Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO_2 Upset the Current Balance?

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During the last glacial period, Earth's climate underwent frequent large and abrupt global changes. This behavior appears to reflect the ability of the ocean's thermohaline circulation to assume more than one mode of operation. The record in ancient sedimentary rocks suggests that similar abrupt changes plagued the Earth at other times. The trigger mechanism for these reorganizations may have been the antiphasing of polar insolation associated with orbital cycles. Were the ongoing increase in atmospheric CO_2 levels to trigger another such reorganization, it would be bad news for a world striving to feed 11 to 16 billion people.

One of the major elements of today's ocean system is a conveyor-like circulation that delivers an enormous amount of tropical heat to the northern Atlantic. During winter, this heat is released to the overlying eastward moving air masses, thereby greatly ameliorating winter temperatures in northern Europe. The record contained in ice (*1*) and sediment (*2*) indicates that this current has not run steadily, but jumped from one mode of operation to another. The changes in climate associated with these jumps have now been shown to be large, abrupt, and global (*3–5*). Although the exact linkages that promote such climate changes have yet to be discovered, a case can be made that their roots must lie in the ocean's large-scale thermohaline circulation [see (*2*)]. The results of a wide variety of modeling exercises clearly demonstrate that because waters dense enough to sink to the deep sea can be generated at more than one place on the planet, several quasi-stable patterns of circulation exist (6). Variations in the conditions governing the density of high-latitude surface waters can lead to abrupt reorganizations of the ocean's circulation. The surprise revealed to us by the climatic record is the extent, rapidity, and magnitude of these atmospheric changes.

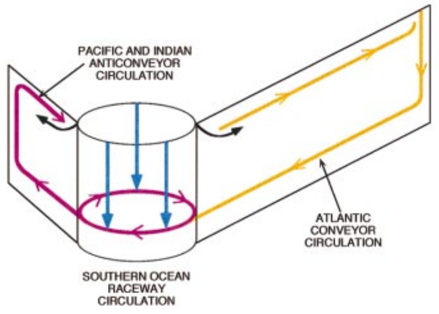
Although to date the documentation of abrupt global climate change is confined to the last 110,000 years, the time interval preserved in the Summit Greenland ice cores (*1*), there is reason to suspect that this phenomenon has operated off and on, throughout the history of the Earth. The evidence comes from the well-documented cyclicity in sedimentary rock sequences. In many of these sedimentary cycles, the boundaries between the individual units are sharp rather than gradational, as might be expected if the sediment composition followed the sinusoidal insolation cycles.

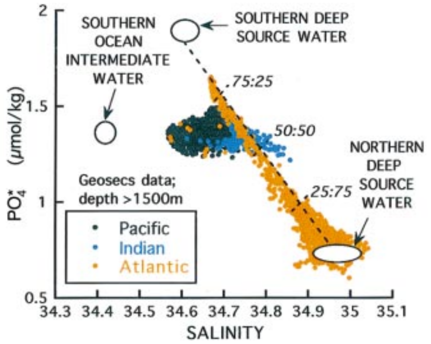
Might the ongoing buildup of greenhouse gases in our atmosphere trigger yet another reorganization of the climate system? Were this to happen a century from now, at a time when we struggle to produce enough food to nourish the projected population of 11 to 16 billion, the consequences could be devastating. Thus, it behooves us to get a better grasp than we now have of this phenomenon.

How Today's Ocean Functions

A complex of currents collectively known as the Conveyor (*7*) dominates circulation in today's Atlantic Ocean (see Fig. 1). The waters in the upper 1500 m of the Atlantic Ocean carry heat to its northern reaches. Much of this transport is by western boundary currents. During the cold winter months, this heat is transferred to the overlying atmosphere, greatly supplementing that received from the sun (*8*). The primary beneficiary of this extra heat is northern Europe, where winters are far warmer than one would otherwise expect.

Cooling in the North Atlantic increases the density of this upper ocean water to the point where it sinks to the bottom and flows southward, forming the lower limb of the Conveyor. This limb extends all the way to the southern tip of Africa where it joins the raceway, which transports water around the





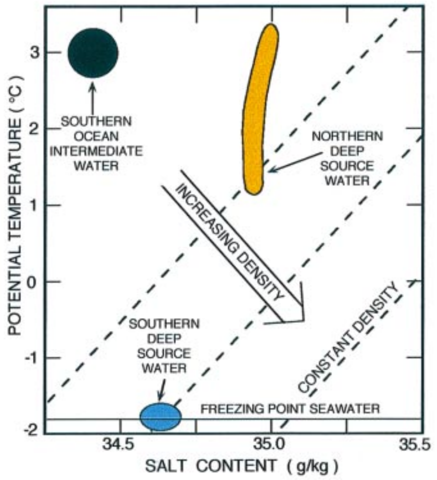


Fig. 1. The present-day large-scale thermohaline circulation pattern of the ocean. (**Top**) Salty upper Atlantic water moves northward into the vicinity of Iceland, where it is cooled through contact with cold winter wind. This thermally densified salty water sinks to the bottom and flows to the south, forming the Conveyor's (orange) lower limb. After passing the tip of Africa, it joins the Southern Ocean raceway, which carries water around the Antarctic continent. Here it is blended with brine-densified winter waters that pour off the shelves surrounding the Antarctic continent into the abyss (blue). The mixture (purple) thus formed enters the Pacific and Indian Oceans as bottom water forming the lower limbs of large anti-Conveyor circulation cells. Penetrating into all three oceans are tongues of intermediate depth water formed along the northern margins of the Southern Ocean (black). This water is mixed downward into the deep ocean, forming the third end member. As can be seen in the PO versus salinity diagram (**below**), its presence is made known by a deviation toward lower salinity. The PO_4^* of these waters is about 1.4 µmol/kg, their salinity about 34.4 g/liter, and their potential temperature about 3°C (**right**).

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continent of Antarctica (Fig. 1). This raceway is also fed by newly generated deep water descending along the margins of the Antarctic continent. It dispenses the mixture formed from these feed waters northward into all three major oceans. In the case of the Indian and Pacific oceans, this input constitutes the dominant supply, as deep water is not formed at the northern end of either of these oceans. In the Pacific Ocean, the low salt content of surface waters prevents sinking of water into the interior. In the Indian Ocean, surface waters are too warm.

Today the amount of water fed into the circum-Antarctic raceway from the deep Atlantic is roughly equal to the amount descending from the perimeter of the Antarctic continent (*9*). In the northern Atlantic, winter cooling initiates convective plumes that carry open ocean surface water to the abyss. In the Southern Ocean, deep waters are generated beneath the sea ice fringing the Antarctic continent (*10*).

All polar surface waters are deficient in salt. The reason is that fresh water is transported as vapor from low to high latitudes where it enters the ocean as precipitation and continental runoff. This delivery of fresh water works to squelch deep water formation.

In the Southern Ocean, seasonal growth of sea ice occurs along the perimeter of Antarctica. This ice holds the temperature of the underlying water at the freezing point (that is, at the maximum thermal density), and the growth of sea ice leads to a rejection of salt-rich brines into the underlying water. In this way, the most dense waters in today's surface ocean are generated. These waters cascade off the shelves that surround Antarctica into the abyssal ocean (*11*).

The situation in the northern Atlantic is different. Here the rapid throughput of Conveyor water stems the buildup of fresh water. Furthermore, as illustrated in Fig. 2, because of the positioning of our planet's major mountain ranges relative to its prevailing planetary winds, the Atlantic loses more water by evaporation than it gains from precipitation and continental runoff (*12, 13*). Hence, surface waters in the north Atlantic are saltier than those in the north Pacific. As a result of the combination of evaporative enrichment of salt and rapid throughput by the Conveyor, the northern Atlantic has the saltiest of all high-latitude surface waters. When cooled to just 2° to 3°C, these surface waters become nearly as dense as the brine-densified winter waters beneath Antarctica's fringing sea ice.

The aggregate rate of generation of new deep waters must counterbalance the density loss in the ocean's interior caused by the downward mixing of warm and hence low-density upper ocean water. Away from the poles, the oceanic water column is strongly stratified. Cold deep waters are separated from the warm surface waters by the main thermocline. Even though the thermocline constitutes a strong barrier to vertical exchange, wind and tidal stresses induce these waters to gradually mix. This mixing tends to reduce the density of the cold deep water. The density deficit created in this way drives the renewal of deep waters. In today's ocean, an amount of new deep water equal to roughly one thousandth the volume of the deep sea descends each year.

As mentioned above, a puzzling aspect of today's circulation is the near equality between the amounts of deep water contributed to the circum Antarctic mixmaster from the north and from the south. Although many of the details of exactly how and where these two source waters form remain obscure, the ratio of their contributions can be determined from the composition of deep water in the Indian and Pacific oceans, in particular from the magnitude of a quasi-conservative property, PO_4^*, obtained by combining the phosphate and oxygen contents of the water in the following way (*14*):

$$PO_4^* = PO_4 + \frac{O_2}{175} - 1.95\ \mu\text{mol/kg}$$

The coefficient 175 is the ratio of the number of oxygen gas molecules consumed during respiration for each phosphorus ion released (*15*). This coefficient is nearly constant throughout the deep sea (*15*). The PO_4^* value (0.73 μmol/kg) of deep waters formed in the northern Atlantic is different from that for those formed around Antarctica (1.95 μmol/kg) (*14*). The difference between these values (1.22 μmol/kg) is much larger than the range displayed by the source waters in either region (that is, 0.03 and 0.05 μmol/kg, respectively), giving this property a high sensitivity for distinguishing the contributions of the two end members. The PO_4^* values for deep waters throughout the Pacific and Indian oceans are amazingly uniform (1.38 ± 0.04 μmol/kg). This value can be generated by mixing 47 ± 3% waters of northern origin and 52 ± 3% waters of southern origin. But the salinity-PO_4^* values for deep waters deviate somewhat from the join connecting the end member compositions. Much of this deviation can be explained by the downward mixing of northward-penetrating intermediate waters originating in the Southern Ocean (*9*). Because these intermediate waters have a PO_4^* value close to that for the primary deep water mix, their addition does not alter the usefulness of PO_4^* for the determination of the relative contributions from the two deep water source regions (see Fig. 1).

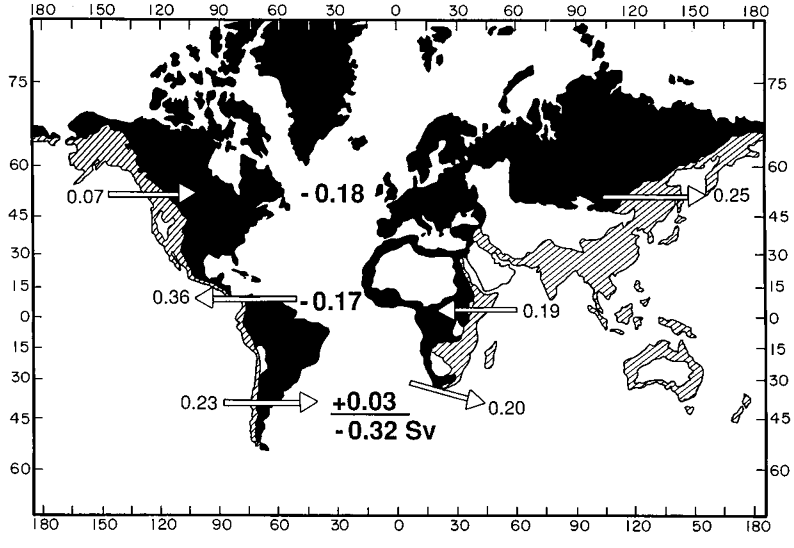

Fig. 2. Hydrologic budget (*12*) for the Atlantic Ocean and its continental drainage basin (shown in black). The lands shown by shading drain to the Pacific and Indian oceans. The white areas are deserts from which no drainage occurs. Westerly winds in the Northern Hemisphere transport more water vapor across Asia than enters across the American cordillera. Easterly winds carry more water vapor out across Central America than enters across Africa. The light numbers give the inputs and losses of water vapor in three latitude zones: north temperate, tropical, and south temperate. The bold numbers give the net loss from each of these zones and for the Atlantic as a whole. The net result based on the Oort's (*12*) global humidity and wind data set is a loss of 0.32 Sv (that is, a bit over the flow of the Amazon River) from the Atlantic to the Pacific. Were this flux not compensated by an exchange of more salty Atlantic waters for less salty Pacific waters, the salinity of the entire Atlantic would rise about 1 gram per liter per millennium.

Why are these two sources of deep water

currently nearly equal in strength? In simple terms, today's thermohaline circulation has a design that matches two requirements. First, the aggregate rate of deep water formation must counter the reduction in density through downward mixing of warm upper ocean water; second, the salt left behind in the Atlantic through excess evaporation must be transported back to the Pacific for recombination with the excess fresh water deposited there. By chance, in today's sea, these balances are achieved by nearly equal rates of deep water formation in the northern Atlantic and in the Southern Ocean. However, the exact nature of these controls is uncertain (*16*).

It is not difficult to see why the pattern of ocean circulation is thus subject to reorganization. For example, in today's northern Atlantic, the Conveyor's upper limb delivers about 15 Sv (*13*) of water averaging about 35.8 g/liter in salt content. Transport through the Bering Straits delivers about 1 Sv of water averaging 32 g/liter in salt content (*17*). The excess of rainfall and continental runoff over evaporation is about 0.3 Sv (*18*). This blend generates 16.3 Sv of North Atlantic Deep Water (NADW), averaging 34.91 g/liter in salt content, which feeds the Conveyor's lower limb. If the excess of precipitation plus runoff over evaporation were to be increased by 50% (that is, to 0.45 Sv), the salt content of outgoing NADW would drop to 34.59 g/liter. In order to compensate for the resulting reduction in density, the winter surface waters from which deep water formed would have to be cooled by an additional 1.4°C. But even if this were accomplished, the global salt budget would be disrupted. In order for salt balance to be restored, the Conveyor would have to more than double its flow. This speedup would result in a mismatch between re-densification and de-densification of the deep sea. And so it would go. Chances are that the system would not be able to accommodate the change in fresh water input without developing an instability capable of triggering a reorganization of the global circulation system.

Thus, model simulations of the ocean's thermohaline circulation are particularly sensitive to fresh water input (*19*). Modelers have explored the amounts, rates and locations of fresh water input required to trigger a Conveyor shutdown. They also have explored the aftermath of such shutdowns seeking to determine whether the Conveyor circulation is replaced by an alternate scheme or whether after some period of dormancy it pops back into action.

Evidence for Past Reorganizations

Climate records contained in Greenland ice (see Fig. 3) reveal that during the last 60,000 years conditions switched back and forth between millennial duration intervals of intense cold and moderate cold (*1*). The transitions occurred on the time scale of a few decades to as little as a few years (*20*). Each interval of intense cold was matched by an ice-rafting event in the northern Atlantic (*21*) and by a greatly increased influx of dust onto the ice cap (*4*). Because the dust deposited onto the Greenland ice cap during glacial time has been shown to originate in the Gobi Desert (*22*), the storminess over Asia must have undergone pronounced changes (*4*). Abrupt shifts in the atmosphere's methane content were synchronous with Greenland's abrupt air temperature shifts, thereby demonstrating that changes in the extent and temperature of Earth's wetlands also took place (*23*). Mountain glaciers at 40°S in Chile and in New Zealand evidently underwent expansions and contractions in synchrony with those experienced by the Northern Hemisphere's great glacial-age ice sheets (*24*). These changes were not confined to glacial times, for an intense brief cold event occurred about 8000 years ago after temperatures had reached near or above recent levels (*25*).

These large shifts in climate suggest to me that the inventory of water vapor in the atmosphere can be much different than it is today. Two observations indicate that this was actually the case. First, tropical snowlines of glacial age were lowered by 900 m (*26*). Second, the $\delta^{18}O$ value for ice of glacial age from elevations of 6 km in the tropical Andes was lowered by 8 per mil (*27*). Taken together, these observations appear to require that during peak glacial time the absolute water vapor content of the tropical boundary layer air was 80 ± 7% of today's value and that of high mountain air was less than half today's value (*28*). Such a reduction in the content of the Earth's dominant greenhouse gas (that is, H_2O) is sufficient to account for the 3.5 ± 1.5°C cooling of the tropical ocean surface during glacial times (*29*).

However, as the above evidence relates to events on the continents, why conclude that the roots of these changes lay in the ocean? Admittedly, the case behind this conclusion remains circumstantial. Certainly the tendency toward reorganizations displayed by ocean circulation models provides support for this conclusion. By contrast, no general circulation model of the atmosphere (including those coupled to an ocean) can be induced to jump into quite different globe-encompassing states of operation. Indeed, even when the ocean beneath the model's atmosphere is induced to undergo an abrupt change in circulation pattern, dramatic climate responses are limited mainly to the region surrounding the

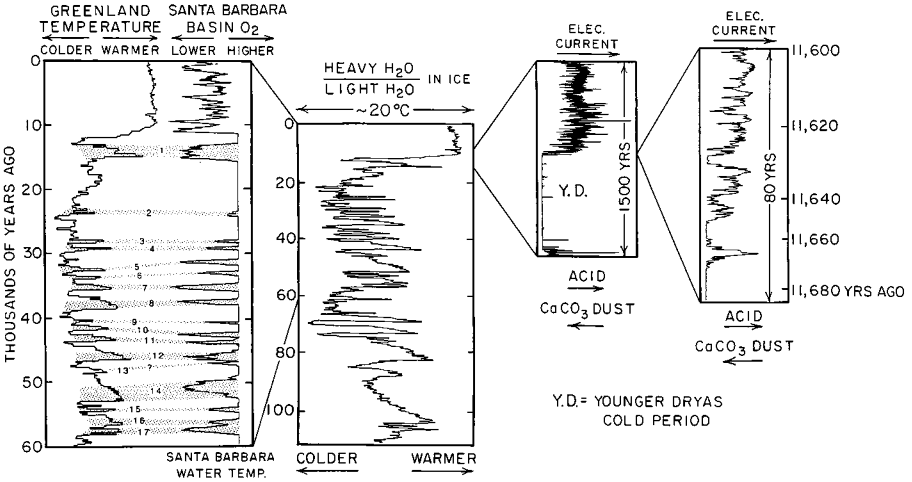

Fig. 3. As shown in the center panel, the oxygen isotope record from the Summit Greenland ice cores (GRIP and GISP2) clearly demonstrates that except for the last 10,000 years, the last 110,000 years were punctuated by large and abrupt climate changes (*1*). As shown in the left-hand panel, these same changes appear in the marine record from the Santa Barbara Basin as alternations between periods of vigorous and sluggish ventilation (*35*). The large and abrupt changes in electrical conductivity shown in the right-hand panel reflect shifts from intervals of extreme cold when the influx of $CaCO_3$-bearing dust greatly exceeded that of proton-bearing acids to warmer intervals when this onslaught of dust from Asia was stemmed (*22*). The blowup portrays that these shifts were not only abrupt but quite noisy. Taken together, this evidence suggests that Greenland air temperatures, Asian winds, and northern Pacific surface salinities underwent large and synchronous changes that were accomplished on the time scale of a few decades (*55*). The flickering action associated with these transitions could cause havoc in agricultural production were another such change to occur 100 or so years from now.

northern Atlantic, which benefits from the Conveyor's heat transport. But this is a two-edged sword. The failure of general circulation models to spontaneously reproduce the abrupt changes in temperature and rainfall pattern so clearly recorded in the geologic record for the last glaciation sends a strong message that these models are somehow deficient. Because models of the atmosphere are generally not programmed for interactive dust loading, they, of course, cannot reproduce the large dust flux changes documented in ice cores (*30*) and loess. Until we have identified and remedied the deficiencies that prevent the atmosphere portions of the models from undergoing mode changes, we will not be able to assess whether the observed type of mode switches recorded in the Greenland ice cap can be triggered directly within the atmosphere or whether, as I believe, triggering from the ocean is required.

For the Bolling-Allerod warm–Younger Dryas cold oscillation, sedimentary records document changes in the operation of the marine system coincident with those on land. Evidence for the abrupt changes bounding these events shows up in sediments from the northern Atlantic (*31*), the Cariaco Trench (*32*), the Gulf of California (*33*), the western Pacific (*34*) and the Santa Barbara Basin (*35*). Only in the Santa Barbara Basin has the entire series of millennial duration events seen in the Greenland ice core been reproduced (see Fig. 3). During the intervals of extreme cold in Greenland, the bottom waters in this 500-m-deep closed basin were sufficiently oxygenated to allow worms to stir the upper sediment, while during periods of intermediate cold and during the Bolling-Allerod and the Holocene, these bottom waters were too oxygen starved to host worms. These alternations between low and moderate oxygen content are matched by large changes in $\delta^{18}O$ and $\delta^{13}C$ values in both the benthic and planktonic foraminifera (*36*). The likely explanation is that during periods of extreme cold, the thermocline of the northern Pacific was directly ventilated, in contrast to the situation today where the surface waters are too low in salt content to permit local ventilation of the thermocline. Rather, the supply water travels all the way from south temperate latitudes, losing most of its oxygen to respiration along the way.

Additional evidence is obtained by combining two quite different observations (Fig. 4). The first is the contrast between the stable isotope records in Greenland and Antarctic ice for the period of deglaciation (20,000 to 10,000 years ago). Correlations based on methane concentration and on the $\delta^{18}O$ values in trapped O_2 (*37*) indicate that steps marking the transition from the glacial to Holocene for these two places were antiphased. The second is the temporal record of the changes in the $^{14}C/^{12}C$ ratio in the atmosphere and upper ocean reservoir, as recorded in tree rings, coral, and varved sediments subject to independent absolute dating. The record in the varved sediment of the Cariaco Trench (*38*) implies that at the onset of the Younger Dryas the $^{14}C/^{12}C$ ratio in these reservoirs began a steep rise of ~5%, which lasted for about two centuries. During the remainder of the Younger Dryas (~1000 years), the ratio slowly declined, eliminating much of this excess. Taken together, these two sets of observations suggest that a shutdown of the Conveyor not only initiated the cold climate regime of the Younger Dryas, but also caused newly produced ^{14}C atoms to remain in the atmosphere and upper ocean. Then after 200 years, a new circulation mode kicked in that resumed the downward transport of ^{14}C into the deep sea reservoir. Because this new mode did not alleviate the cold conditions in the regions surrounding the northern Atlantic, this burial of ^{14}C could not have been by the Conveyor. Rather, it likely involved a different style of deep ventilation in the Southern Ocean that not only carried radiocarbon to the deep sea, but also led to a warming of Antarctica (*39*). Thus, we have convincing evidence for the bimodal character of ocean circulation.

Were These Reorganizations Confined to the Late Quaternary?

Ubiquitous cycles in sedimentation have long been known. They are represented in sequences of all ages and in a wide variety of depositional environments. Most famous perhaps are the coal-bearing cyclothems (*40*) of Pennsylvanian age (see Fig. 5). Although in most cases the exact periodicity of these cycles remains unknown, for a growing number of cases estimates have been made based on the number of cycles between radiometrically dated horizons (*41*). In many cases, the results are consistent with one or more Milankovitch frequencies. The best documented are the cycles in the Newark series Triassic age lake beds (*42*). Here cycles of ~20,000, 100,000, and 400,000 years have been shown to dominate the entire 15-million-year history

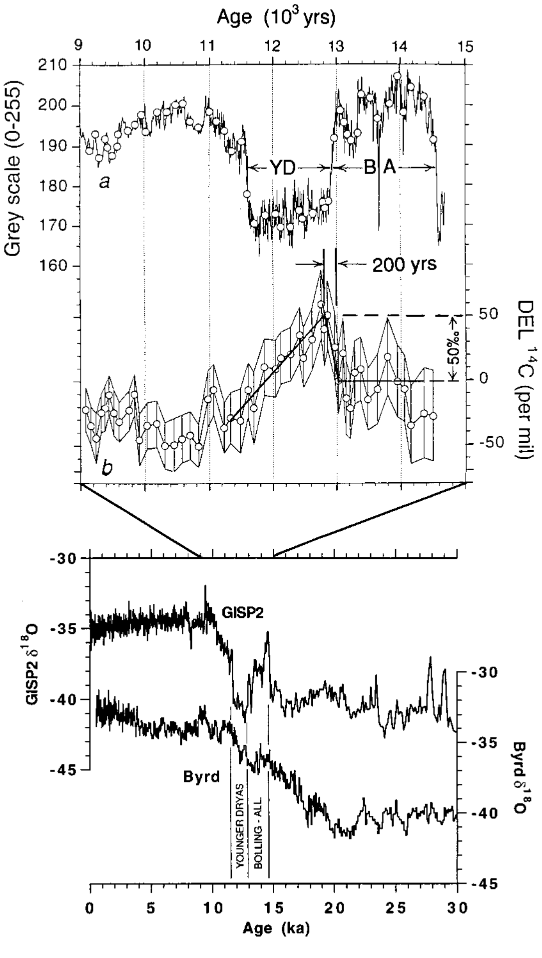

Fig. 4. Evidence in support of the existence of a bipolar seesaw in thermohaline circulation during the period of deglaciation. In the lower panel is shown the correlation between the stable isotope records for ice cores from Greenland (GISP2) and Antarctica (BYRD). This correlation is based on measurements of $^{18}O/^{16}O$ ratios of O_2 trapped in bubbles in the ice (*37*). The time scale is based on annual layer counts in the GISP2 core (*55*). As can be seen, an antiphasing exists between the ^{18}O increases (that is, warmings) at the two locales. That this antiphasing is related to changes in the rate of deep sea ventilation is dramatically demonstrated by the record of atmosphere–upper ocean $^{14}C/^{12}C$ ratio reconstructed from radiocarbon measurements on foraminifera from varved marine sediments, in the Cariaco Trench (*38*). As shown in the upper panel, during the first 200 years of the Younger Dryas (Y.D.) cold event (marked in Cariaco sediments by a prominent color change), newly produced radiocarbon atoms were backlogged in the atmosphere–upper ocean reservoir, reflecting a shutdown of deep ventilation (that is, the Conveyor). During the remainder of the Y.D., this radiocarbon excess was gradually removed by downward mixing into the large deep sea reservoir. Because the cold climate generated by the shutdown of Conveyor circulation was not ameliorated by this renewed ventilation, the burial of ^{14}C more likely occurred in the Southern Ocean than in the northern Atlantic (*39*).

of this mid-continent closed-basin lake.

The advent of hydropiston coring from drilling ships has provided long records that clearly show that Milankovitch frequencies dominate the sedimentary record for the past six or so million years (*43*). In the Mediterranean Basin, a record covering almost all of the last 11 million years has been pieced together from marine sedimentary sections exposed on land in Crete and Sicily (*44*). A 20,000-year cycle recorded as couplets of white marl and dark saprotite was operative throughout this entire time interval. But not all sedimentary cycles can be attributed to this pacing. For example, Anderson has clearly shown that millennial duration cycles dominated the sedimentary record in Permian sedimentary rocks from the Delaware Basin (*45*).

What is surprising about these sedimentary cycles is that the rather small forcing associated with orbital variations drove the pronounced sedimentary cycles preserved in the geologic record. As an explanation, I suggest that regardless of the geometry of the ocean basins, of the positions of the mountains relative to the planetary winds, and of the magnitude of pole to equator temperature gradient, it is likely that at any given time, more than one place on the Earth existed where deep waters could form. Where the most dense water could be generated would depend on the pattern and magnitude of fresh water transport through the atmosphere. Furthermore, the magnitude of these transports would change with seasonal distribution of insolation. In particular, it would vary at the frequency of the precession cycle (~20,000 years), which sets the position in the Earth's eccentric orbit at which the June solstice takes place. If the June position corresponds to the perigee of the orbit, the insolation will be lower than average, and vice versa. The magnitude of this contrast is influenced by cyclic changes (100,000 and 400,000 years) in magnitude of the orbit's eccentricity. Hence, if then as now, changes in thermohaline circulation served as powerful amplifiers of insolation cycles, these frequencies would be expected to appear in the sedimentary record. Even though the 40,000-year cycle in the magnitude of the tilt of the Earth's spin axis (obliquity) does not alter the contrast in insolation between the poles, it does alter the equator to pole contrast and hence water vapor transport. But, as was the case during the last glacial period, the frequencies of these reorganizations need not have been those of orbital cycles. Internal oscillations of a wide spectrum of frequencies could also have been operative.

A puzzling characteristic of these sedimentary cycles is that in many instances the boundaries between individual units are sharp rather than gradational as might be expected if sedimentation were driven by a linear response to the sinusoidal orbital forcing. Although this sharpness can be explained by thresholds in sedimentary conditions or by diagenesis, it is tempting to attribute the abruptness of at least some of these transitions to climate changes triggered by reorganization of the ocean's thermohaline circulation. Only by restudying these sequences with the idea that abrupt climate changes may have occurred will it be possible to evaluate the role of reorganizations of ocean circulation in the distant past.

Whatever their origin, these sequences appear to require changes in sea level on the same time scale as the sedimentary cycles themselves. The only viable mechanism for such changes appears to be the waxing and waning of continental ice masses. If so, as was the case during the Quaternary, the changes in ice volume may have occurred in response to differing global climate states, each matched to a separate mode of large-scale ocean circulation. Thus, even though the case for driving by reorganizations in thermohaline circulation remains to be developed, it is something that should be given careful attention.

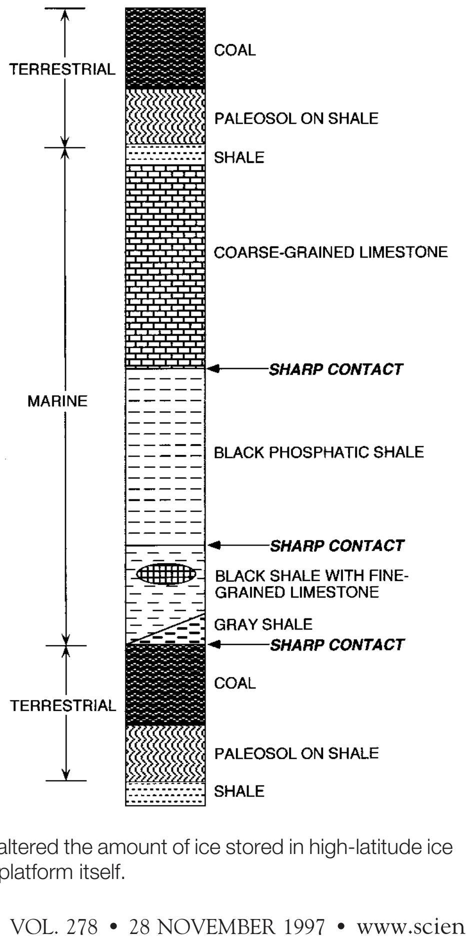

Fig. 5. Typical middle Pennsylvanian cyclothem (*40*). Each of these coal-bearing sedimentary cycles begins with a soil horizon formed on the shale unit that caps the preceding cycle at a time when the continental platform was perched above sea level. Overlying this soil is a coal seam formed from peat laid down in a fresh water swamp. The coal gives way abruptly to a shale and carbonate horizon presumably laid down as mud upon the invasion of the platform by the rising sea. This unit gives way abruptly to a black phosphatic shale. The mud and silt deposition is suddenly replaced by the depositon of biogenic $CaCO_3$. Finally, the depositional cycle is completed with the addition of a second mud unit, presumably in response to the retreat of the sea off the platform. Once the retreat is complete a soil begins to form on the recessional mud initiating the next cycle. In order to account for the 50 or so successive cyclothems, it is necessary to call upon oscillations in sea level superimposed on a steadily sinking platform. The amount of sediment accumulated during each cycle roughly matches the subsidence. The alternating exposure of the platform above sea level and invasion by the sea require the growth and retreat of a continental ice cap. It is possible to explain the sharpness of the subunit boundaries as a consequence of crossing sharp environmental, invoking only slow changes in the level of sea. But it is also possible that the sharp boundaries between subunits reflect abrupt changes in the sedimentary environment related to reorganizations of the ocean's thermohaline circulation. These reorganizations would not only have altered the amount of ice stored in high-latitude ice caps but also the tropical climate conditions on the platform itself.

Future Reorganization?

The buildup of the greenhouse gases CO_2, CH_4, and N_2O in our atmosphere is bound to continue for more than a century. China's rapid industrialization has led to upward revision of predictions regarding the magnitude of this buildup. While previously we thought in terms of doubling the strength of the CO_2 content of the preindustrial atmosphere, current thought is moving toward a tripling. Simulations of the response to such a large buildup differ in detail, but all coupled ocean-atmosphere general circulation models predict major changes in temperature, rainfall, and soil moisture. Further, in cases where simulations include coupled atmosphere and ocean models (*46*, *47*), large greenhouse buildups lead to collapses of thermohaline circulation (see Fig. 6). While these collapses are not accompanied by the type of global atmospheric responses seen in the glacial record, as suggested above, this may well reflect an inherent inadequacy in the atmosphere models. The occurrence of a large climate event plausibly linked to a circulation change about 8000 years ago, when temperatures typically were similar to or warmer than today's, raises the likelihood that thermohaline collapse is capable of perturbing climate during warm times as well as cold (*25*).

An important question to be explored in this connection is whether the shutdowns of thermohaline circulation experienced by coupled ocean-atmosphere models when perturbed by excess greenhouse gases are valid predictors of what might happen in the real world. No one would deny that these models have deficiencies. For example, even though the magnitude of the model's Southern Ocean deep water formation is comparable to that for the real ocean, the models do not generate this deep water in the right place. In the real ocean, deep water is formed mainly beneath sea ice along the margins of the Antarctic continent (*48*). Because the current models cannot duplicate processes on this small scale, they instead produce deep water well away from the continental margin. In order to accomplish this production, modelers must set the surface boundary conditions so that waters of sufficiently high salinity are present during the cold winter months. To do this, they use a strategy designed to eliminate a problem encountered by the current generation of coupled ocean-atmosphere models: the sea to air heat and fresh water fluxes required to stabilize the model's atmosphere differ significantly from the air to sea fluxes required to stabilize the model's ocean. Modelers introduce grid square by grid square difference terms for heat and fresh water transfer between ocean and atmosphere that are designed to stabilize both portions of the linked model. These terms compensate for the model's misrepresentations of heat and salt transport from one place to another within the sea. Thus, the models move equivalent amounts of heat and fresh water through the atmosphere. Examination of the geographic distribution of these flux-correction terms reveals that, especially for high-latitude grid squares, the fresh water flux corrections are often large (that is, comparable in magnitude with the actual fluxes). Indeed, it is by means of these difference terms that the polar surface water salinities are maintained at the values required for deep ventilation to balance the density loss created by the downward transport of heat.

Hence, it must be concluded that predictions made with these models regarding the response of the ocean's thermohaline circulation to the buildup of the atmosphere's greenhouse blanket could be in error. Even so, there is no reason to believe that these models are supersensitive to perturbations. It may well be just the opposite. So, until the next generation of models comes along, we must take seriously the predictions by the existing ones that a large buildup of greenhouse gases might cause the ocean's thermohaline circulation to collapse. We also must take seriously the possibility that such a collapse would have profound consequences to atmospheric operation and hence global climate. Of course, those who challenge the validity of the sizable greenhouse warmings predicted by these models will fault this result on the grounds that the warming and freshening of polar waters necessary for a thermohaline shutdown will not occur.

That abrupt changes in climate have occurred during interglacial as well as glacial periods is clearly documented. Not only did a brief but pronounced cold event occur in the early Holocene (see above), but it has been shown that the last major interglaciation (that is, the Eemian) was terminated by a brief but intense cold period in the northern Atlantic region. This cooling shows up in the marine record as a sudden resumption of ice rafting and a sudden return of the cold water species *N. pachyderma* left coiling (*49*) and in the continental record as an abrupt demise of tree pollen (*50*).

Clearly, if we are to prepare properly for the consequences of the buildup of CO_2 and other greenhouse gases in the atmosphere, we must greatly improve our knowledge of the deep water formation process. To me, it is the Achilles heel of the climate system. It is embarrassing to admit that in the case of the Southern Ocean, we have yet to match the production of deep water at specific locales with the aggregate amount required to account for the ^{14}C budget of the deep sea (which constrains production over the last several centuries). Nor can we account for the chlorofluorocarbon inventory in the deep Southern Ocean (which constrains production over the last few decades). Both of these constraints point to a rate of Southern Ocean deep water production of about 15 Sv (*9*). Yet attempts to add up the contributions from the presumed sites of this production fall well short of this total. Most physical oceanographers look to the Weddell Sea as the dominant source region, yet it appears to be supplying only a few (2 to 4) Sverdrups of new deep water (*51*). Hence, before we can launch adequate programs designed to assess the state of health of the Southern Ocean deep water formation, we must succeed in matching local production with total production.

But how can we distinguish oceanographic changes driven by mankind's activities from natural fluctuations? In order to do this, it is necessary to have a long enough record to establish the frequencies and amplitudes of fluctuations that occurred before the advent of anthropogenic forcing. In the case of the polar oceans, this proves to be a difficult task. For example, although not the main site of deep water formation in the northern Atlantic, the Greenland Sea marks the farthest penetration of the waters of the Conveyor's upper limb. Measurements of tritium and its decay product, ^{3}He, demonstrated that during the 1970s deep convection carried surface waters to the bottom of this basin (*54*). However, subsequent surveys suggest that after 1980 no significant further ventilation of the deep Greenland Sea has taken place (*52*). Does this signal an impact of the greenhouse warming or is it just another in a long series of natural fluctuations? We cannot tell.

Similarly, a comparison of ice margin positions based on logs kept by whalers with recent satellite measurements has suggested that the extent of ice cover around the Antarctic margin decreased between 1960 and 1975 (*53*). Putting aside the possibility that the interpretation of these log entries is faulty, we still cannot tell whether this change is a result of greenhouse warming or just another of a long series of ice front fluctuations.

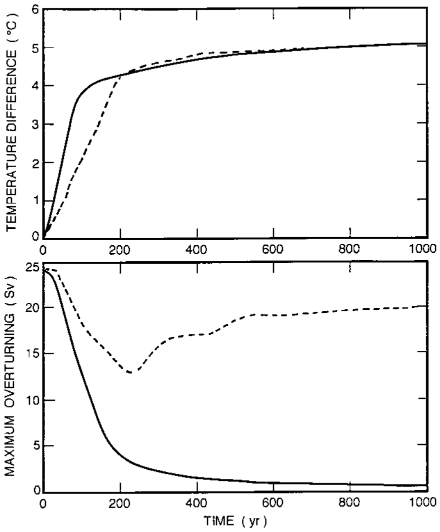

Fig. 6. Impact on thermohaline circulation in simplified three-basin ocean model coupled to a simple energy balance atmospheric model. Stocker and Schmittner (*47*) present various scenarios, two of which are reproduced here; in one, the CO_2 content of the atmosphere is increased at the rate of 1% per year (solid line) and in the other, it is increased at the rate of 0.5% per year (dashed line). In both cases, the CO_2 content increase continues until 750 ppm is reached, after which the CO_2 content is held at this value. The resulting rise in global mean air temperature for the two scenarios is shown in the upper panel and the impact on the strength of Conveyor circulation is shown in the lower panel. As can be seen for the rapid increase scenario, the Conveyor is shut down and remains so for at least 1000 years. For the slow increase scenario, the Conveyor sags to half its strength but then recovers to 75% its original strength. Because this model constitutes only a rough approximation to the real world, the results must be taken with some caution. However, as they are consistent with earlier modeling results by Manabe and Stouffer (*46*) using a full 3D ocean overlain by a full general circulation model for the atmosphere, they certainly provide no solace regarding the potential impacts of the ongoing greenhouse warming on the ocean's thermohaline circulation.

Summary

Through the record kept in Greenland ice, a disturbing characteristic of the Earth's climate system has been revealed, that is, its capability to undergo abrupt switches to very different states of operation. I say "disturbing" because there is surely a possibility that the ongoing buildup of greenhouse gases might trigger yet another of these ocean reorganizations and thereby the associated large atmospheric changes. Should this occur when 11 to 16 billion people occupy our planet, it could lead to widespread starvation, for in order to feed these masses, it will be necessary to produce two to three times as much food per acre of arable land than we now do. More problematic perhaps than adapting to the new global climate produced by such a reorganization will be the flickers in climate that will likely punctuate the several-decade-long transition period (Fig. 3, right panel).

So what do we do? Everyone would agree that the smaller the CO_2 buildup the less the likelihood of dire impacts. But we are hooked on cheap energy and the demand for it continues to grow. Furthermore, no viable and acceptable option to fossil fuels has yet been devised. Although efforts to bring about more efficient use of energy must be redoubled, it is my feeling that this route is not likely to succeed in bringing about an adequate reduction in CO_2 emissions. Hence, as a backstop, we must strive to develop an energy supply that does not load the atmosphere with CO_2. To this end I see a ray of hope. The idea is to separate the hydrogen atoms contained in fossil fuels by reacting them with steam. The H_2 produced in this way would be used in fuel cells, and the CO_2 would be captured at its source, liquified, and injected either into continental reservoirs or onto the sea floor (*54*). While perhaps doubling the cost of energy, this is something that could be accomplished. But as such a transition in energy-generation technology would require at least 50 years to implement, we must get off to a running start to put into place this insurance policy.

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13. The Sverdrup (Sv) is a unit of water transport. One Sverdrup is equal to $1 \times 10^6\ \mathrm{m^3/s}$. The transport by today's Conveyor is about 15 Sv compared to that of all the world's rivers of about 1 Sv.
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