Because of the difference in vapor pressure, the water evaporating from the surface ocean has a one percent lower ^{18}O to ^{16}O ratio than sea water itself. As the air mass containing this water vapor is cooled as it moves poleward, precipitation occurs. Because of the vapor pressure difference, the ^{18}O to ^{16}O ratio in the precipitation is one percent greater than that in the cloud water vapor. So, the first rain to fall has an isotopic composition identical to that for sea water (i.e., the ^{18}O enrichment during condensation cancels the depletion during evaporation). However, the removal of this ^{18}O-enriched rain lowers the ^{18}O to ^{16}O ratio in the remaining cloud water vapor. Hence, the next rain to form will have an ^{18}O to ^{16}O ratio lower than that in sea water (see Figure 26). Each succeeding precipitation event will further decrease the ^{18}O to ^{16}O ratio in the residual water vapor. As air masses reaching the interior of the Antarctic continent contain only a very small fraction of their initial water vapor, their ^{18}O to ^{16}O ratio reaches levels 5 to 6 percent lower than that for sea water. The colder the air mass, the smaller its residual water vapor content and the lower its ^{18}O to ^{16}O ratio. This leads to a close tie between mean annual isotopic composition of high latitude precipitation and mean annual air temperature (see Figure 26). This strong correlation is the basis for the Antarctic ice-core-temperature record shown in Figure 24. The lower ^{18}O to ^{16}O ratios in glacial-age snow compared to modern snow at the same location bear witness to colder glacial temperatures.

A second manifestation of ^{18}O s two extra neutrons is a four percent higher ^{18}O to ^{16}O ratio in the oxygen in the calcium carbonate shells formed by marine foraminifera. In this case, temperature also plays a role. The colder the water temperature, the larger the fractionation (see Figure 27). Hence the ^{18}O to ^{16}O ratios in these shells also provide us with a proxy for sea water paleotemperatuere.

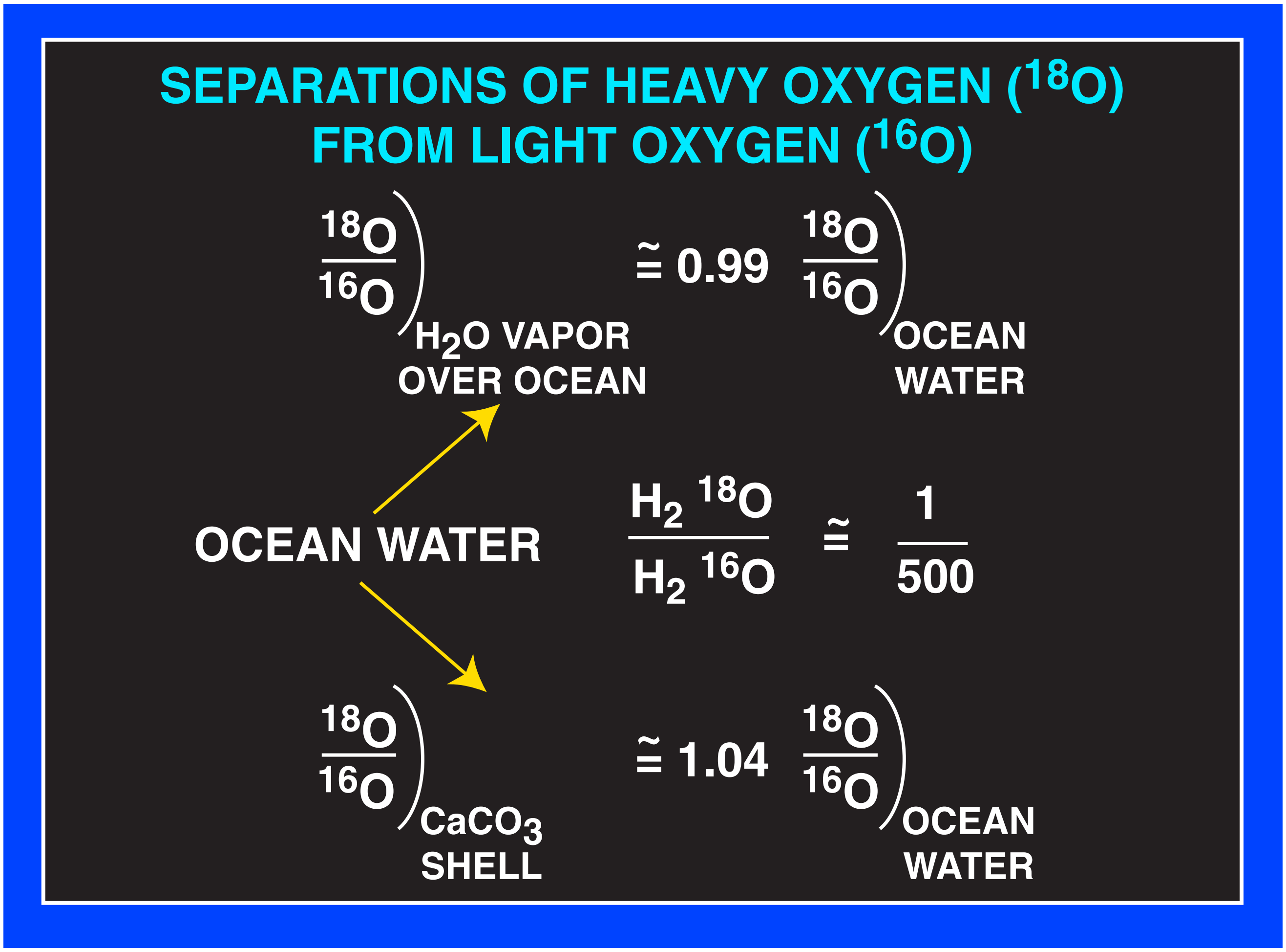
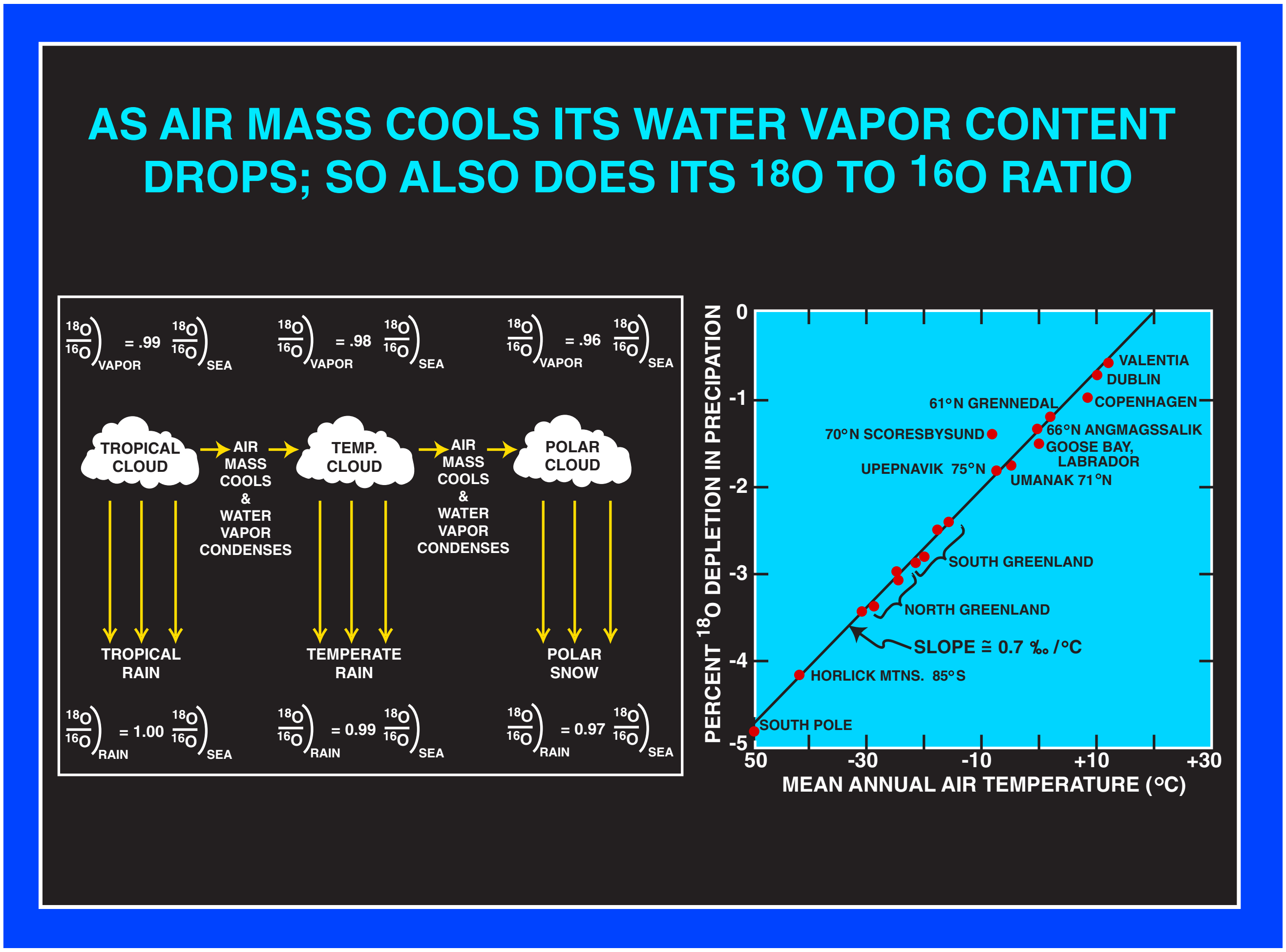

SEPARATIONS OF HEAVY OXYGEN (^{18}O)
FROM LIGHT OXYGEN (^{16}O)
$\left(\frac{^{18}O}{^{16}O}\right)_{H_2O\ VAPOR\ OVER\ OCEAN} \cong 0.99 \left(\frac{^{18}O}{^{16}O}\right)_{OCEAN\ WATER}$
OCEAN WATER
$\frac{H_2\,^{18}O}{H_2\,^{16}O} \cong \frac{1}{500}$
$\left(\frac{^{18}O}{^{16}O}\right)_{CaCO_3\ SHELL} \cong 1.04 \left(\frac{^{18}O}{^{16}O}\right)_{OCEAN\ WATER}$

Figure 25



AS AIR MASS COOLS ITS WATER VAPOR CONTENT DROPS; SO ALSO DOES ITS 18O TO 16O RATIO
18O/16O VAPOR = .99 18O/16O SEA
18O/16O VAPOR = .98 18O/16O SEA
18O/16O VAPOR = .96 18O/16O SEA
TROPICAL CLOUD
AIR MASS COOLS & WATER VAPOR CONDENSES
TEMP. CLOUD
AIR MASS COOLS & WATER VAPOR CONDENSES
POLAR CLOUD
TROPICAL RAIN
TEMPERATE RAIN
POLAR SNOW
18O/16O RAIN = 1.00 18O/16O SEA
18O/16O RAIN = 0.99 18O/16O SEA
18O/16O RAIN = 0.97 18O/16O SEA
PERCENT 18O DEPLETION IN PRECIPATION
0
-1
-2
-3
-4
-5
50
-30
-10
+10
+30
MEAN ANNUAL AIR TEMPERATURE (°C)
VALENTIA
DUBLIN
COPENHAGEN
61°N GRENNEDAL
70°N SCORESBYSUND
66°N ANGMAGSSALIK
GOOSE BAY, LABRADOR
UPEPNAVIK 75°N
UMANAK 71°N
SOUTH GREENLAND
NORTH GREENLAND
SLOPE ≅ 0.7 ‰ /°C
HORLICK MTNS. 85°S
SOUTH POLE

Figure 26

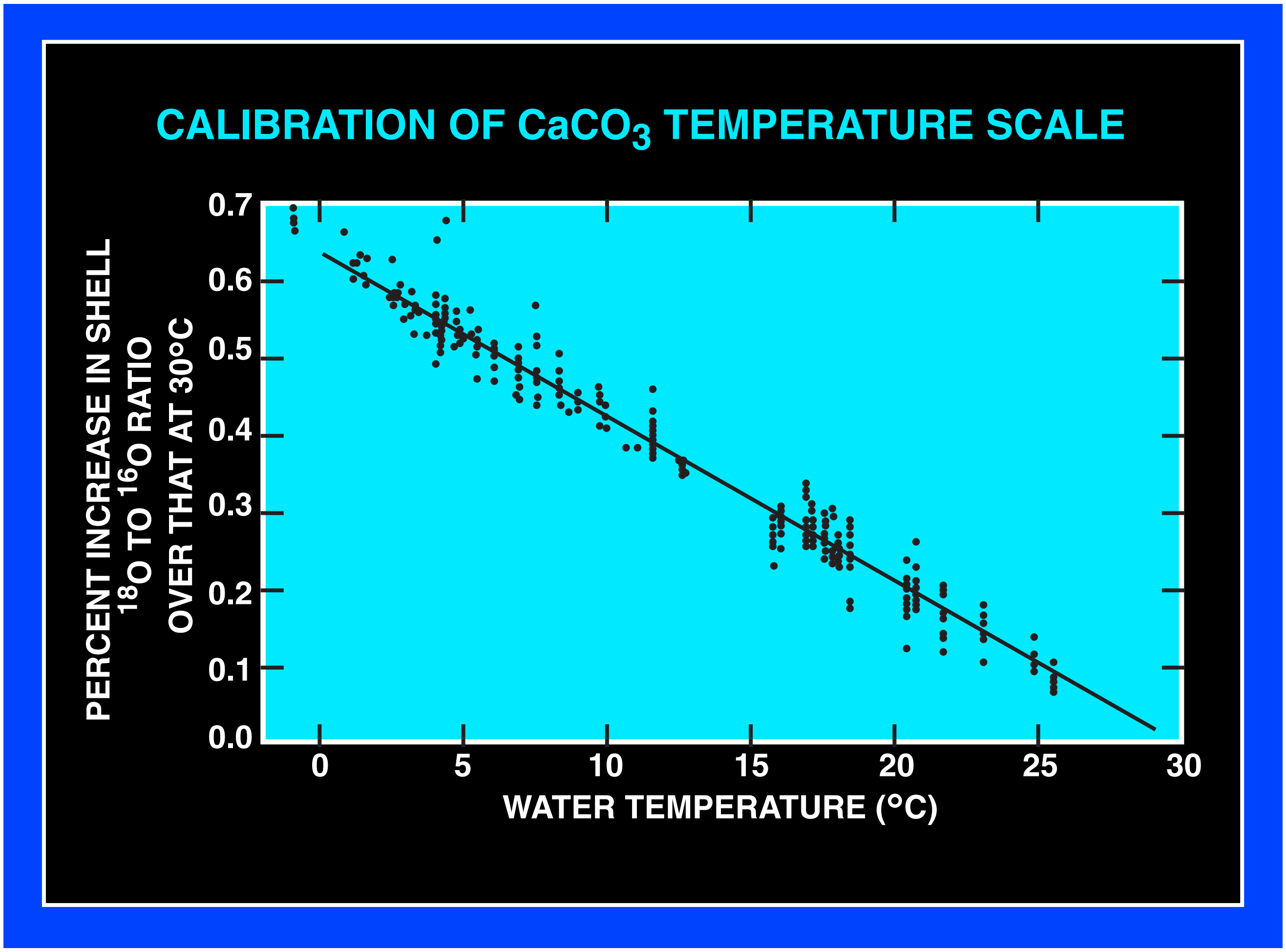

CALIBRATION OF CaCO3 TEMPERATURE SCALE
PERCENT INCREASE IN SHELL
18O TO 16O RATIO
OVER THAT AT 30°C
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
WATER TEMPERATURE (°C)

Figure 27

As is the case for many of our proxies, there are complications related to the fact that they respond to more than one environmental variable. We have already seen that in addition to air temperature, mountain snowline elevations are sensitive to the amount of snow which falls each year. In the case of the ^{18}O to ^{16}O ratio in marine calcium carbonate shells, the major complication is that the isotopic composition of sea water varies with climate. The reason is that the large continental ice sheets which formed during glacial time were depleted in ^{18}O, as are present-day ice caps. This missing ^{18}O was left behind in the ocean. As shown in Figure 23, the shells of bottom-dwelling foraminifera formed during glacial time were enriched in ^{18}O relative to those which form today. For several decades, paleoclimatologists struggled to figure out how much of the glacial ^{18}O increase was the result of colder bottom-waters and how much was the result of larger ice caps. Only recently has this issue been resolved to the satisfaction of most of us. A little more than half of the change was due to ice volume and a little less than half due to colder bottom waters.

It is interesting to note that the oldest fully formed human skull (see Figure 28) found to date has an age of 160,000 years. As shown by the arrow in Figure 24, this person lived during the time of the penultimate glacial period. While endowed with full brain capacity, it was not until 150,000 years later at the onset of the present interglacial climate that humans began to transform the landscape through irrigation and to exert control over hitherto wild animals.

The ice core record of the atmospheric CO_2 content is of particular interest (see Figure 24). The low CO_2 in the atmosphere during glacial times could logically be called upon to explain part of the planet s cooling. However, when compared to the recent CO_2 rise, there is a disconnect. The mean Earth temperature during peak glacial time averaged

Modern look. This skull of an adult male from Ethiopia is about 160,000 years old, but it already looks like a modern human's.

Figure 28

4° to 5°C colder than today s. The atmosphere s CO_2 content was 74 percent (200/270) of that for pre-industrial time. Prior to the Industrial Revolution, the Earth s temperature was about 1°C cooler than now. At that time, the CO_2 content of the atmosphere was 76 percent (280/370) what it is now. Further, models suggest that at most, only about half of the temperature change during the past century can be attributed to CO_2. Hence, lower atmospheric CO_2 was likely only a relatively small contributor to the cold global temperatures of glacial time.

Superimposed on each of the 100,000-year duration declines toward peak glacial cold is a distinct 22,000-year cycle which appears to be driven by changes in the strength of the temperature contrast between the seasons. As shown in Figure 29, the imprint of the 22,000-year cycle is particularly strong in the record of atmospheric methane concentrations.[2] These cycles are caused by the precession of the Earth s rotation axis. When, as now, Northern Hemisphere summers occurred as the Earth rounded the far end of its elliptical orbit and winters occurred as it rounded the near end, the contrast in solar insolation between the summer and winter seasons was somewhat smaller than average. In the Southern Hemisphere, the opposite is now the case and the seasonal insolation contrast is currently somewhat larger than average (see Figure 30). However, 11,000 years ago Northern Hemisphere summers occurred when the Earth was closest to the Sun. Summers in the Northern Hemisphere then were warmer than they are now (see Figure 31). Somehow the Earth s climate has responded to these cyclic orbital parameter changes in seasonal contrast. However, when introduced into models, just as was the case

[2] The most important source of atmospheric methane is swamps and wetlands. The invasion of O_2 into sediments is greatly impeded when sediment pores are filled with water. In the absence of an adequate O_2 supply, sediments become anaerobic and methanogenesis replaces respiration. In today s atmosphere, methane molecules survive oxidation for only one decade. Because of this rapid turnover, the record of atmospheric methane content kept in ice cores provides a measure of the rate of production of this gas and hence of the extent of wetlands.

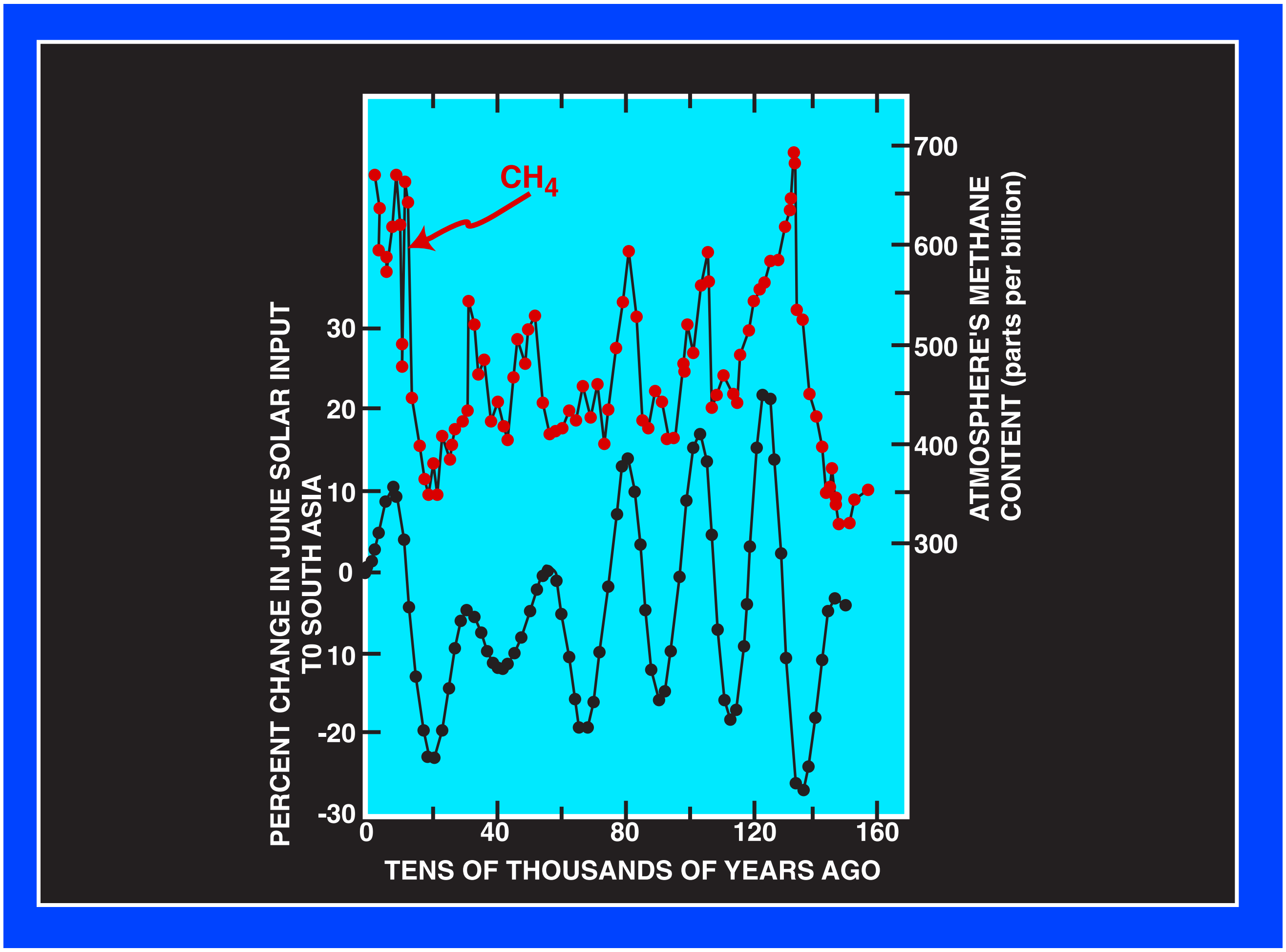

CH4
PERCENT CHANGE IN JUNE SOLAR INPUT
T0 SOUTH ASIA
30
20
10
0
10
-20
-30
0
40
80
120
160
TENS OF THOUSANDS OF YEARS AGO
700
600
500
400
300
ATMOSPHERE'S METHANE
CONTENT (parts per billion)

Figure 29

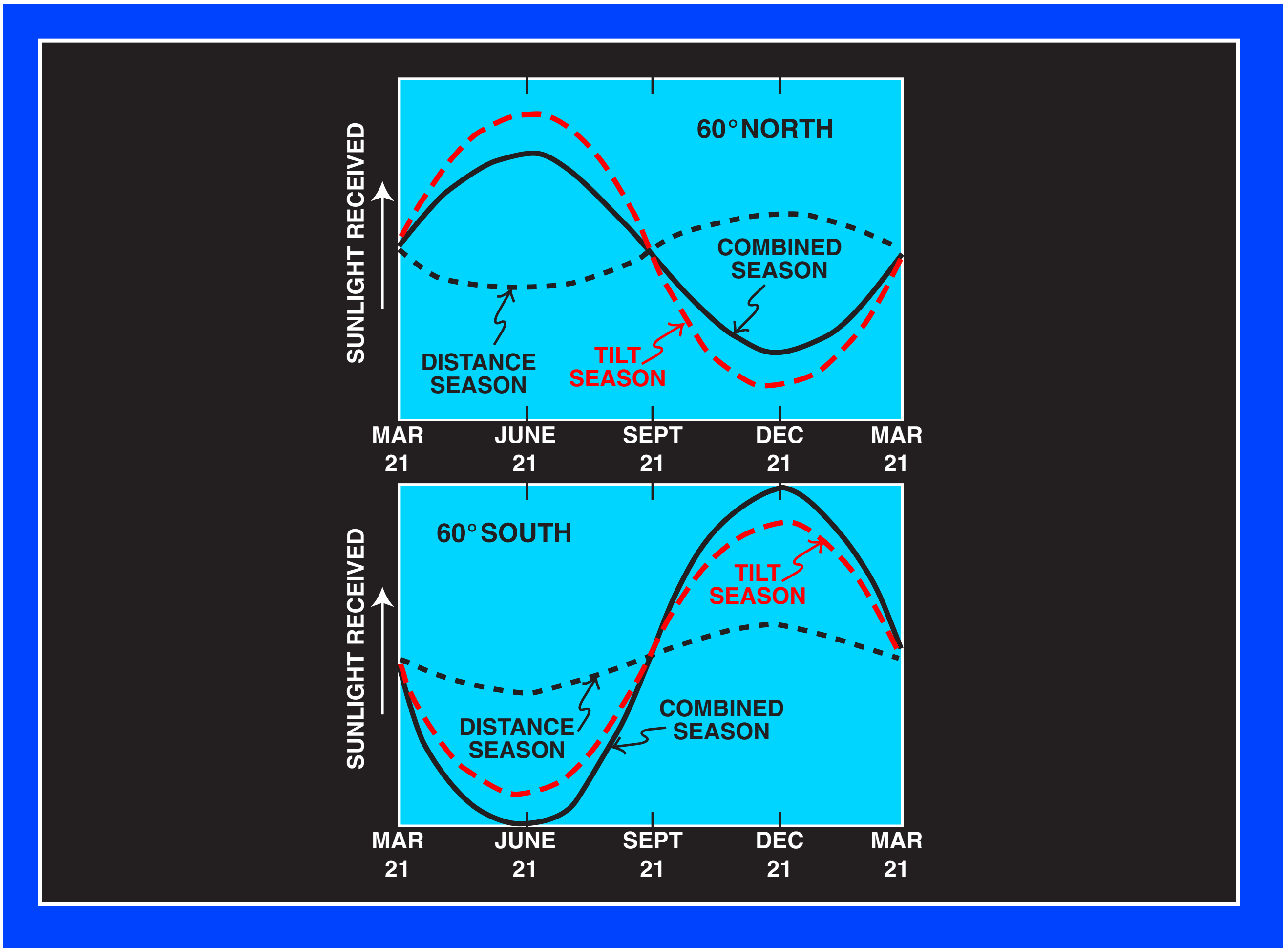

60° NORTH
SUNLIGHT RECEIVED
COMBINED SEASON
DISTANCE SEASON
TILT SEASON
MAR 21
JUNE 21
SEPT 21
DEC 21
MAR 21
60° SOUTH
SUNLIGHT RECEIVED
TILT SEASON
COMBINED SEASON
DISTANCE SEASON
MAR 21
JUNE 21
SEPT 21
DEC 21
MAR 21

Figure 30

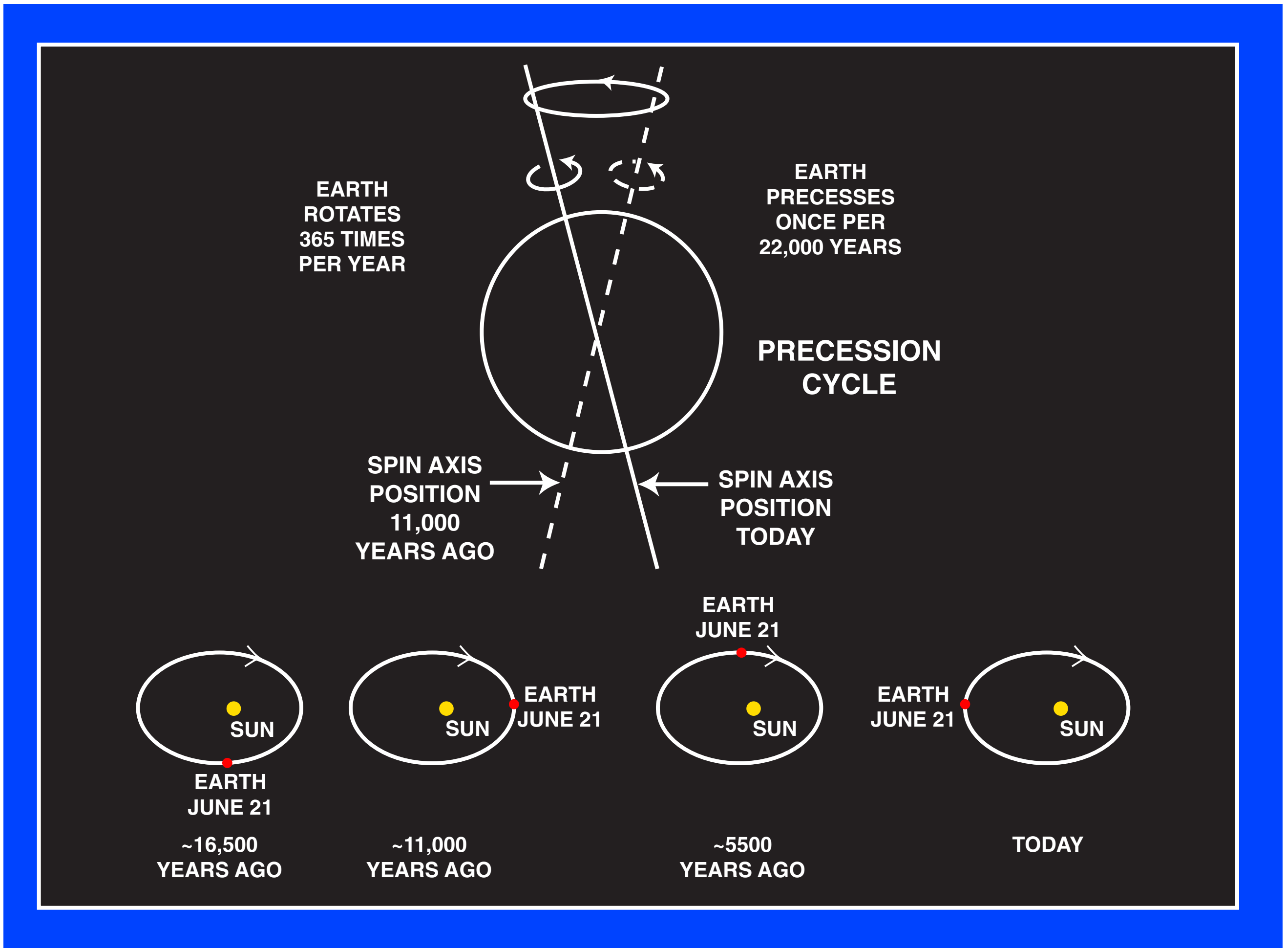

EARTH
ROTATES
365 TIMES
PER YEAR
EARTH
PRECESSES
ONCE PER
22,000 YEARS
PRECESSION
CYCLE
SPIN AXIS
POSITION
11,000
YEARS AGO
SPIN AXIS
POSITION
TODAY
SUN
EARTH
JUNE 21
~16,500
YEARS AGO
SUN
EARTH
JUNE 21
~11,000
YEARS AGO
EARTH
JUNE 21
SUN
~5500
YEARS AGO
EARTH
JUNE 21
SUN
TODAY

Figure 31

for the very small changes in solar irradiance, no measurable impacts on climate are produced. So once again the geological record seems to be telling us that our climate system appears to have been extremely responsive to small nudges.

Abrupt changes: the evidence

For many years, it was believed that major climate changes were paced by cycles in the Earth s orbital characteristics. In terms of the few centuries since the beginning of the Industrial Revolution, these changes occur so slowly that they can have no bearing on the warming since the late 1800s. It was not until the long borings in the Greenland ice cap were made that it became clear that cycles in seasonal contrast were not the only source of climate irregularity. What stunned the paleoclimate community was that unlike the records observed in ocean sediment and in Antarctic ice, those for Greenland were dominated by large and abrupt changes (see Figure 32). Only during the most recent 12,000 years did conditions stabilize. During the previous 100,000 years, climate as recorded in Greenland rarely stood still. Rather, it periodically underwent large jumps. When it wasn t jumping, it was drifting.

One might ask why these changes don t show up in the marine sediment record. In fact, they do, but only in places where the sediment accumulates at a very high rate (10 to 100 centimeters per 1000 years). Until the record in Greenland was obtained, scientists had focused their attention on studies of sediments from the open ocean where accumulation rates rarely exceeded a few centimeters per 1000 years. In their search for food, worms churn these sediments to depths of 6 to 10 centimeters and in so doing they destroy any record of millennial duration climate changes.

This, however, cannot be the explanation for the absence of millennial changes in the Antarctic ice record. While lacking the annual layers so valuable in Greenland ice,

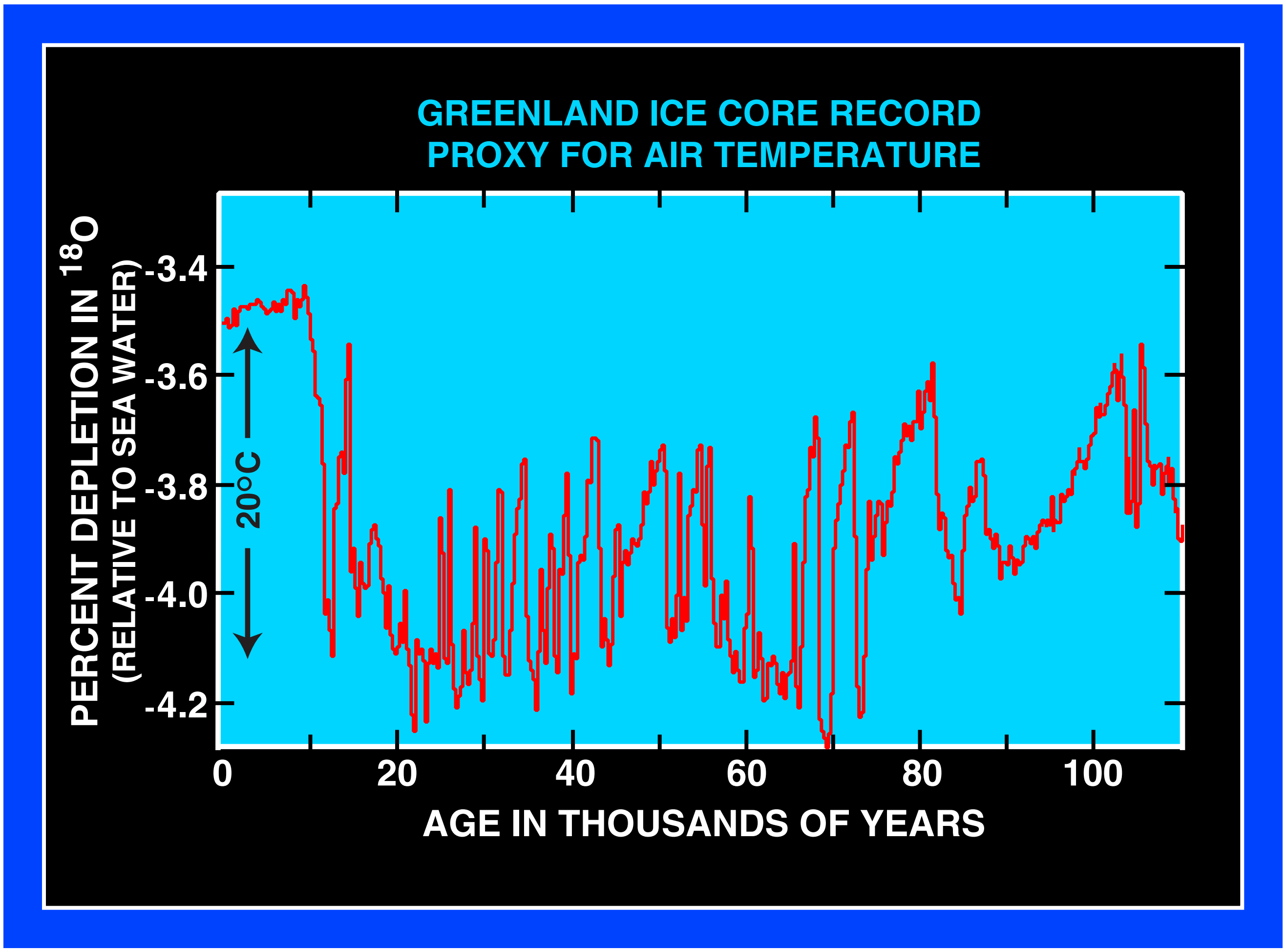

GREENLAND ICE CORE RECORD
PROXY FOR AIR TEMPERATURE
PERCENT DEPLETION IN 18O
(RELATIVE TO SEA WATER)
-3.4
-3.6
-3.8
-4.0
-4.2
20°C
0
20
40
60
80
100
AGE IN THOUSANDS OF YEARS

Figure 32

nevertheless the record is undisturbed and should certainly preserve millennial-duration events seen in Greenland. A closer look at these records reveals that millennial-duration events are present but unlike Greenland, they are dwarfed by the longer-term cyclic changes in climate.

By counting the annual layers preserved in Greenland ice, it was shown that the climate jumps were accomplished in just a few decades! Electrical conductivity measurements made by scratching a pair of electrodes along a freshly cut ice surface (see Figure 33) reveal that during these transitions climate appears to have flickered much as do fluorescent lights when first turned on. The air temperature changes associated with these jumps were a whopping 6° to 10°C. In addition, the infall rates of both soil dust and of sea salt onto the Greenland ice cap jumped back and forth by factors of three and accompanying each temperature jump was an abrupt shift in atmospheric methane content. During glacial time the dominant source of methane was swamps in the tropics, and that of soil dust reaching Greenland was deserts in Asia. Thus from the Greenland ice core record alone it was shown that the jumps in climate impacted a large portion of the planet. The periods of intense cold in Greenland corresponded to periods of less extensive methane-producing tropical wetlands and to periods of more frequent dust storms in the Asian deserts.

In the discussion of the factors influencing Earth temperature, dust and sea salt were not mentioned. While currently minor players, during peak glacial time the dust and sea salt burdens of the atmosphere were perhaps ten times larger than today s. At that time they must have contributed to the cooling of the planet. As can be seen in Figure 34, especially when blown out over the ocean, dust increases the reflectivity of the planet. As

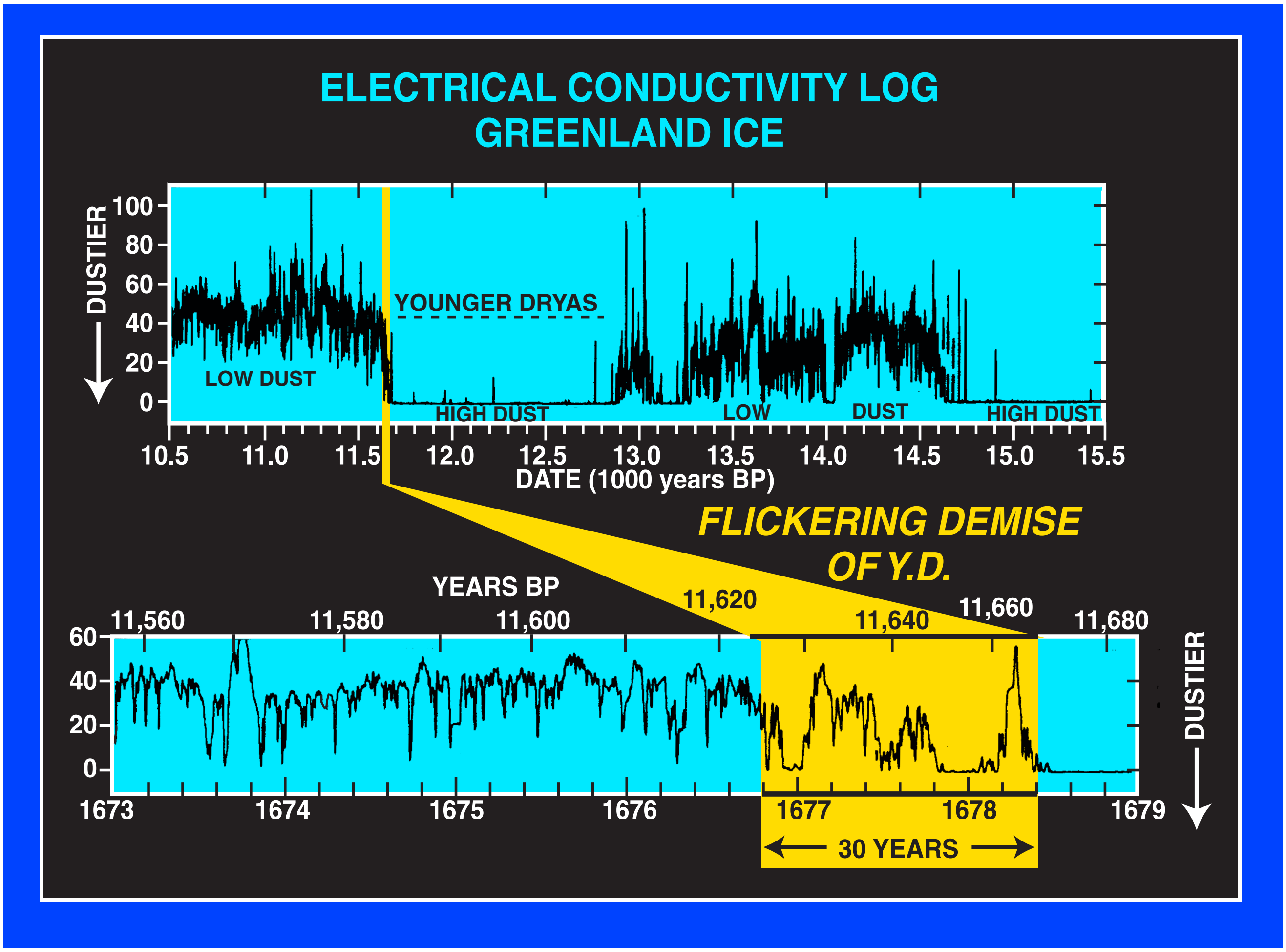

ELECTRICAL CONDUCTIVITY LOG
GREENLAND ICE
DUSTIER
100
80
60
40
20
0
YOUNGER DRYAS
LOW DUST
HIGH DUST
LOW
DUST
HIGH DUST
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
DATE (1000 years BP)
FLICKERING DEMISE
OF Y.D.
YEARS BP
11,560
11,580
11,600
11,620
11,640
11,660
11,680
60
40
20
0
1673
1674
1675
1676
1677
1678
1679
30 YEARS
DUSTIER

Figure 33

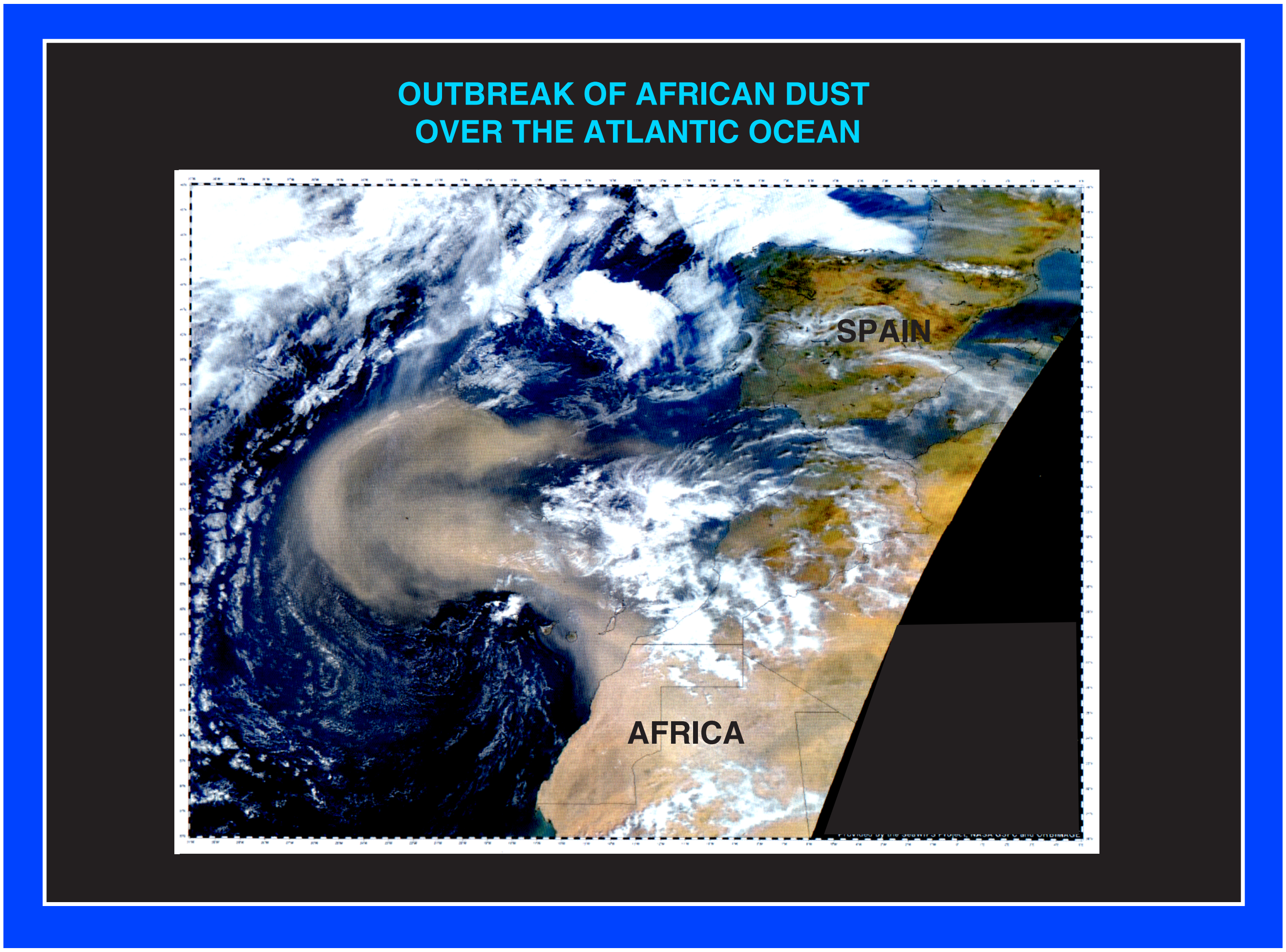

OUTBREAK OF AFRICAN DUST
OVER THE ATLANTIC OCEAN
SPAIN
AFRICA

Figure 34

sea salt aerosols serve as cloud condensation nuclei, they may well have enhanced the Earth s reflectivity.

The Dasgaard-Oeschger events

Punctuating much of the ice core record of the last period of glaciation in Greenland are a series of Dansgaard-Oeschger (D-O) events which in many ways resemble the YD. The climate in Greenland appears to have jumped back and forth between a state of extreme cold and a state of moderate cold. During the intervals of extreme cold, the rain of soil dust and sea salt onto the ice cap was three times higher than during the intervening intervals of moderate cold. The methane content of the air trapped in the ice also underwent sympathetic jumps. The shifts from ultra cold to moderate cold were extremely sharp, occurring in just a few decades.

Stefan Rahmstorf of the Potsdam, Germany modeling group pointed out an interesting coincidence. Aware of Gerard Bond s finding that the 1500-year cycle in the abundance of red-coated grains continued largely unchanged back through the entire glacial period (see Figure 35), Rahmstorf noted that the abrupt warmings (including that which brought the YD to an end) fell uncannily close to time marks spaced at 1470 years (i.e, the mean duration of Bond s red-grain cycles). Following Bond s proposal, that the 1500-year cycle observed in North Atlantic deep sea sediments is paced by the Sun, Rahmstorf proposed that so also were the Dansgaard-Oeschger events (see Figure 36). As hits occurred at only half of the time marks, Rahmstorf had to conclude that only during certain time intervals was the climate system poised to respond to a solar nudge. If Rahmstorf s idea proves to be correct, then in its glacial condition, the Earth appears to have been far, far more responsive to small nudges than it has been during the last 12,000 years. As we don t yet even understand how the tiny changes in solar irradiance caused

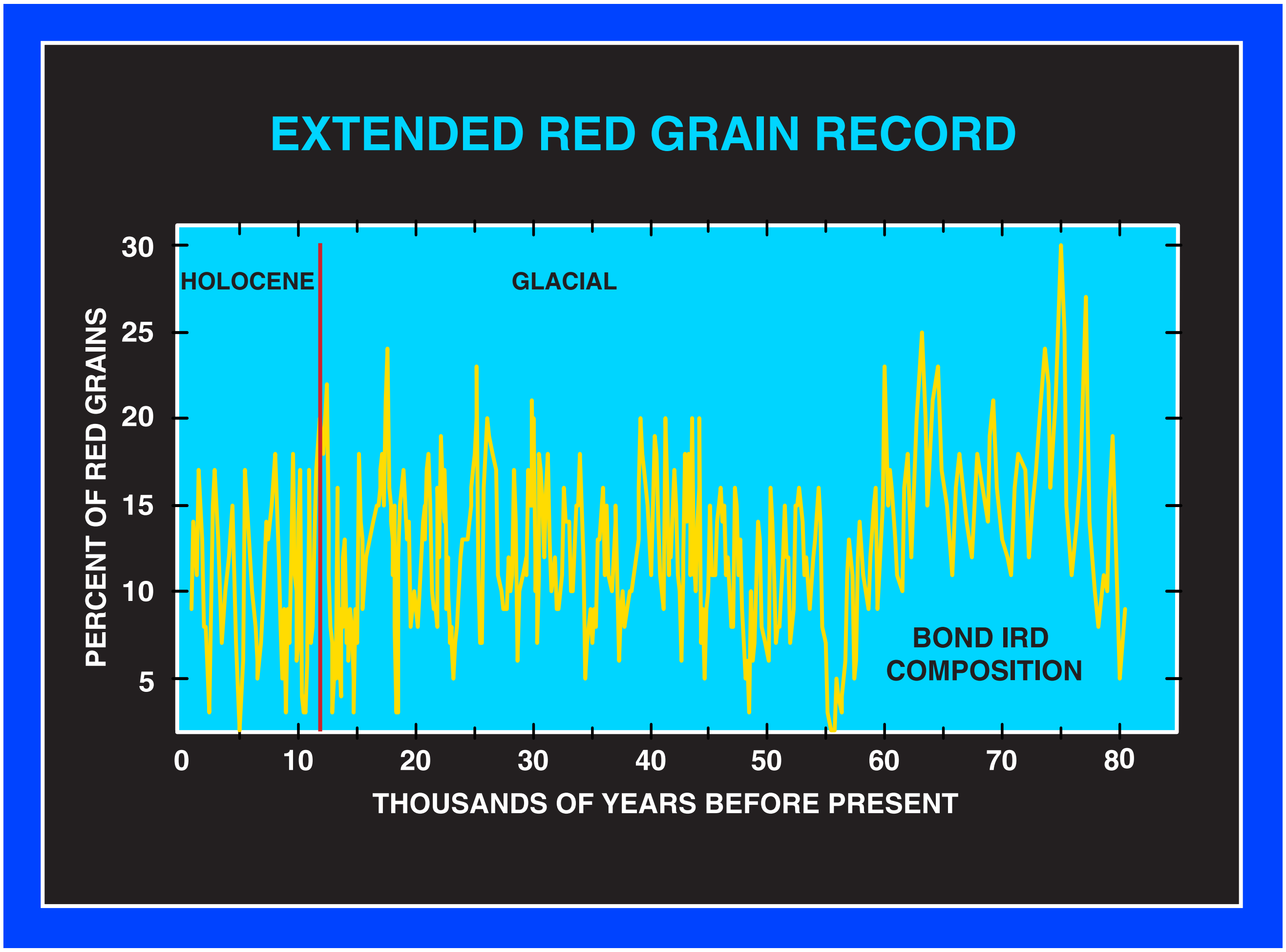

EXTENDED RED GRAIN RECORD
HOLOCENE
GLACIAL
BOND IRD
COMPOSITION
PERCENT OF RED GRAINS
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
THOUSANDS OF YEARS BEFORE PRESENT

Figure 35

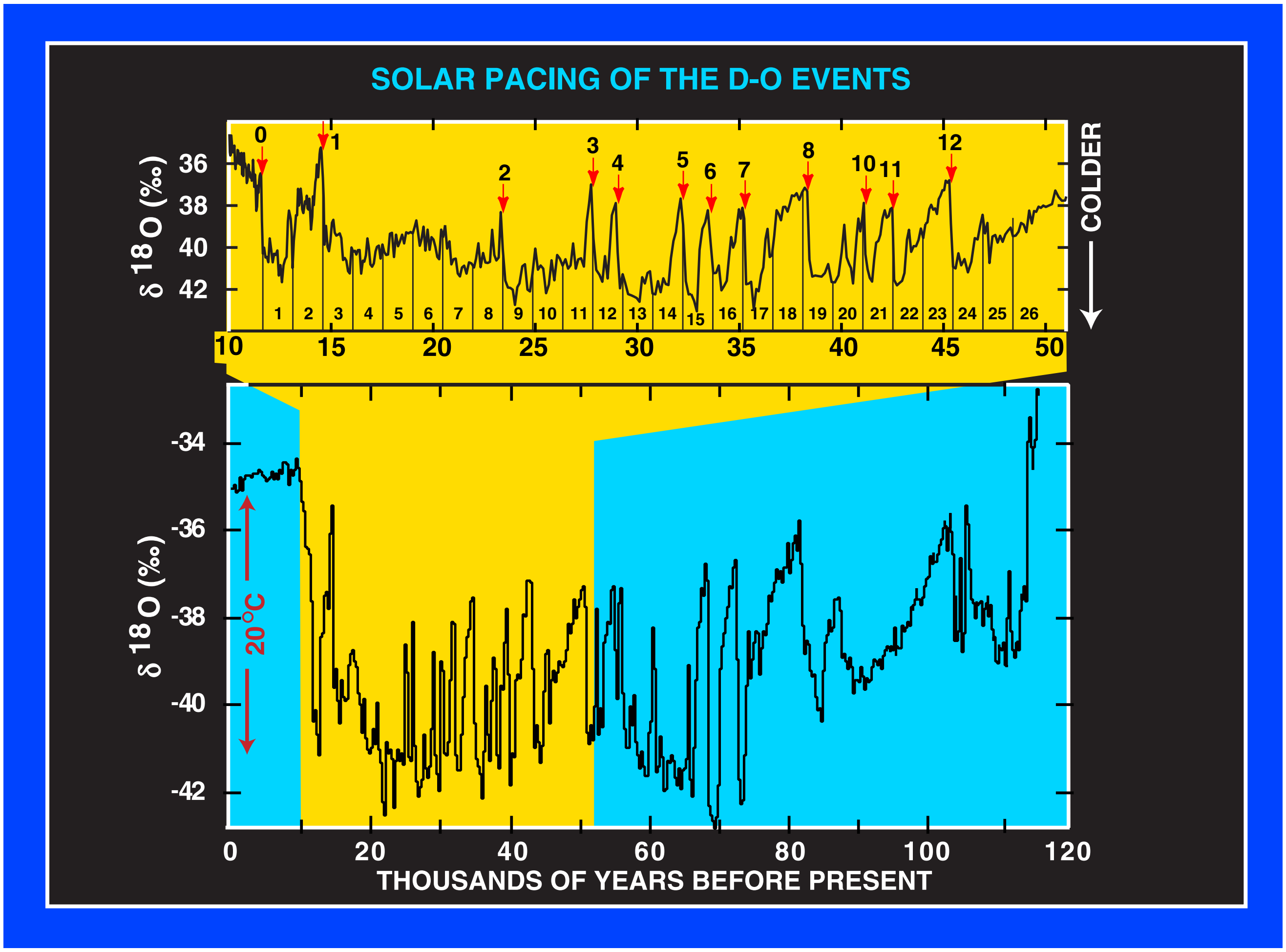

SOLAR PACING OF THE D-O EVENTS
δ 18 O (‰)
36
38
40
42
0
1
2
3
4
5
6
7
8
10
11
12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
10 15 20 25 30 35 40 45 50
COLDER
δ 18 O (‰)
-34
-36
-38
-40
-42
20°C
0 20 40 60 80 100 120
THOUSANDS OF YEARS BEFORE PRESENT

Figure 36

temperature to swing back and forth by 1°C during the present interglacial, explaining the much larger jumps of glacial time will prove to be a very tough nut to crack.

Lecture #3

The trigger for abrupt climate change: shutdowns of the ocean s conveyor circulation

Although our understanding of how the climate system accomplishes its jumps from one mode of operation to another is far from complete, the scenarios which receive the most attention are those which involve the ocean s large-scale circulation system. The deep sea is filled with cold water. The reason is that as sea water cools, it becomes ever more dense. Thus, for the same reason that oil floats on water, warm water floats on cold water. This situation is, however, hardly static, for the water in the deep sea is being steadily heated by the downward mixing of the overlying warm water and also by the upward diffusion of heat through the sea floor. As the deep waters warm, they become less dense allowing surface waters of higher density to sink to the abyss and underride the deep water column. In today s ocean, this renewal process goes on at a rate such that the waters in the deep sea are replaced about once each 800 years. In other words, the amount of new deep water sinking to the abyss in 800 years is enough to fill the deep sea.

This situation is made more complicated (but more interesting) by variations in dissolved salt. On average, each liter of sea water contains 35 grams of dissolved salts (mainly sodium chloride). However, the sea s salt is not uniformly distributed. Of interest to us is the fact that the greater its salt content, the more dense it is. Polar surface waters turn out to be somewhat less salty than tropical surface waters and surface waters in the Atlantic Ocean are saltier than their counterparts in the Pacific Ocean. So important is salt to the densification of sea water that new deep water forms only in those high latitude (i.e., cold) regions where the salt content is the highest. In today s ocean, two such places exist: one in the northern Atlantic and the other along the margin of the Antarctic continent. The deep Pacific and Indian Oceans are currently filled with a 50-50 mixture of waters produced in these two source regions. The deep Atlantic is dominated by water produced in the northern Atlantic.

Of great importance to the scenario that the trigger for abrupt change resides in the ocean is the fact that although water can be transported as vapor through the atmosphere from one part of the ocean to another, salt moves only through the sea. In those regions of the ocean where the gain of fresh water by precipitation and river runoff exceeds the loss by evaporation, the salt content is diluted. For the ocean to be at steady state, this ongoing dilution must be balanced by a continuing replacement of these fresher waters by saltier counterparts from elsewhere in the ocean. In other words, water vapor transport through the atmosphere must be compensated by the transport of salt within the sea.

Of primary interest is the Atlantic Ocean s conveyor-like circulation (see Figure 37). Surface waters made more salty by evaporation flow northward to the vicinity of Iceland where they are cooled by the frigid winter winds coming off Canada and Greenland. Already salty, these waters are cooled to the point where they become sufficiently dense to sink to the abyss. Once at depth, they move southward through the deep Atlantic and eventually pass eastward around the tip of Africa where they join the rapidly circulating circum-Antarctic current. Here they blend with deep waters formed along the margin of the Antarctic continent. A portion of this blend peels off and floods the deep Indian Ocean. Another portion peels off and floods the deep Pacific Ocean. As the waters of the lower limb of the Atlantic s conveyor are a bit more salty than those

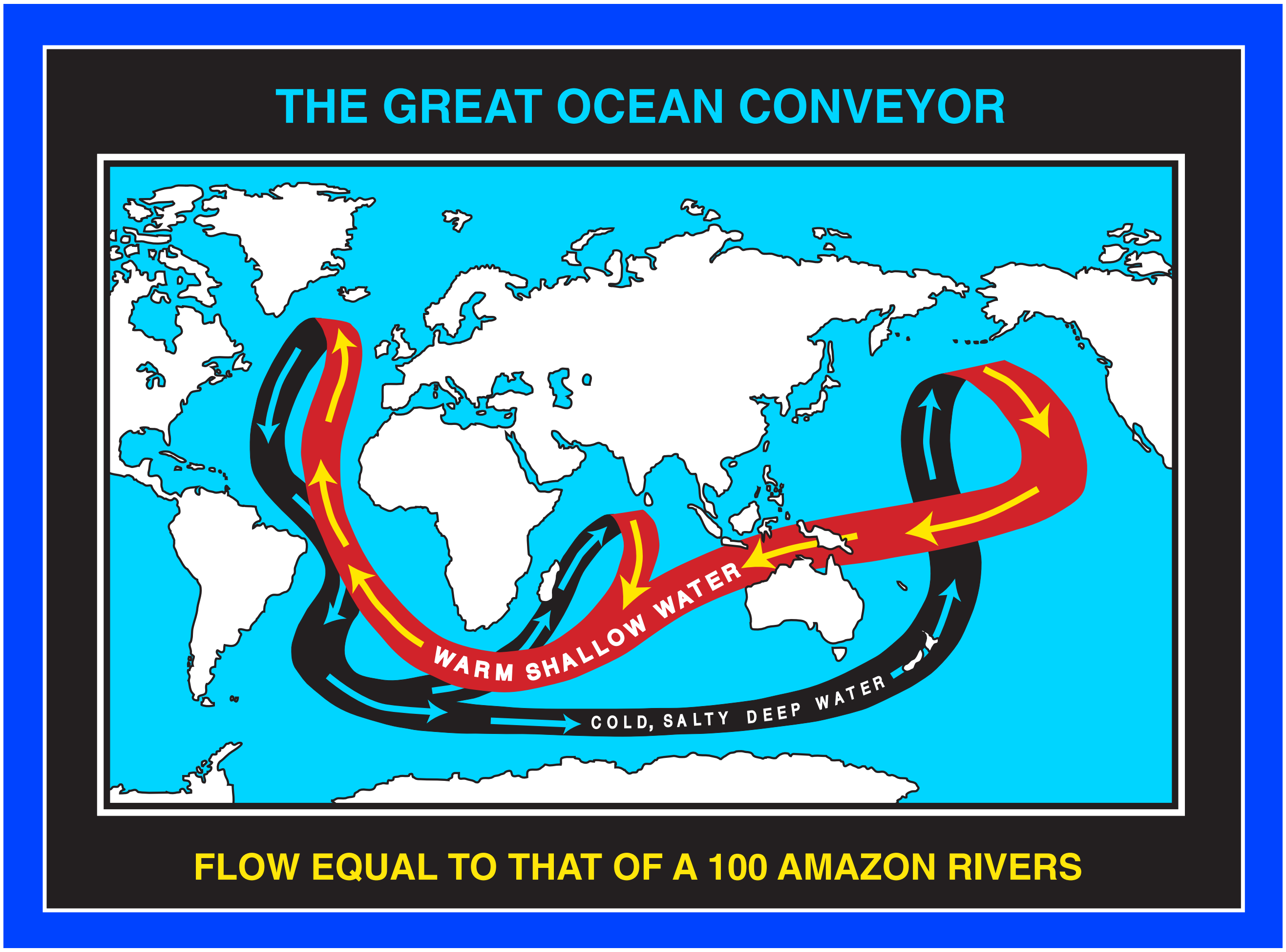

THE GREAT OCEAN CONVEYOR
WARM SHALLOW WATER
COLD, SALTY DEEP WATER
FLOW EQUAL TO THAT OF A 100 AMAZON RIVERS

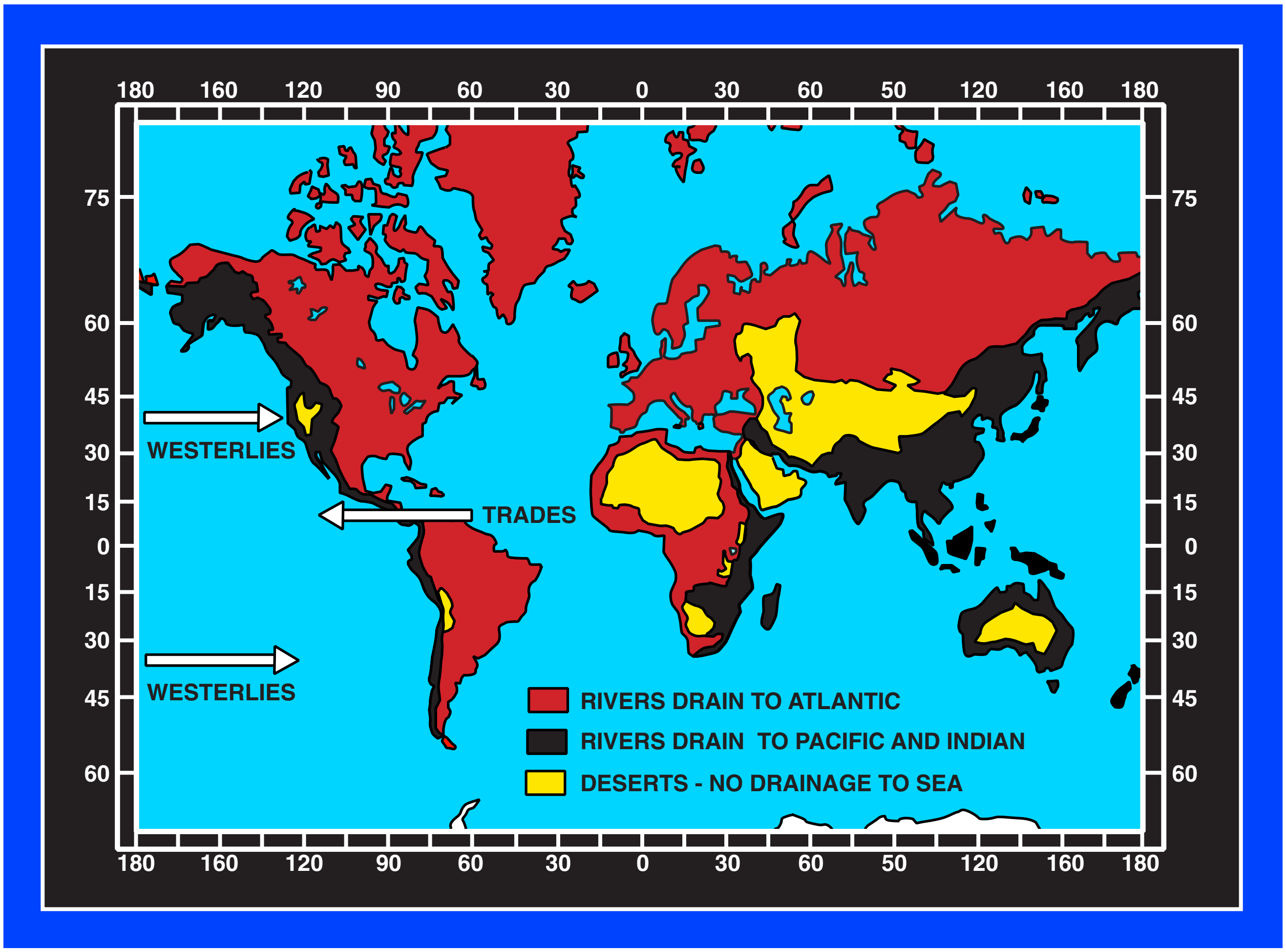
Figure 37

with which they blend, they carry with them the excess salt left behind in the Atlantic as the result of the transport of water vapor from the Atlantic Ocean to the Pacific Ocean.

One might ask why there is a net transport of water vapor from the Atlantic to the Pacific. The reason has to do with the position of the great mountain belts and the direction of the planetary winds (see Figure 38). At temperate latitudes west winds dominate. After passing across the Pacific Ocean they encounter the so-called American Cordillera, a chain of high mountains which extends from Alaska all the way to Patagonia. As it passes up and over this topographic barrier, the air is cooled. The cooling causes water vapor to condense. The resulting precipitation falls on the western slopes of the cordillera and is carried by rivers back to the Pacific. As no similar topographic barrier exists in Eur-Asia or Africa, water vapor picked up over the Atlantic Ocean by the westerlies is not recaptured to the extent of that picked up over the Pacific.

In the tropics, the trade winds flow from east to west compensating for the west to east transport of air in temperate latitudes. Although the trade winds also encounter the American Cordillera, the result is not the same as for the westerlies. The reason is that in Panama and other parts of Central America the mountains are not very high, allowing vapor evaporated from the Atlantic to fall as rain in the Pacific.

The result is that there is a net transport of water vapor from the Atlantic Ocean to the Pacific Ocean. The magnitude of this net loss of water from the Atlantic is such that if not compensated by salt export, over a period of one thousand years the salt content of the Atlantic would rise by about one gram per liter. Of course, export of salt from the Atlantic does occur, balancing the loss of water vapor. As already stated, today this export is primarily via the lower limb of the Great Ocean Conveyor.



180 160 120 90 60 30 0 30 60 50 120 160 180
75
60
45
30
15
0
15
30
45
60
WESTERLIES
TRADES
WESTERLIES
RIVERS DRAIN TO ATLANTIC
RIVERS DRAIN TO PACIFIC AND INDIAN
DESERTS - NO DRAINAGE TO SEA

Figure 38

If for some reason the balance between the export of water vapor and the export of salt were to be disrupted, then in order to compensate, the ocean s circulation system would be forced to reorganize. Indeed, as we shall see, a number of such disruptions appear to have occurred during the last glacial period.

The great Agassiz Flood triggers conveyor shutdown

The transition from the cold and chaotic climate of glacial time to the warm and stable climate of the last 12,000 years was punctuated by a millennium-duration cold relapse which was given the name Younger Dryas (YD) by Scandinavian paleobotanists. They chose this name because sediments formed at low elevation during YD time contain the remains of a flower (the Dryas, see Figure 39) which today flourishes only high in the mountains. Its presence at low elevation heralded the return of colder conditions.

A reasonably strong case can be made that the YD was triggered by a shutdown of the Great Ocean Conveyor which had snapped back into action 15,000 years ago at the close of glacial time. Further, a prime suspect responsible for triggering of this shutdown has been identified. At the time of the sudden onset of the YD, 10,000 cubic kilometers of water stored in a lake, which had formed in front of the retreating North American ice sheet, was suddenly released. Now extinct, Lake Agassiz (see Figure 40) occupied a depression produced by the weight of the two kilometer-thick ice cap.

The margin of the retreating ice sheet formed the northern and eastern shorelines of this lake. Prior to the YD, the lake spilled to the south over a rock lip into the Mississippi River drainage. Then one day, the lake broke through the ice which formed its eastern margin and deluged through the Great Lakes region and St. Lawrence River valley into the northern Atlantic where it diluted the surface water salt content and thereby shut down the conveyor.

Figure 39