Does the ocean–atmosphere system have more than one stable mode of operation?

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The climate record obtained from two long Greenland ice cores reveals several brief climate oscillations during glacial time. The most recent of these oscillations, also found in continental pollen records, has greatest impact in the area under the meteorological influence of the northern Atlantic, but none in the United States. This suggests that these oscillations are caused by fluctuations in the formation rate of deep water in the northern Atlantic. As the present production of deep water in this area is driven by an excess of evaporation over precipitation and continental runoff, atmospheric water transport may be an important element in climate change. Changes in the production rate of deep water in this sector of the ocean may push the climate system from one quasi-stable mode of operation to another.

MANY feedback loops that may amplify climatic change have been proposed, one of which has recently caught the imagination of palaeoclimatologists. Suggested by the atmospheric CO_2-content record recovered from the polar ice caps[1-3], this scenario involves interactions between climate and ocean circulation[4-7].

To appreciate the significance of the observations on polar ice, one must be aware of their context. Over the past several decades studies on deep-sea cores have provided a detailed history of climate during the past million years[8-10]. The first picture that emerged was that continental glaciers have waxed and waned on a timescale of 100 kyr[9]. These climate cycles are asymmetric, involving long periods of glacial buildup suddenly terminated with rapid warmings. Further work revealed that these long intervals of glacial buildup were modulated by cycles of ~20 and ~40 kyr duration[11,12], closely allied in timing and relative amplitude to variations in seasonal contrast produced by cyclic changes in the Earth's orbital elements[11,12]. Orbital forcing is accepted widely as the primary cause of glacial cycles (Fig. 1). Because the exact linkage between changes in seasonality and changes in climate has yet to be established, however, the issue remains open. Although it is plausible that non-linearities in the response of snow and ice cover to seasonal variations drive glacial growth and retreat[13], it is not clear whether this mechanism alone is sufficient to do so.

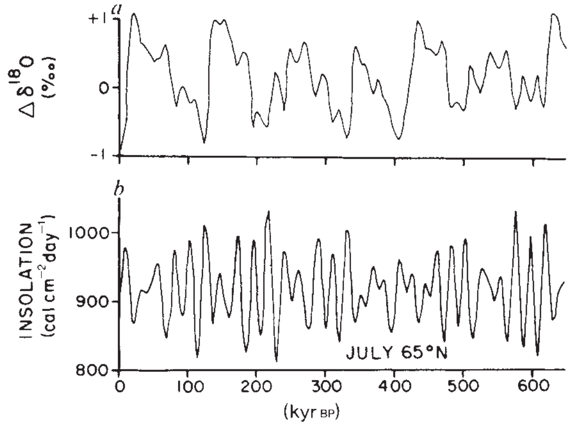


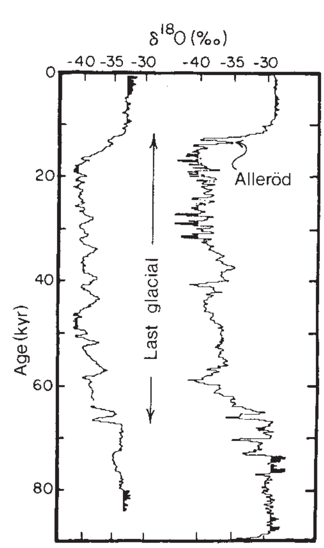
Fig. 1 *a*, Composite of the $^{18}O/^{16}O$ record for planktonic foraminifera from several deep-sea cores[12]. This record primarily reflects changes in the amount of continental ice in the Northern Hemisphere. The more positive the $\delta^{18}O$ value, the more ice. *b*, Variation with time of the July insolation at 65° N (ref. 51). The rapid disappearances of the ice that terminate the episodes of very large ice cover correspond to prominent peaks in summer insolation for the latitudes at which the excess ice was located. In addition, there is a strong coherence between the ~20 and ~40 kyr spectral components of ice volume and insolation records. Taken together these ties between insolation and ice volume have convinced most scientists concerned with palaeoclimates that the Earth's glacial cycles are driven by changes in seasonality brought about by cyclic changes in the Earth's orbital elements.

Ice-core record

Scientists examining the oxygen isotope record preserved in ice cores from Greenland and Antarctica (see Fig. 2), checked whether the major features of this record matched those found in the deep sea. In one sense they did match. Glacial conditions prevailed from before 50 to ~10 kyr BP at which time a transition to interglacial conditions occurred. Once this transition was complete, climate remained remarkably uniform. No evidence for the 20 and 40 kyr cycles characteristic of orbital forcing appears in the ice-core record, in part because the record extends to only ~100 kyr BP and in part because of the exponential foreshortening with depth of the thickness of ice representing a single year. This flow-induced distortion produces a considerable uncertainty in the ice-core chronology before 10 kyr BP.

Although not showing the orbital periodicities, the ice-core record for glacial time does show many brief events during which climatic conditions returned about halfway to their interglacial state. Because such events would be blurred totally by the stirring of worms in all deep-sea sediments with typical accumulation rates (that is, a few centimetres per kyr), this finding is not in conflict with the marine record. However, as

Fig. 2 Oxygen isotope records for ice cores[43] from Camp Century, Greenland (on the right) and Byrd Station, Antarctica (on the left). These records reflect mainly changes in air temperature over the ice cap. The more negative the $\delta^{18}O$ value, the colder the air temperature. The timescales are very approximate as there are as yet no direct radiometric ages for the glacial sections of the ice. Note that the glacial portion of the Greenland record shows a number of events of <1,000 yr duration. These events are muted (or absent) in the Antarctic record.



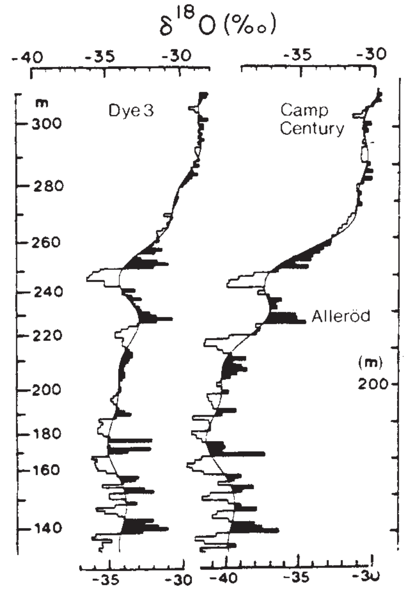


Fig. 3 Comparison between the $^{18}O/^{16}O$ records for the Camp Century and Dye 3 sites in Greenland for the time period ~40 to ~8 kyr BP. For each core a depth scale (metres above bedrock) is given. After some adjustment of the Dye 3 depth scale a good match is achieved between the records in the two cores. (Results obtained by Dansgaard *et al.*[14].)

these idiosyncrasies of the ice-core record were not seen in other records, the initial temptation was to pass them off as climate 'noise' without global significance. A rapid succession of findings has since changed this view of the noise, now the focus of much interest.

First, $^{18}O/^{16}O$ measurements by Dansgaard *et al.* on a second long core from Greenland[14] revealed the same events as the first (see Fig. 3), indicating that the events were both real, and occurred throughout Greenland. Second, the events were recorded not only by $^{18}O/^{16}O$ ratio changes but also by dust[15], ^{10}Be (ref. 16), SO_4, NO_3 and Cl content[17] changes in the ice. The ice formed during the warm events is similar to interglacial ice with respect to these properties. Third, the $^{18}O/^{16}O$ pattern found for the most recent Greenland event was also recorded in $CaCO_3$ from lake sediments in Switzerland[18], which gave credence to a correlation made early on by Dansgaard *et al.*[19] (see Fig. 4). In interpreting their $^{18}O/^{16}O$ results for the Camp Century Greenland ice core, they suggested that the strong oscillation just before the onset of postglacial time was a record of the Alleröd–Younger Dryas oscillation seen in pollen records throughout Europe. During the Alleröd, trees abruptly replaced the grasses and shrubs that had characterized glacial time, only to be replaced by the cold flora characteristic of glacial time (see Fig. 4). This so called 'Younger Dryas' cold period lasted ~800 yr (that is, from ~11 to ~10.2 kyr BP) before Holocene forests appeared. However, these results did not influence broader thinking about glacial cycles and their causes.

A few years earlier Berner *et al.* found that the CO_2 content of the air trapped in ice from the glacial sections of the Greenland and Antarctic cores was about two-thirds that for air trapped in ice from the interglacial sections[1]. Intrigued by the $^{18}O/^{16}O$ events found in the ice and the apparent correlation of the last of these with an oscillation in plant cover seen throughout Europe, Oeschger and co-workers found that there were CO_2 changes associated with these events[20,21]. In the Dye 3 core, oscillations (as recorded by the $^{18}O/^{16}O$ ratio) were accompanied by CO_2 oscillations of ~60 p.p.m. (see Fig. 5). The CO_2 change was about two-thirds of the change that accompanied the major glacial-interglacial transition[1-3]. Although Fig. 5 shows only the CO_2 records for the oscillations within glacial time, a similar CO_2 change is found during the Alleröd–Younger Dryas interval at the end of glacial time[20].

Oeschger and co-workers are now searching for the CO_2 events in ice cores from the Antarctic. Whereas the other changes found in Greenland (that is, ^{18}O, ^{10}Be, dust, etc.) may have been restricted to the region under the influence of the northern Atlantic, the CO_2 change must, of course, be global. Until confirmed in Antarctic ice, the possibility remains that the sharp changes in CO_2 content found in Greenland are artefacts of summer melting, which may have occurred during the warm events as it did at this low elevation site during much of the Holocene. We emphasize that although it was the discovery of CO_2 events that prompted serious consideration of possible ocean circulation-climate linkages, our speculations below about possible multiple climatic modes do not depend on the validity of the CO_2 changes.

Causes of atmospheric CO_2 change

The finding from ice-core studies that the CO_2 content of air extracted from glacial ice was lower than that extracted from postglacial ice[1-3] stimulated investigations as to the origin of natural CO_2 changes, which must be rooted in ocean chemistry[22,23]. The first scenario for the 90-μatm rise in CO_2 content at the close of glacial time called for the deposition of organic residues on the coastal shelves during the transgression of the sea that accompanied deglaciation. The subsequent finding of brief CO_2 events within glacial time, however, led to a re-examination of the question. If these CO_2 changes are typical of the atmosphere, then explanations involving the transfer of nutrient substances between the ocean and its shelf sediments must be abandoned. Such transfers could certainly not occur fast enough to produce 60-p.p.m. CO_2 changes in ~100 yr. To be viable, hypotheses will have to invoke redistributions of C, P and fixed N in the sea. Such redistributions are feasible if the ocean mixing and/or biological cycling change substantially[4-7,24]. This explains why CO_2 measurements on ice cores

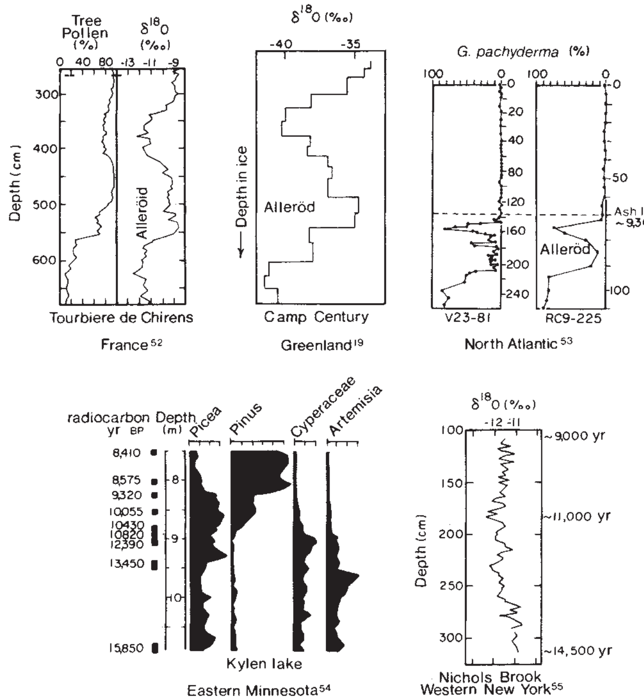


Fig. 4 Examples of records for the time period 13–9 kyr BP from Europe (pollen and $^{18}O/^{16}O$ in $CaCO_3$), Greenland ($^{18}O/^{16}O$ in ice) and the North Atlantic (% *G. pachyderma* in the planktonic foraminifera). All show the pronounced Alleröd–Younger Dryas oscillation. By contrast no such oscillation is seen in either pollen diagrams or $^{18}O/^{16}O$ records from the United States.

suggested links between climate and the joint operation of the atmosphere and ocean system.

Three quite different scenarios have been proposed. Broecker[24] pointed out that the evidence from deep-sea cores cited in support of his shelf-deposition hypothesis could also be explained by a change in the C to N and/or C to P ratio in the organic residues falling to the interior of the sea. A 30% decrease in this ratio was needed to explain the CO_2 drop at the end of glacial time.

Broecker and Takahashi[4] pointed out that a change in the transfer rate of water between the cold- and warm-water spheres of the ocean would produce a redistribution of ΣCO_2 between these reservoirs and a consequent change in atmospheric CO_2 content. The reason is that the biological 'pumping' of carbon by organisms from the surface ocean to the deep ocean is compensated partly by a flow of CO_2 through the atmosphere from the cold- to the warm-water sphere. Hence, a change in the rate of transfer of water between these spheres alters the balance between these two competing effects. To explain the lower CO_2 content during glacial time, Broecker and Takahashi invoked a several-fold higher rate of transfer of water between these spheres.

Three groups[5-7] have arrived independently at a different ocean scenario. Having pointed out that a reduction in the NO_3 and PO_4 contents of polar surface waters (that is, more effective biological use) would produce the desired glacial CO_2 reduction, all three groups demonstrated that a decrease in the rate of exchange between polar surface waters and the rest of the ocean may result in reduced nutrient content of polar surface waters and, in turn, of the CO_2 content of the atmosphere.

As the Broecker-Takahashi (B-T) ocean mixing scenario requires enhanced mixing during glacial time whereas the Princeton-Bern-Harvard (P-B-H) scenario requires reduced mixing, the balance of evidence must be carried by marine sediments, which would allow one of these hypotheses to be eliminated. Indeed, the P-B-H hypotheses predict higher than Holocene $\delta^{13}C$ values for planktonic forams grown in the Antarctic during glacial time whereas the B-T hypothesis predicts lower values. Unpublished ^{13}C results by N. Shackleton and R. Fairbanks on planktonic foraminifera from Antarctic deep-sea sediments strongly suggest that the reduction in surface water nutrient content required by the P-B-H hypotheses for glacial time did not occur. Radiocarbon age differences (determined by accelerator mass spectrometry) between planktonic and benthic forams from glacial horizons in deep-sea sediments eventually may provide another basis for making a distinction[25,26]. It is possible that neither of these scenarios is correct.

Although little is known about either ocean circulation or biological cycling in the past, one important clue has been found.

Table 1 Freshwater budget for the North Atlantic Basin, including the Arctic, Mediterranean and Caribbean

Source	Input rate fresh water ($m\ yr^{-1}$)	Freshwater flux (sverdrup)
River runoff[50]	+0.21	+0.33
Precipitation[50]	+0.87	+1.36
Evaporation[50]	−1.21	−1.89
Mediterranean exchange*	−0.07	−0.10
Nett†	−0.20	−0.30

The combined area of the North Atlantic basin (0°–80° N) excluding the Mediterranean Sea is $4.9\times10^{13}\ m^2$. For freshwater flux, 1 sverdrup represents a flow of a million cubic metres per second.

* The exchange between the more salty waters of the Mediterranean Sea and the less salty waters of the open Atlantic leads to a loss of fresh water from the Atlantic. This process is driven by the high evaporation rate (relative to precipitation and runoff) for the Mediterranean Sea.

† Using a deep water production rate in the northern Atlantic of $20\times10^6\ m^3\ s^{-1}$ and a salinity excess for this water of 0.50‰, a fresh water flux of 0.3 sverdrups would be obtained, indicating that no large discrepancy exists between oceanographic and meteorological budgets.

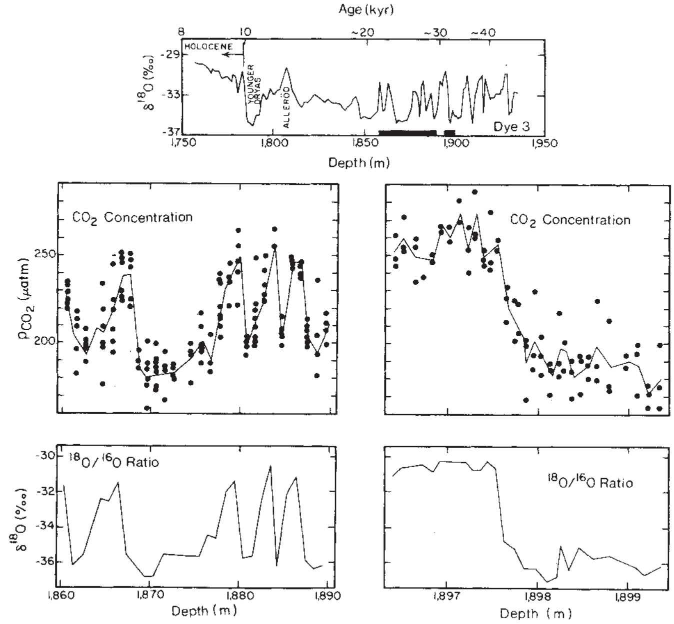


Fig. 5 Detailed P_{CO_2}–$\delta^{18}O$ comparison for two sections of the Dye 3 Greenland core[20,21]. The location of these sections are shown in the upper panel by the dark bands. The longer band represents a time interval of ~8 kyr and the shorter a time interval of ~2 kyr. The sudden air temperature warmings indicated by the rise in ^{18}O are accompanied by sharp rises in CO_2 content of air trapped in the ice. (CO_2 results obtained by Oeschger *et al.*)

Evidence from faunal, chemical[27] and isotope studies[23,28-31] of deep-sea sediments suggests that the production of deep water in the northern Atlantic, of great importance to the present-day circulation scheme, was reduced greatly during the peak glacial time. Most convincing is the finding by Boyle that the Cd content of benthic foraminifera from the Atlantic Ocean was higher during glacial time than today[27]. In the present-day ocean, the Cd and PO_4 contents of various water types in the sea are correlated almost perfectly. Thus, the Cd distribution in the glacial ocean is a good substitute for the P distribution. Boyle has demonstrated that the Cd/Ca ratio in benthic foraminifera is proportional to the corresponding ratio in the water in which they grow. In the present-day ocean, the low PO_4 and Cd content of Atlantic relative to Pacific deep water is attributable directly to the formation of deep water in the northern Atlantic. The reduction in this difference (suggested by the glacial foram results) is thus indicative of a reduction in the magnitude of the deep-water production in the northern Atlantic at that time.

Taken together, these arguments for the reduction of deep-water production in the northern Atlantic during glacial time are convincing. Is it possible then that the brief warm events recorded in the ice cores represent periods during which the glacially weakened northern Atlantic deep-water source was rejuvenated?

Distribution of oscillations

Adequate records are available currently to provide a picture of the geographical distribution for only the most recent fluctuation. This last oscillation appears in the records from both the Camp Century and Dye 3 cores from the Greenland ice cap and is found in pollen and $^{18}O/^{16}O$ ratio records from bog and lake sediments in western Europe. Evidence is also found in sediments in the northern Atlantic with an unusually high accumulation rate. Ruddiman and McIntyre showed that ~13 kyr BP the boundary between polar waters and temperate waters moved from its glacial position to near its present position (see Fig. 6), and remained there ~1 kyr before returning to its glacial position for several hundred years[32]. Finally; it returned to its present position where it remained throughout the Holocene.

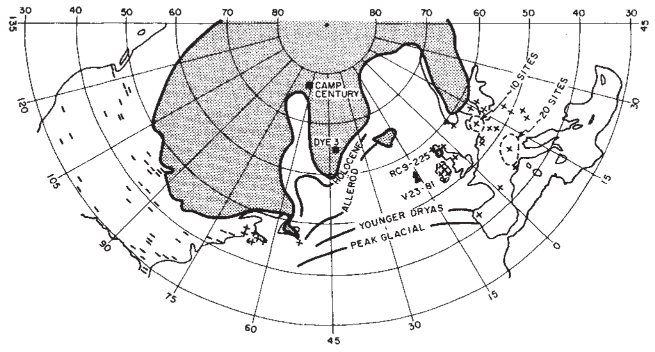


Fig. 6 Map showing the locations of sites at which sediments spanning the 13–9 kyr BP time interval have been studied[33–36]. At sites designated by a+ an oscillation in climate corresponding to the Alleröd–Younger Dryas is found. At sites designated by a− this oscillation has not been reported. The stipling corresponds to the area covered by ice just before the onset of the Alleröd[56]. Positions of the polar front in the northern Atlantic during peak glacial, Alleröd, Younger Dryas and Holocene time, as reconstructed by Ruddiman and McIntyre[32], and the locations of the two long ice borings in Greenland and of the two ocean cores referred to in Fig. 4 are shown.

There are >50 European sites whose pollen records contain an oscillation in the 13–10 kyr period[33]. In contrast to the European pollen record is the lack of evidence for this event in the United States[34]. Recent research on cores from lakes and bogs in New Brunswick, Nova Scotia and Newfoundland[35,36], however, indicate that the oscillation was felt in the eastern regions of maritime Canada. This evidence is summarized in Fig. 6. Thus, as proposed by Mercer[37], we may be dealing with a regional change in climate involving primarily the area under the climatic influence of the northern Atlantic Ocean. Because evidence for such an oscillation has been found elsewhere, that is, in the cordillera of South America[38–41] and in New Zealand[42], the situation may well be more complicated. This event is muted or absent in the $^{18}O/^{16}O$ ratio for the Byrd Station Antarctica record (see Fig. 2)[43].

Climate impact of deep-water production

The turning on and off of deep-water production in the northern Atlantic would be expected to produce a regional climate change. The rate of production of deep water is now ~20 Sverdrups (that is, 20,000,000 $m^3 s^{-1}$)[44]. The water feeding the source region for the deep water has a temperature of ~10 °C, whereas the new deep water leaving the region has a temperature of ~2 °C. Thus, as a byproduct of deep-water formation $\sim 5 \times 10^{21}$ cal of heat are released to the atmosphere each year, an amount corresponding to ~30% of the solar heat reaching the surface of the Atlantic Ocean in the region north of 35° N.

To test the geographical distribution of the impact of turning on and off this source of heat, an experiment was performed using the general circulation model for the atmosphere developed by the Goddard Institute for Space Studies. A comparison was made between the air temperature for a model run with present-day ocean conditions and for a model run with the surface ocean temperatures in the region north of the glacial polar front (see Fig. 6) cooled to the levels estimated by the CLIMAP (1981) reconstruction for glacial time[45]. The results of this experiment will be published elsewhere. The air-temperature anomaly generated by this change in sea surface temperature spreads across Europe. A cooling is seen in extreme north-eastern North America whereas no corresponding anomaly is seen in the United States or over Antarctica. The results are, therefore, consistent with the pollen and ice-core evidence. Although this experiment does not prove that the Alleröd–Younger Dryas event was caused by changes in the rate of deep-water production in the northern Atlantic, it does suggest that were such changes to have occurred they would have produced climate changes with the observed regional pattern.

Deep-water production changes

The most difficult question is why the production of deep water in the northern Atlantic may have resumed for brief intervals during glacial time. For an answer, we must consider the processes important to the present-day production of deep water in the northern Atlantic and for the absence of equivalent production in the northern Pacific. Oceanographers agree that the contrast between the two northern oceans is rooted in the large salinity difference. The waters of the northern Atlantic are saltier than the mean for the upper ocean, whereas the waters of the Pacific are fresher. The Atlantic's extra salt allows waters of density as great as any found in the deep sea to be generated during the winter months. By contrast, even if cooled to their freezing point, northern Pacific waters achieve a density no greater than that of intermediate depth water.

An approximate fresh water budget for the northern Atlantic and its satellite sea, the Mediterranean, is given in Table 1. Despite the fact that this region receives a sizeable portion of the world's river runoff, it loses an even greater amount of water through an excess in evaporation over precipitation. The resulting net loss of fresh water leads to the salt enrichment observed in the northern Atlantic. The salt budget for the North Atlantic must be balanced by the export of salty deep water to the Pacific and Indian Oceans. On a global scale, the water (and salt) budgets of the surface ocean must balance; thus, the fresh water lost from the Atlantic must re-enter the ocean elsewhere. Polewards of 30° N, atmospheric transport produces a net divergence of water vapour over the North Atlantic and convergence over the North Pacific east of the dateline[46]. Thus, if we are to understand what maintains deep water production in the present-day ocean, we must understand why fresh water is being pumped through the atmosphere from the North Atlantic to the North Pacific.

Warren, addressing this question[47], has shown that this pumping can be explained nicely by the temperature difference between the two oceans. The waters north of 30° latitude in the Atlantic are warmer than their Pacific counterparts. Thus, water is being distilled off the 'warm' Atlantic and condensed on the 'cold' Pacific. If so, then it is the temperature difference on which we must focus. What maintains it?

To some extent the warmer temperatures for the surface of the northern Atlantic must be related to the deep-water formation process. Upper waters in the Atlantic are advected northward into the regions of deep-water production. This advection carries heat to high latitudes. By contrast, in the northern Pacific, deep water upwells to the surface and is carried southward in the upper ocean. In this sense the situation is self-sustaining. Stommel[48] and Rooth[49] have discussed the possibility that thermohaline circulation has more than one stable mode. The deep-water circulation pattern maintains surface temperature of the northern Atlantic at a higher value than that for the Pacific. This temperature difference causes the Atlantic to be enriched in salt, whose excess leads to deep-water formation. At steady state, deep-water production must carry away just the amount of excess salt left behind by the atmospheric transport of water from the Atlantic to the Pacific. The standing excess of salt in the northern Atlantic is presumably just high enough to allow the generation of water sufficiently dense to enter the deep Atlantic.

This brings us to the fundamental question of this review—does the ocean–atmosphere system have more than one mode of operation? The idea that the Earth could, under the same solar heating regime, have quite different temperatures depending on its ice albedo or atmospheric greenhouse gas content is not new. Climate modellers have long been aware of the white Earth catastrophe scenario. If somehow the Earth were to be covered with ice, the greatly increased reflectivity of its surface would cause the temperature to fall below the freezing point and thereby stabilize the change. They have also considered the

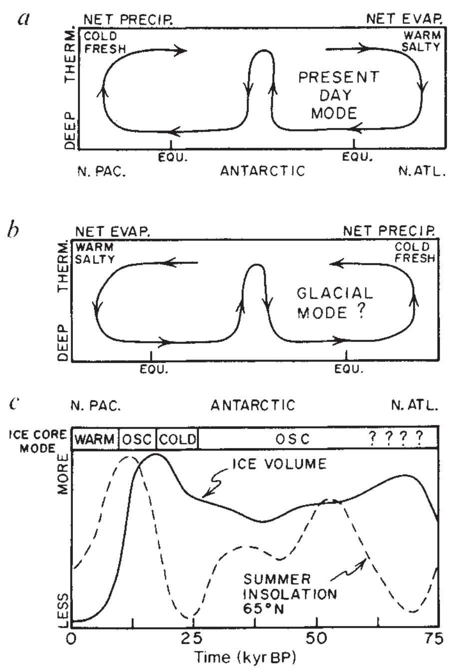


Fig. 7 *a, b,* Two possible extreme modes of ocean circulation are proposed here, corresponding to the warm and cold intervals seen in the ice-core record. *c,* The times when the ice-core record shows the system to have been locked in its warm mode, to have been locked in its cold mode or to have been oscillating between these modes are shown with the ice-volume record and the Northern Hemisphere high-latitude summer insolation record. The intervals of warm Greenland climate correspond to intervals of low ice volume and high summer insolation and the intervals of cold Greenland climate correspond to times of high ice volume and low summer insolation. The intervals when Greenland climate oscillated between warm and cold corresponded to times when the ice volume–summer insolation product had intermediate values. This suggests that the atmospheric transport of water vapour between the Atlantic and Pacific changes with ice cover and summer insolation.

greenhouse catastrophe. If somehow the carbon locked up in sediments were to be released to the atmosphere, the enhanced infrared absorption would raise the planetary surface temperature to the point where carbonate minerals and organic residues could no longer form and thereby stabilize the change. Based on the CO_2 results from ice cores, Oeschger suggested that the Earth had two modes of ocean–atmosphere–biosphere–cryosphere operation. Each oscillation observed in the ice cores involves a jump from one mode of operation to the other.

It is tempting to speculate that one of Oeschger's two modes corresponds to the situation when deep-water production in the northern Atlantic is 'strong' and the other to the situation when deep-water production is 'weak'. If this is the case, then the palaeoclimatic record tells us that, for the summer insolation and ice-cover situation that prevailed during the full interglacial time, the system was in the 'strong' mode and for the corresponding situation that prevailed during full glacial times it was in the 'weak' mode. Because in the present-day ocean the deep-water production corresponds to salt enrichment in the Atlantic, it is tempting to postulate that during full glacial time the opposite was true. Then, salt was being enriched in the Pacific and deep-water flow was the reverse of what it is now (see Fig. 7). Based on oxygen isotope studies on North Pacific cores, deep water may have been produced in the Pacific Ocean during glacial time (N. Shackleton, personal communication). On the other hand, it is possible that the rate of salt enrichment in the Atlantic was considerably less during glacial time, causing a reduction in deep-water production rather than a reversal in flow. Boyle's Cd data favours this latter point of view.

The Oeschger climate oscillations occur in intervals with climates lying between those characterizing full glacial and full interglacial time. If, as the summer insolation at high northern latitudes increased and once again the atmospheric vapour transport balance favoured salt buildup in the Atlantic, then the production of deep water would resume (or intensify), releasing excess heat to the atmosphere over the northern Atlantic. This excess heat would lead eventually to increased discharge of ice from the caps surrounding the Atlantic. If 3% of the excess ice present during full glacial time were added to the Atlantic Ocean by melting during a 100 yr interval, the mean freshwater flux would be 0.6 sverdrups (that is, twice the present imbalance between fresh water and loss for the Atlantic). Thus, the melt water generated in this way would significantly reduce deep-water production, returning northern Atlantic climates to their glacial state. This, in turn, would halt ice retreat and allow the northern Atlantic salt buildup to resume. Thus, it is possible that during periods of ice retreat the system oscillates between the North Atlantic 'strong' and 'weak' modes of deep-water production. Although the physics of such an oscillation has yet to be elucidated, two elements are evident. The first involves water storage in and release from the large Northern Hemisphere glacial ice caps adjacent to the Atlantic. The other involves the transport of salt through the deep sea. As water now resides for many hundreds of years in the deep sea, transients in the deep-ocean salinity distribution created by ventilation changes may be an important element in the oscillator.

Climate modelling

Until now, our thinking about past and future climate changes has been dominated by the assumption that the response to any gradual forcing will be smooth. But if, as proposed by Oeschger, the system has more than one quasi-stable mode of operation, then the situation is more complex. Present general circulation models will at best allow us to study only the changes that will take place if the system remains in its current operational mode. Thus, if the changes that characterized glacial time and those that will characterize the coming CO_2 superinterglacial time involve mode switches, investigations of the transient climate response have to allow for this possibility.

Despite the tenuous nature of the information presently available and of the difficulties inherent in thinking in terms of mode changes, we must begin to explore this alternate track. The programme elements required are clear. At least we must have a joint ocean–atmosphere general circulation model that will allow the exploration of several possible connections between planetary radiation, atmospheric water transport, ocean circulation, atmospheric trace gas content and the marine and terrestrial biosphere. If we are to have confidence that these models provide reliable analogues to the real world, we must gather more information about how each of the important subsystems operates in the present. Finally, we must extract all possible information from the palaeoclimatic record. Even given the full use of present resources, it will be several decades before we possess sufficient understanding to predict future climates. Unless we intensify research in these areas, the major impacts of CO_2 will occur before we are prepared fully to deal with them.

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ARTICLES

Powerful extragalactic masers

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Two strong extragalactic OH masers have been detected in the galaxies NGC3690 and Mrk 231 which are in the same class as the megamaser source IC4553 (Arp 220). The amplification model for the background continuum proposed for IC4553 can account for most of the powerful OH maser lines and for part of the H_2O emission. Most masing galaxies have sufficient infrared flux to pump the masing regions, except that the H_2O pumping must occur at a much higher conversion efficiency than the OH pumping.

THE extraordinary strength of the few OH and H_2O extragalactic masers[1-11] suggests that there are emission processes occurring in these sources which differ significantly from those that occur in galactic masers[12,13]. By far the most luminous OH maser detected to date is in the source IC4553 (refs 4, 14), whose maser emission is superposed exactly on the continuum source in the nucleus of the galaxy[14,15]. This strongly suggests the presence of amplification of the flux from the nuclear continuum source by a foreground molecular region. The masing region may have a relatively low gain and may not have been observable in the absence of the background source.

This article presents the recent detection of two powerful OH megamasers in the galaxies NGC3690 and Mrk231. Because of their similarity to the emission in IC4553, most of the powerful extragalactic OH maser emission can be interpreted with the continuum amplification model proposed for IC4553. This concept can be extended to the H_2O maser emission as well.

New detections

A search for OH absorption or emission in 110 galaxies with strong continuum sources in June 1984 used the 91-m telescope of the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia, which brings the total number of galaxies searched at Arecibo and Green Bank to 240. A cooled gallium arsenide field-effect transistor receiver with a total system temperature of 27 K was used in combination with a 396-channel autocorrelation receiver, which was split in two banks for the two circular polarizations. The sensitivity of the 91-m telescope is 1.1 K Jy^{-1} at 18 cm. Very gentle third-order baselines were subtracted from the data.

Strong OH emission was detected in two systems, NGC3690 and Mrk231[16]. Several new OH absorption features were detected, among which are the line NGC3079[5] and a tentative detection in the H_2O maser galaxy NGC4258. The absorption results will be published separately (W.A.B. *et al.*, in preparation). The results on the new OH maser sources are summarized in Table 1 and Figs 1 and 2.

NGC3690. The nuclear activity in the interacting galaxy pair NGC3690/IC694 (Mrk171) is one of the prime examples of starburst activity[17]. The pair of Sc galaxies is depicted in plate 299 of Arp's catalogue[18]. NGC3690 exhibits the most luminous optical emission lines of any non-Seyfert Markarian galaxy[19] and is also a very strong infrared source[20-22]. The radio source in NGC3690 has a triple structure and the 10-μm emission and optical line emission are superposed perfectly on this triple[17]. Prominent neutral hydrogen absorption towards the radio nucleus of NGC3690 has been seen at the VLA[23]. This broad and deep absorption line has a double structure with a separation of 160 km s^{-1} and can most readily be interpreted in terms of nearly edge-on absorbing disks (in agreement with the optical image). Optical studies[24] also indicate a velocity spread across the nuclear region of ~125 km s^{-1} increasing to the west. NGC3690 is a strong CO emitter; emission of this gas follows the infrared and radio structure of the galaxy (P. Salomon, personal communication; W.A.B. and R. W. Freund, unpublished results). The CO emission also has two peaks at ~130-km s^{-1} separation.

The OH emission spectrum of NGC3690 is presented in Fig. 1. The 1,667- and 1,665-MHz lines are clearly visible in the spectrum and are merged slightly. The features have been verified recently using the Very Large Array (VLA)-A. The double structure in the 1,667-MHz line agrees quite well with the two H I absorption features. Assuming the high velocity OH component originates at the west continuum component and