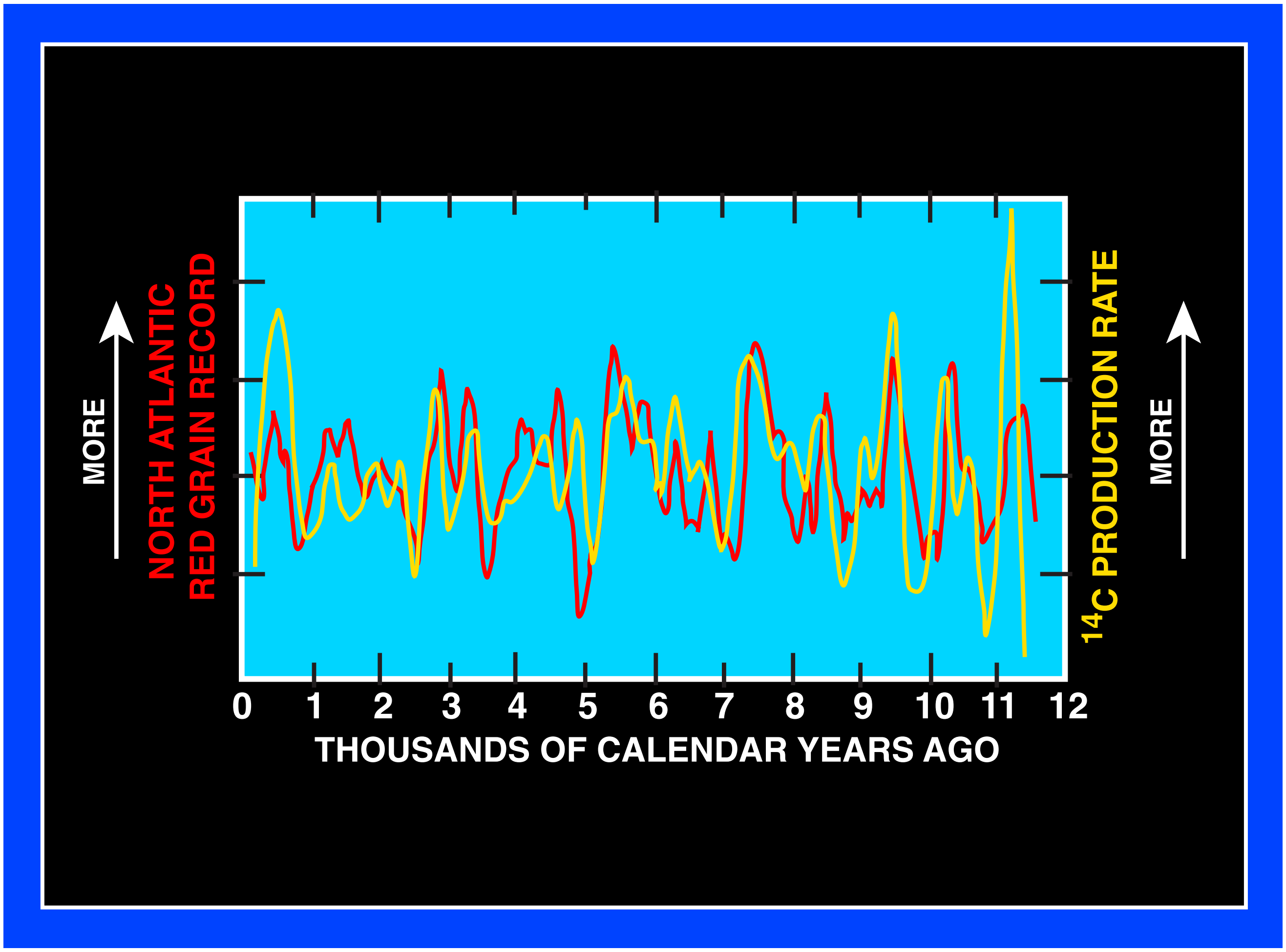
Sidebar #2

they represent times when the glaciers were even smaller than they are today. Radiocarbon dating of dozens of these samples reveal that, for the most part, they formed during periods when red grains were rare (i.e., warm times in the northern Atlantic).

Are the 1500-year cycles driven by the Sun?

Bond s great discovery came when he compared his red-grain record with reconstructions of the rates of production of two so-called cosmogenic isotopes, ^{14}C and ^{10}Be, over the last 12,000 years (see Figure 18). The radiocarbon reconstruction is based on measurements of the ^{14}C to C ratio in wood samples whose calendar age has been determined by annual ring counting. The ^{10}Be reconstruction is based on measurements on samples of Greenland ice whose age has also been determined by annual layer counting. These two radioisotopes are produced by the cosmic ray bombardment of our atmosphere (see Sidebar #3). He found a strong similarity between the red-grain and bombardment records. During the warm part of each of his cycles, the rates of production of these isotopes was lower than average and during the cold parts, they were higher than average. As the production rates of ^{14}C and ^{10}Be in our atmosphere are modulated by the magnetic field generated by ions streaming out from the Sun, this raised the possibility that the cycles in temperature were being driven by the Sun.

The argument runs as follows. As first discovered by Galileo, the Sun s surface is marred by dark spots. These spots come and go following an 11-year cycle (see Figure 19). Electrically charged atoms (i.e., ions) are launched into space from these spots. They generate a magnetic field which acts as a shield against cosmic ray protons headed toward our solar system from the remote regions of the galaxy. The more dark spots, the more ions streaming out from the Sun, the stronger the magnetic shield and hence the fewer ^{14}C and ^{10}Be atoms produced in our atmosphere. Small changes in the production

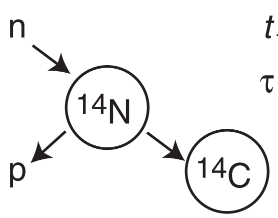


MORE
NORTH ATLANTIC
RED GRAIN RECORD
^{14}C PRODUCTION RATE
MORE
0
1
2
3
4
5
6
7
8
9
10
11
12
THOUSANDS OF CALENDAR YEARS AGO

Figure 18

COSMOGENIC ISOTOPES

^{14}C PRODUCTION



$t_{1/2}$ = 5720 YEARS

τ_{MEAN} = 8250 YEARS

COMBINES WITH 2 OXYGEN ATOMS TO FORM A CO_2 MOLECULE WHICH IN TURN JOINS THE EARTH'S CARBON CYCLE

^{14}C RECORD

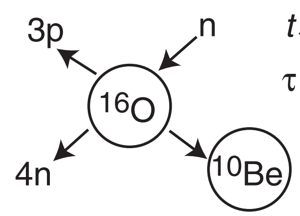
DENDROCHRONOLOGICALLY DATED TREES (BACK TO 12,000 YEARS AGO)

AGE OF TREE RING

$$\left.\frac{^{14}C}{C}\right)_{\text{AT GROWTH}} = \left.\frac{^{14}C}{C}\right)_{\text{MEASURED}} e^{\frac{t}{8250}}$$

MEANLIFE RADIOCARBON

^{10}Be PRODUCTION



$t_{1/2}$ = 1.6 MILLION YEARS

τ_{MEAN} = 2.3 MILLION YEARS

GOBBLED UP BY AEROSOLS WHICH IN TURN GET CARRIED TO THE EARTH'S SURFACE IN RAINDROPS OR SNOWFLAKES

^{10}Be RECORD

^{10}BE CONCENTRATION IN GREENLAND ICE (BACK TO 12000 YEARS AGO)

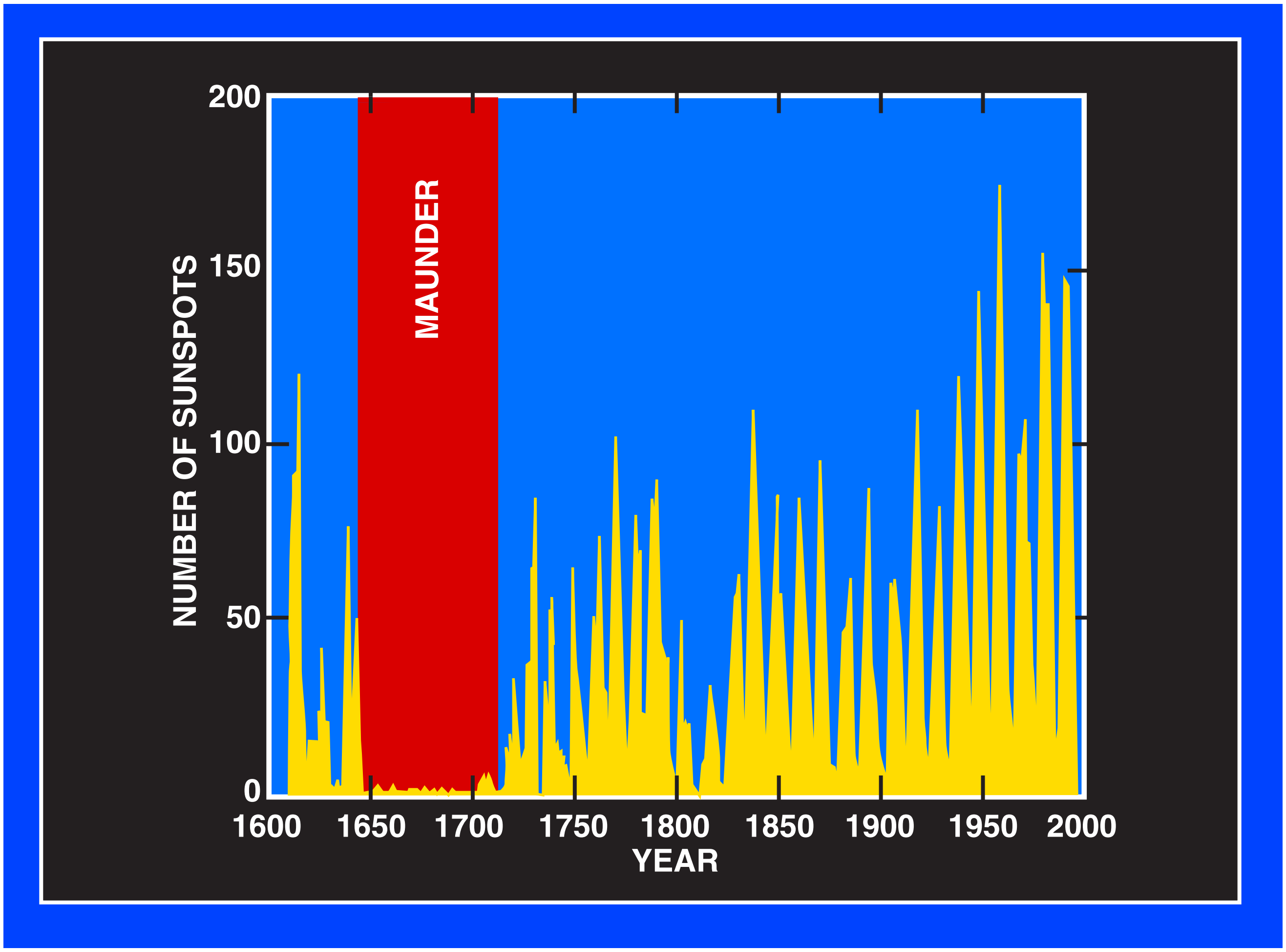
NO CORRECTION FOR LOSS BY RADIOACTIVE DECAY NECESSARY

n *STANDS FOR NEUTRON*

p *STANDS FOR PROTON*

^{14}N, ^{14}C, ^{16}O, *AND* ^{10}Be *ARE ATOM NUCLEII*

Sidebar #3



MAUNDER
NUMBER OF SUNSPOTS
200
150
100
50
0
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR

Figure 19

of both ^{10}Be and ^{14}C have been shown to occur on an 11-year time scale (less production during sunspot maxima).

Our interest here is primarily with a 1500-year cycle rather than the known 11-year sunspot cycle. Key are extended periods when few spots are present. One such period called the Maunder Minimum (see Figure 19) began in 1645 AD, some 35 years after Galileo first documented the existence of spots on the Sun. It lasted for 70 years (until 1715 AD). During this period the increase in the production rates of both ^{14}C and ^{10}Be was even larger than that during the sunspot minima associated with the 11-year cycle. While the Maunder Minimum is the only such sunspot-free period observed using telescopes, based on the records of the production rates of cosmic ray-produced isotopes, similar intervals have occurred many times over the past 12,000 years. More interesting, their spacing is not regular. They were more frequent during the times of Bond s cold intervals than during his warm intervals. This leads us to believe that the cool periods reflected in Bond s red-grain record were extended periods of low sunspot numbers akin to the Maunder Minimum. Hence, it is the solar irradiance during these spot-free intervals which are probably of importance to climate.

Extremely accurate measurements of the Sun s luminosity have been made from satellites for the past two decades. This record now covers two eleven-year sunspot cycles (see Figure 20). The results show that solar irradiance reaching the upper atmosphere is slightly greater (i.e., one part in 1300) during periods of high sunspot number than during those of low. While it is tempting to conclude that the Sun s energy output was even lower during intervals similar to the Maunder Minimum than during the recent sunspot minima documented by satellites, no convincing way of determining

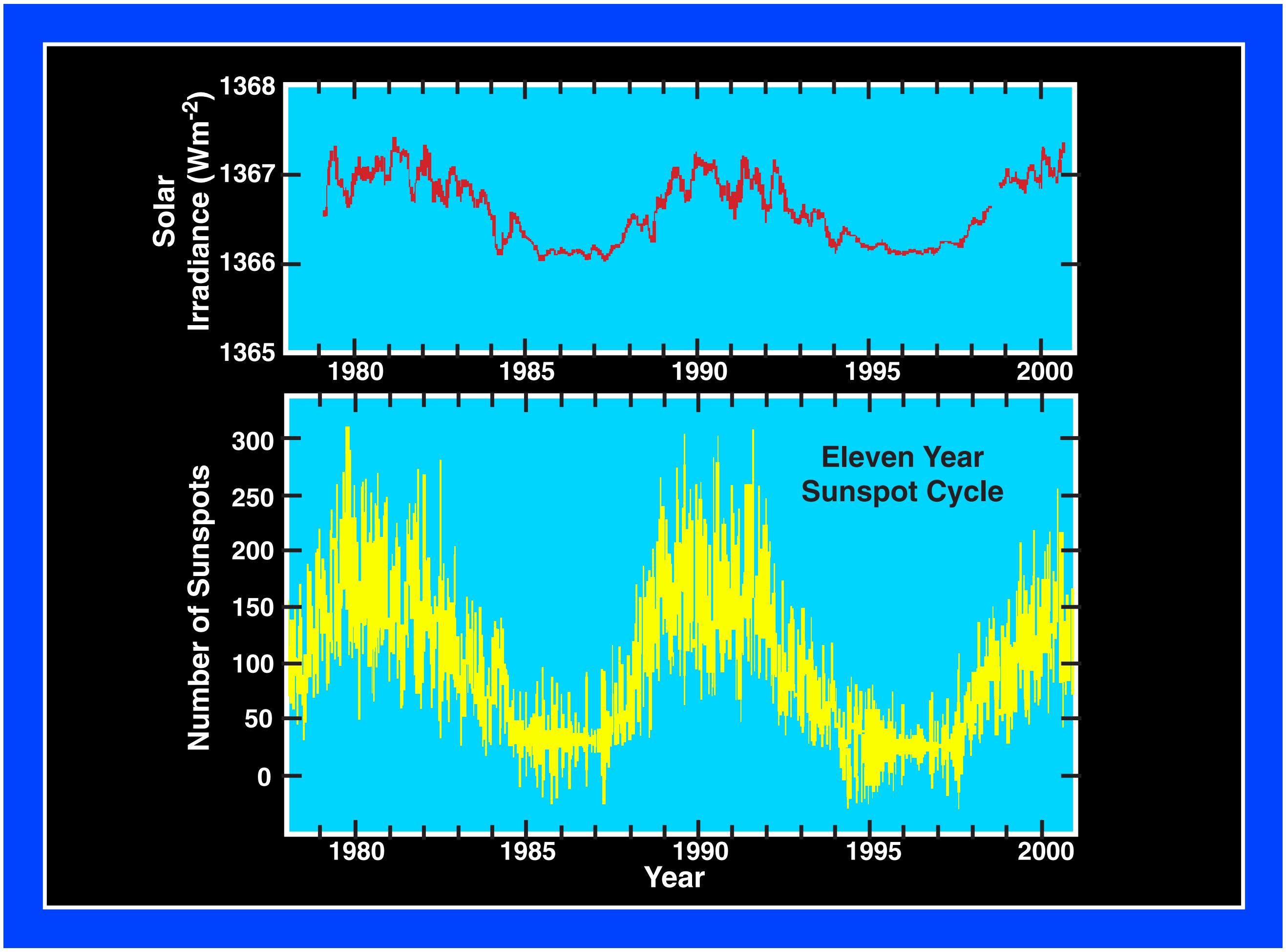

Solar Irradiance (Wm^{-2})
1368
1367
1366
1365
1980
1985
1990
1995
2000
Number of Sunspots
300
250
200
150
100
50
0
Eleven Year Sunspot Cycle
1980
1985
1990
1995
2000
Year

Figure 20

whether this is the case has been discovered. But no one has proposed that these changes were large enough to rival the impact of tripled CO_2.

Having established the correlations between 1) Earth temperature and cosmic ray bombardment, 2) cosmic ray bombardment and sunspot number, and 3) sunspot number and solar irradiance, a case can be made that changes in solar irradiance have driven significant Earth temperature changes over the last 12,000 years.

Correlations are one thing; causation is another. No one has been able to come up with a convincing explanation as to why these very small changes in the Sun s irradiance should have had any effect on Earth climate. This is only one of a number of indications that Earth s climate system responds strongly to seemingly weak nudges. The change in irradiance from sunspot maxima to sunspot minima recorded by satellites is only one part in 1300. By comparison, model simulations suggest that the climate impact of tripled CO_2 is 20 to 30 times larger than that associated with the 11-year sunspot cycle.

Lecture #2

The angry beast

During the last 12,000 years climate has have been remarkably quiescent. It is toward the beginning of this interval that modern human civilization was launched. The first steps appear to have taken place in the Middle East where a transition occurred from hunting and gathering to agriculture and animal husbandry. This transition was plausibly triggered by the shift from a glacial to an interglacial climate that followed a long series of large and abrupt reorganizations of the climate system which characterized glacial time. But before we delve into these reorganizations, we must place them in context.

About 750,000 years ago for reasons we don t yet understand, Earth s climate system switched to a regime characterized by large asymmetric saw-toothed cycles. Each of these cycles involved a bumpy 100,000-year duration decline from peak warm conditions (interglacial) to peak cold conditions (full glacial). At the time of each full glacial a large ice cap covered nearly all of what is now Canada. As shown in Figure 21, smaller ice caps were also present in the southern Andes and New Zealand s South Island. The difference between the extent of ice cover in the Northern and Southern Hemispheres relates to the asymmetry in availability of high latitude land masses rather than asymmetry in climate between the hemispheres. This is made clear by the north-south similarity in the extent of the glacial lowering of snowlines along the America Cordillera (see Figure 22). In both hemispheres, the equilibrium snowlines descended by close to 940 meters. Surface temperatures in the equatorial oceans were 3°C lower than now. Ten times more soil dust and sea salt were transported through the atmosphere. The atmosphere s CO_2 content was only two thirds that during the time preceding the Industrial Revolution (i.e., 200 parts per million). Each of these episodes of glaciation was terminated by an abrupt warming which returned the Earth to full interglacial conditions.

We know about these glacial/interglacial cycles because they are beautifully recorded in sediments from the deep sea (see Figure 23) and in ice from Antarctica (see Figure 24). In both the deep sea records and in Antarctic ice, the key proxy is the ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O). Although these two isotopes of the element oxygen have identical electron clouds and hence undergo the same chemical reactions, the extra weight provided by ^{18}O s two extra neutrons gives rise to a small difference in behavior. For example, a water molecule made with ^{18}O has a one percent lower vapor pressure than water made with ^{16}O (see Figure 25). This difference is the basis for the proxy which allows past temperatures on the Antarctic ice cap to be reconstructed.

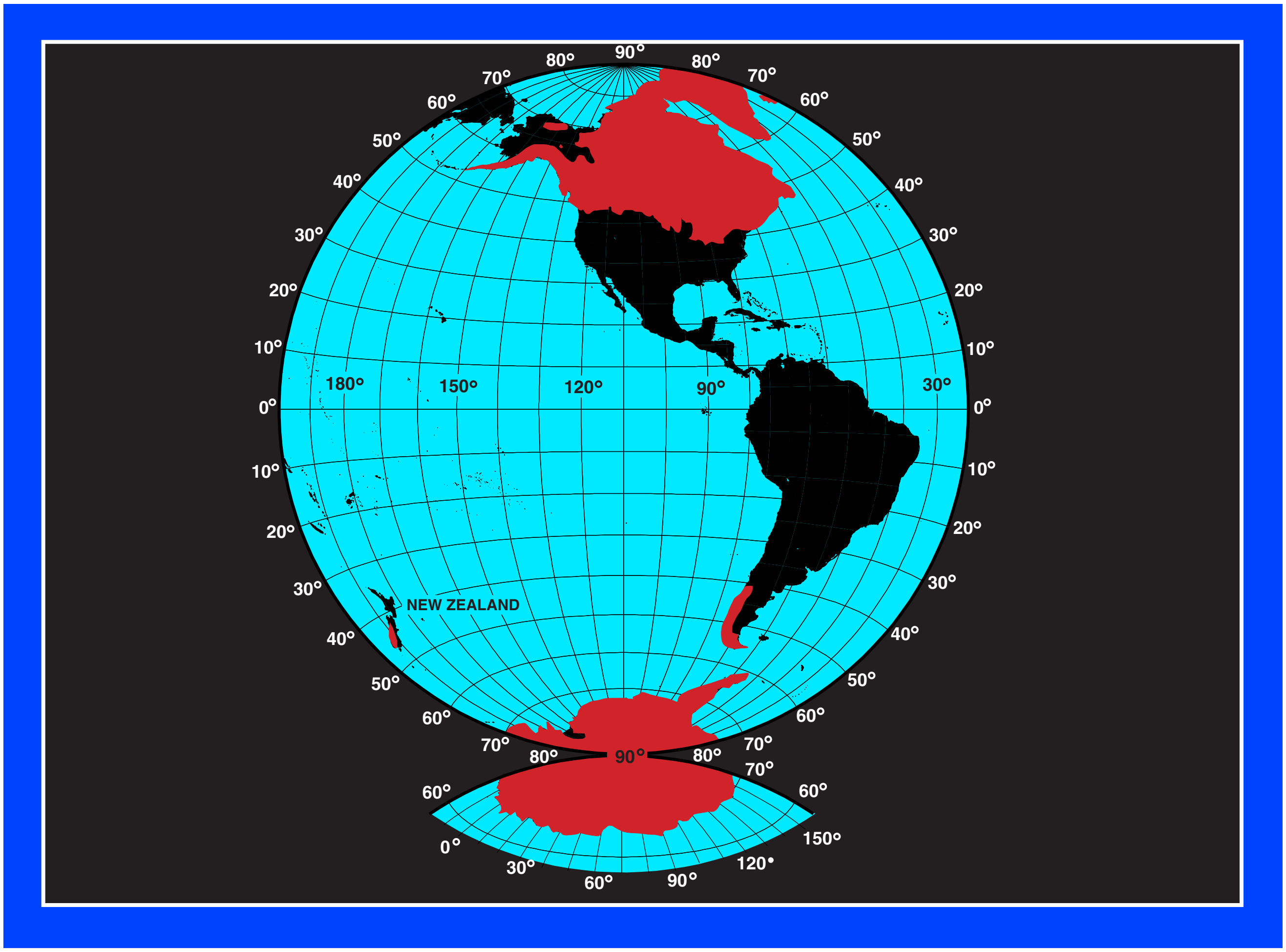
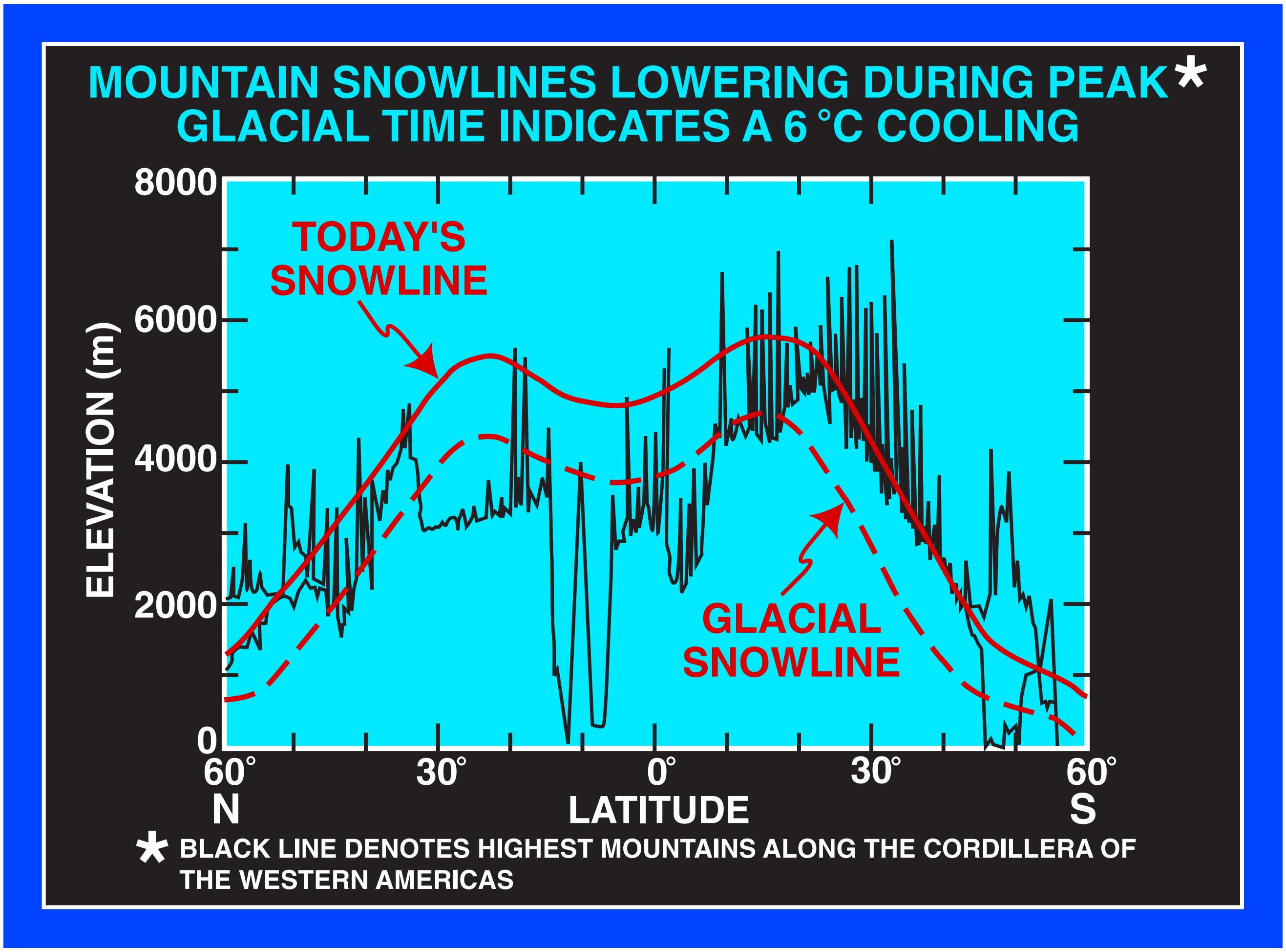
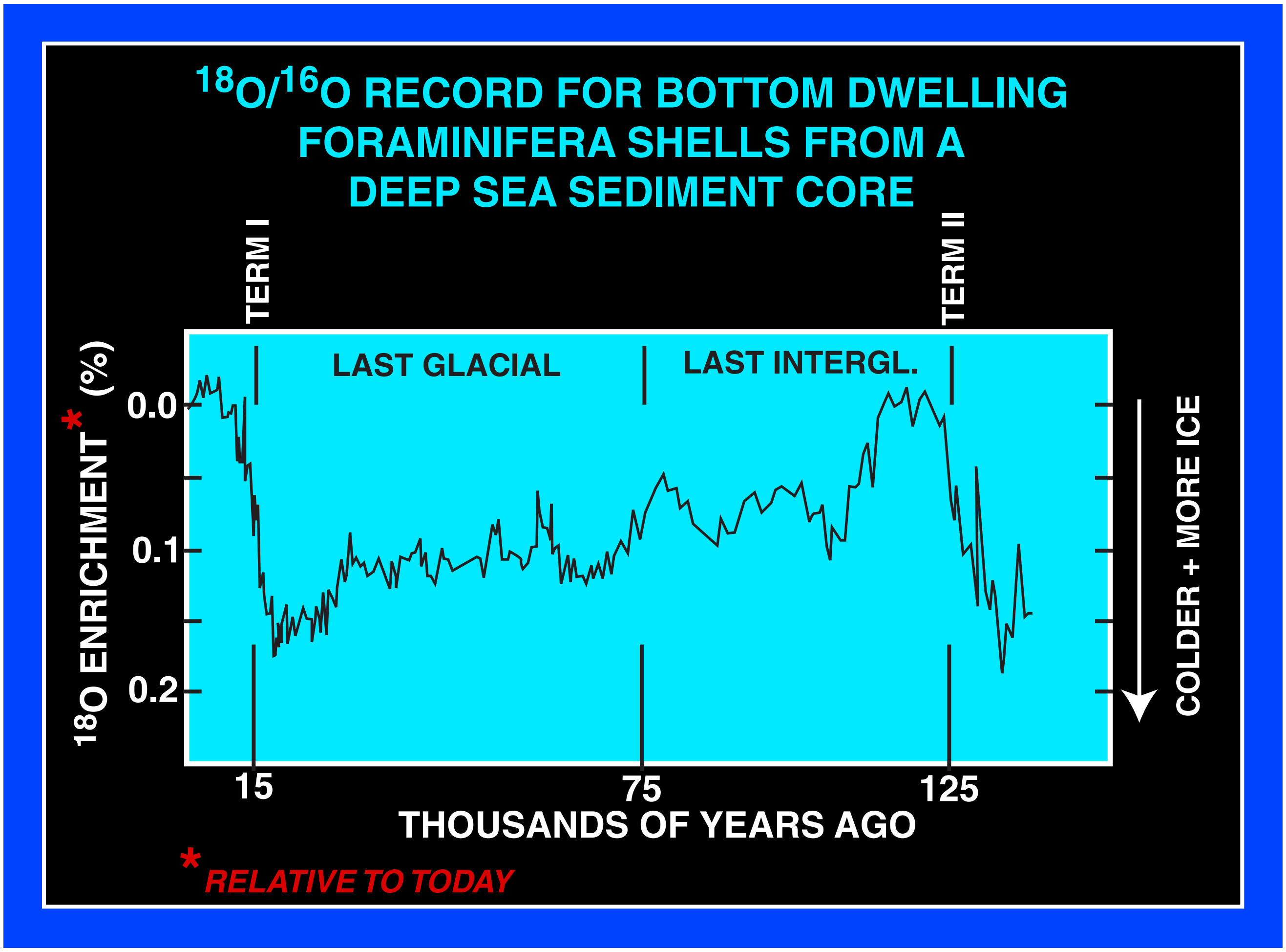


Figure 21



MOUNTAIN SNOWLINES LOWERING DURING PEAK*
GLACIAL TIME INDICATES A 6°C COOLING
ELEVATION (m)
8000
6000
4000
2000
0
TODAY'S
SNOWLINE
GLACIAL
SNOWLINE
60°
N
30°
0°
30°
60°
S
LATITUDE
* BLACK LINE DENOTES HIGHEST MOUNTAINS ALONG THE CORDILLERA OF
THE WESTERN AMERICAS

Figure 22



$^{18}O/^{16}O$ RECORD FOR BOTTOM DWELLING FORAMINIFERA SHELLS FROM A DEEP SEA SEDIMENT CORE
TERM I
TERM II
LAST GLACIAL
LAST INTERGL.
^{18}O ENRICHMENT* (%)
0.0
0.1
0.2
15
75
125
THOUSANDS OF YEARS AGO
COLDER + MORE ICE
*RELATIVE TO TODAY

Figure 23

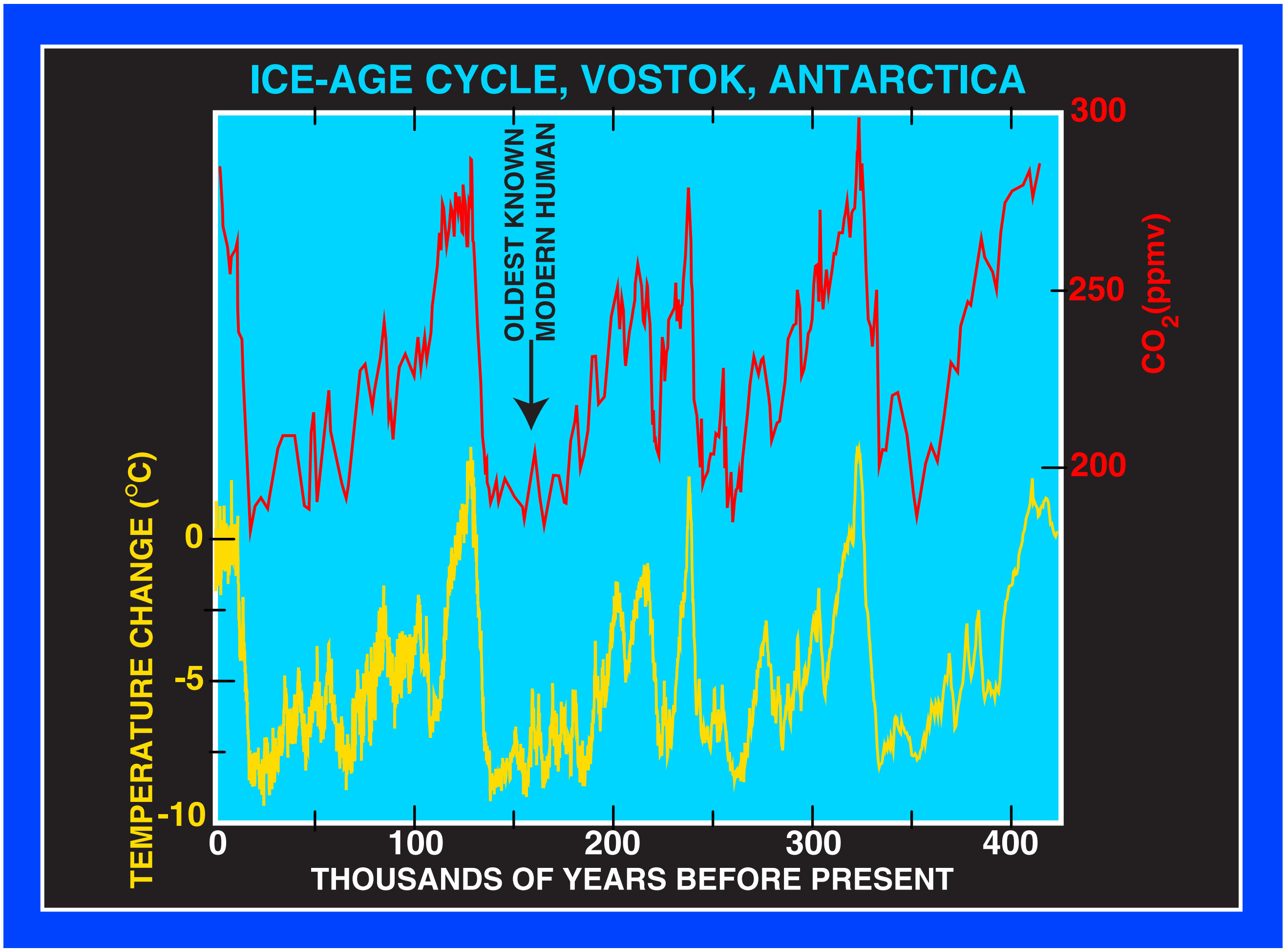

ICE-AGE CYCLE, VOSTOK, ANTARCTICA
OLDEST KNOWN MODERN HUMAN
TEMPERATURE CHANGE (°C)
0
-5
-10
300
250
200
CO2 (ppmv)
0
100
200
300
400
THOUSANDS OF YEARS BEFORE PRESENT

Figure 24