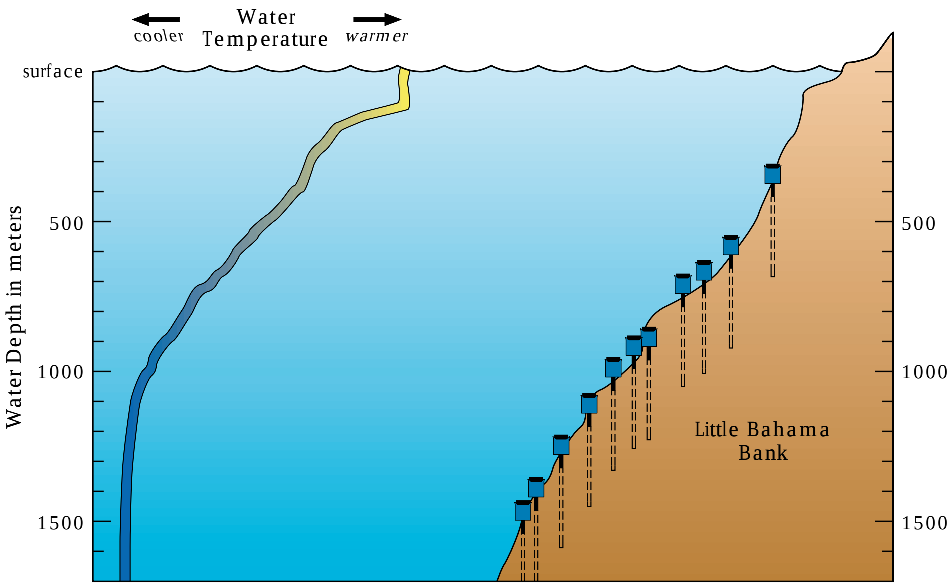

The thermocline at the Bahamas and a schematic representation of sampling strategy. Sediment cores were recovered from the complete bathymetric range within the thermocline. Using radiocarbon age dating and other methods, glacial samples were identified from each core and used to reconstruct the bathymetric profiles presented in the figure on page 14.

Glacial-Interglacial Changes in the Structure and Chemical Properties of the Thermocline

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The ocean's main thermocline is the persistent sharp temperature gradient that characterizes the transition from the top few hundred meters of wind-mixed surface waters to the intermediate and deep waters below. In contrast to the seasonal thermocline that forms annually in response to summer heating of temperate and subpolar surface waters, the position and shape of the main thermocline are controlled by a balance between large-scale surface climatological processes (including the strength and position of trade winds and westerlies, winter heat loss of surface waters at high latitudes) and the constant upward mixing or upwelling of cold deep and intermediate waters.

Columbus Iselin (WHOI's second Director) first noted that the distribution of temperature and salinity in the main thermocline duplicated the winter surface-water distribution of temperature and salinity in the North Atlantic. He proposed that, within the thermocline, water flows along lines of equal water density (isopycnals) from their region of surface outcrop toward the center and southern portions of the subtropical gyre. This prediction was confirmed by measurements of the distribution of tritium and helium isotopes, products of the atmospheric testing of nuclear weapons in the late 1950s and early 1960s. In the 1980s WHOI Senior Scientist Bill Jenkins noted that the observed distribution of these tracers requires lateral mixing along isopyncals to be more effective in controlling thermocline structure than vertical mixing and diffusion.

The subtropical gyre thermocline spans about 1,000 meters (figure above) and varies in temperature from more than 20° C in the upper portion to less than 5° C in the lower portion. Salinity is higher in the shallower levels of the thermocline and lower in the deeper levels, reflecting the low-to-high latitude decrease in salinity observed in the North Atlantic. Low dissolved-oxygen concentrations are usually found in the lower part of the thermocline, where the rates of organic-matter decay and oxygen consumption exceed the replenishment of dissolved oxygen from the surface.

The temperature and salinity of thermocline waters are ultimately controlled by surface-climate processes. Winds in the mid-latitudes interact with the surface ocean to create regions of net upwelling and downwelling. Surface waters in the downwelling region are subducted into the thermocline and mix rapidly along isopycnals. These waters are typically found in the upper 700 meters of the subtropical gyre thermocline, the "well ventilated" portion of the thermocline

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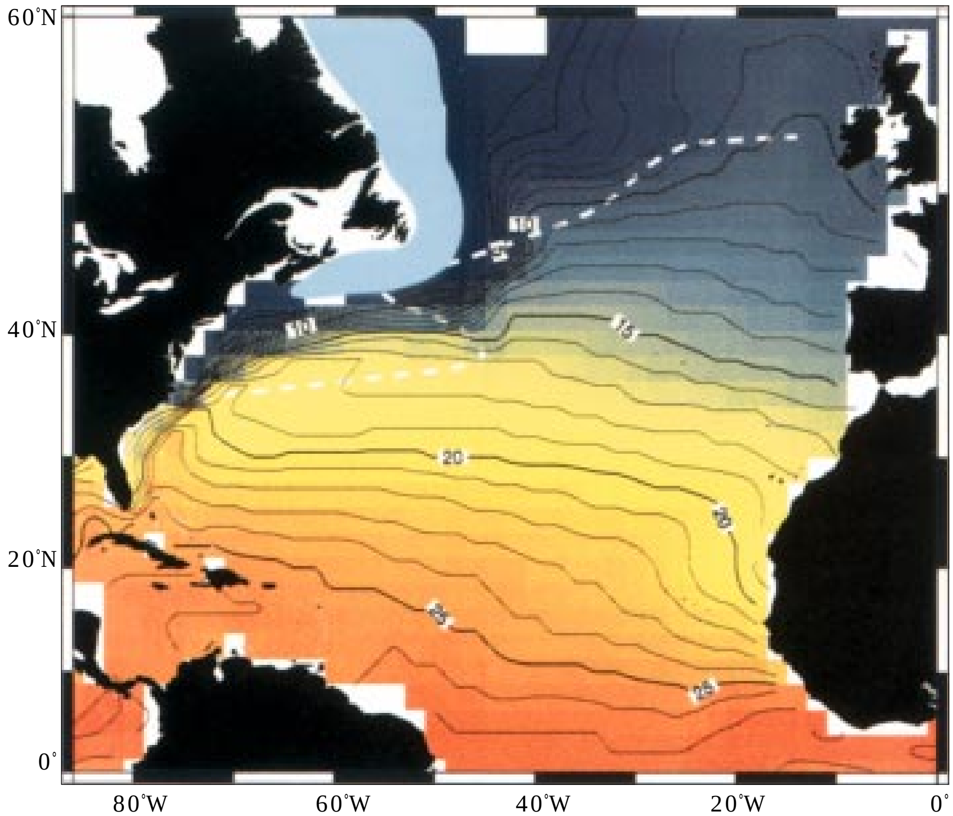

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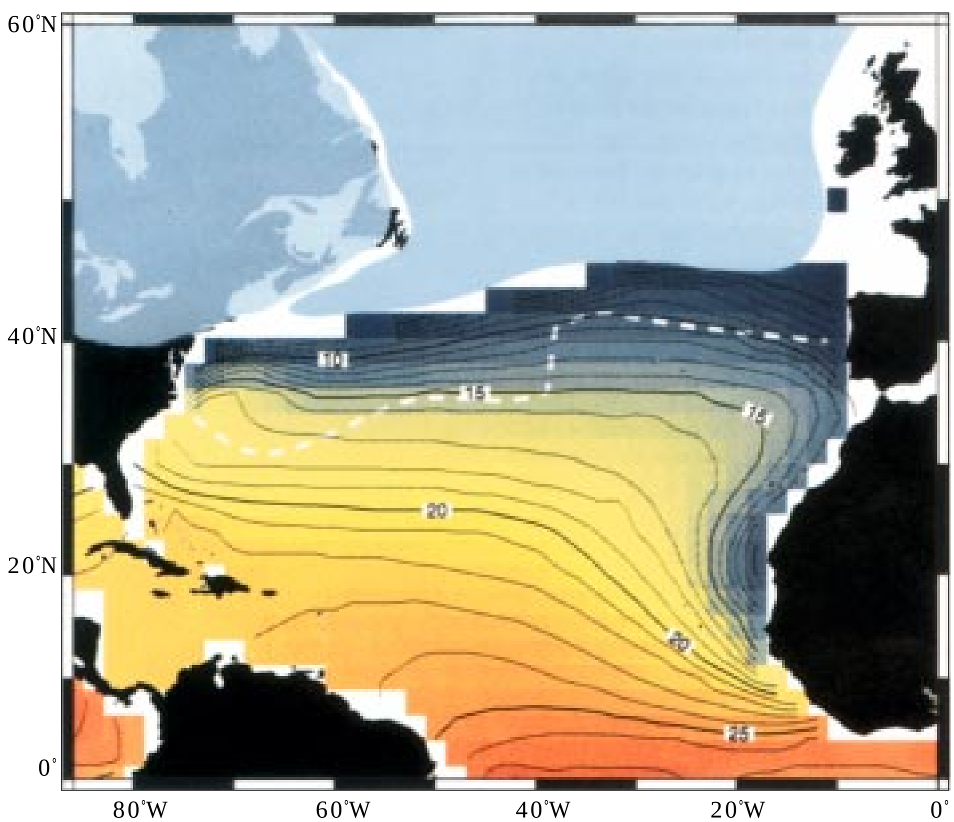
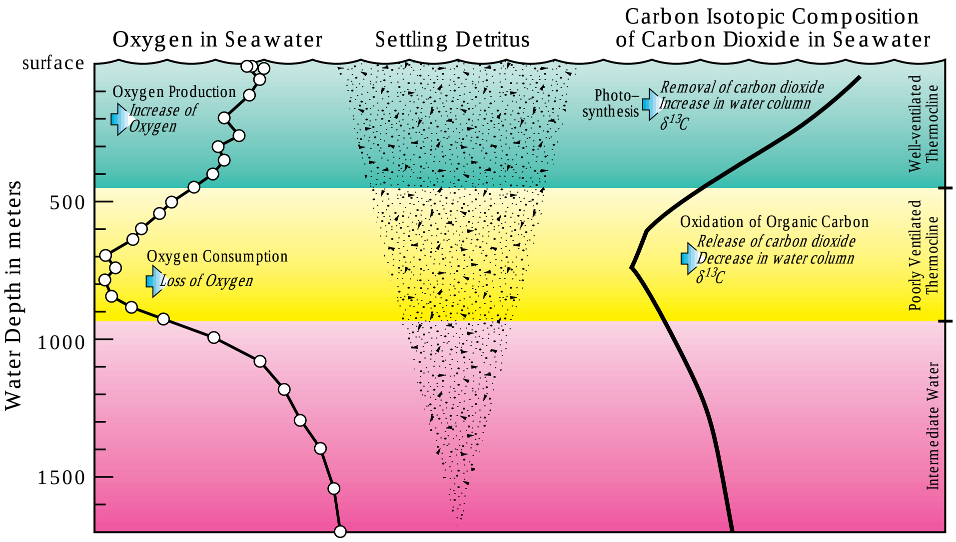


where disolved oxygen is rapidly mixed through flow along isopycnals. The water types of the well-ventilated thermocline outcrop south of the line separating upwelling from downwelling (figure at left) and are characterized by relatively high dissolved-oxygen concentrations.

The surface waters in the upwelling region, north of the dashed line in the figure, require alterations in their temperature or salinity characteristics to increase density; only with increased density would surface water overcome the tendency to upwell. Therefore surface waters north of the dashed line are much less likely to be subducted into the thermocline. This is the outcrop region of the poorly-ventilated portion of the thermocline, which correlates with the dissolved-oxygen minimum observed throughout the entire subtropical-gyre thermocline.

The processes that produce the dissolved-oxygen distribution in the thermocline also fractionate the carbon isotopes in a way that provides paleoceanographers with a method to reconstruct past oxygen distribution (opposite). During photosynthesis, carbon dioxide with a characteristic isotope composition is removed from seawater and converted into plant organic carbon. A portion of this organic carbon settles through the water column and oxidizes, that is, converts back into dissolved, inorganic carbon dioxide. This “remineralization” process removes dissolved oxygen from the water column in about the

The distribution of sea-surface temperatures for winter conditions in the Atlantic today (top) and a reconstruction of the temperature distribution during the maximum of the last glaciation (bottom). The dashed line in each figure separates the region of upwelling (north of the line) from downwelling (south of the dashed line). Surface waters in the downwelling region are most likely to be subducted into the well-ventilated region of the thermocline. The existence of a large ice sheet on North America had a dramatic effect on the temperature distribution in the glacial North Atlantic and caused significant increases in the delivery of well-oxygenated water to the subtropical-gyre thermocline.

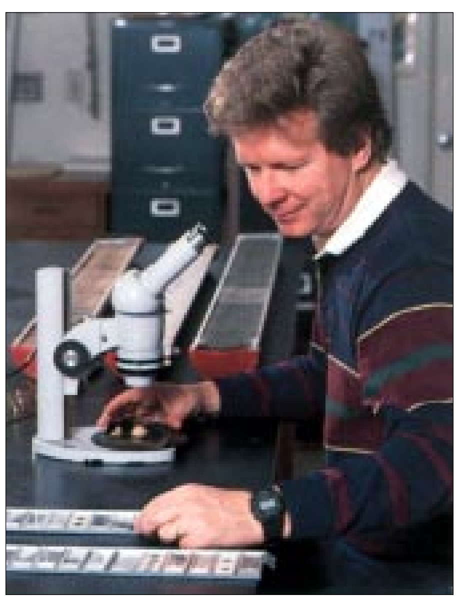


Carbon production in surface waters and subsequent oxidation of the carbon at depth produces water-column gradients in both dissolved oxygen and carbon isotopes. Photosynthesis in surface waters preferentially removes carbon-12 and oxidation at depth releases this carbon back into the water column. This process results in water column profiles of carbon isotopes and dissolved oxygen that are parallel. Organisms living in sediments record the carbon isotope composition of their environment when they produce their calcium carbonate shells (see figure on page 14). The fossil shells of these organisms can then be measured to determine past water column profiles of carbon isotopes.

same ratio as it was produced in the surface water by the photosynthesis process—for every remineralized mole of organic carbon, about 1.3 moles of dissolved oxygen is consumed.

But because of differences in the delivery rates of oxygen to the various depths in the water column, the removal of dissolved oxygen affects the total dissolved oxygen in different ways at different depths. In the well-ventilated depths of the thermocline, oxygen delivery by advection along isopycnals is rapid with respect to the dissolved oxygen loss from organic carbon oxidation; thus the oxygen content of these waters remains high. In the poorly ventilated regions of the thermocline the dissolved oxygen delivery rate is slow compared to the oxygen loss due to organic carbon oxidation, so the dissolved-oxygen concentrations at these depths are reduced compared to depths above and below. This process produces a water-column profile of dissolved oxygen and carbon-isotope composition with similar characteristics: a distinct minimum in both properties at the thermocline's level of poor ventilation.

Paleoceanographers find that the shells of single-celled benthic Foraminifera accurately record the carbon-isotope distributions in today's ocean and use measurements of fossil benthic Foraminifera to reconstruct the past carbon- isotope chemistry of the oceans. Benthic Foraminifera secrete an internal structure of calcium carbonate that has a carbon-isotope composition very similar to their seawater environments. By measuring the same internal structure in well-dated fossils of benthic Foraminifera, past carbon-isotope distributions in the thermocline can be reconstructed. Joint Program graduate Niall Slowey (now at Texas A&M University) and I used this approach to reconstruct the thermocline and oxygen profile for the North Atlantic Ocean during the maximum of the last glaciation, about 20,000 years ago. We collected a suite of high-quality cores from the slopes of the Bahamas, at depth levels that intersect the thermocline of today's ocean (see figure on page 11). The carbon- and oxygen-isotope chemistry of the benthic Foraminifera in the most recent sediments of these cores accurately records the physical and chemical properties of the subtropical gyre in the North Atlantic today (see figure overleaf). We used several independent criteria to identify synchronous samples from the maximum of the last glaciation in the same cores and employed benthic foraminiferal chemistry to reconstruct the thermocline and dissolved-oxygen distribution at that time. (These findings were recently presented in *Nature* volume 358, pages 665-668, 1992.)



TOM KLEINDINST

William Curry examines Foraminifera specimens whose shells are used to reconstruct the thermocline and dissolved-oxygen distribution.

The most striking result from this study was the disappearance of the minimum in carbon-isotope composition and, presumably, dissolved oxygen from the glacial profile (see figure overleaf). Although the benthic Foraminifera in the sediments at the top of the core display a prominent carbon-isotope minimum, that minimum is not apparent in glacial samples. The dissolved-oxygen distribution of the glacial ocean, if the same processes controlled it as those at work today, would be characterized by a monotonic decrease from the surface water down through the upper water column to at least 1,500 meters. Data from other studies suggests that the bathymetric decrease in dissolved oxygen in the glacial ocean continues down through the entire water column to the seafloor.

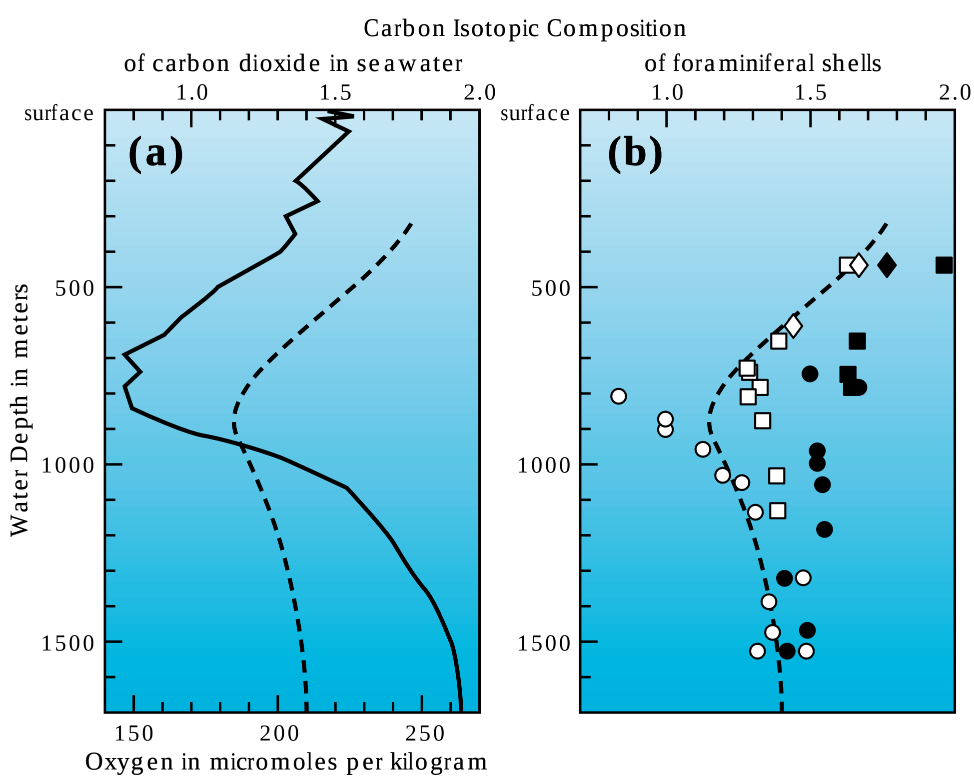
What changes in the ocean could

have produced a subtropical gyre without an oxygen minimum? The simplest explanation invokes the changes in circulation of surface waters and winds in the mid-latitudes of the North Atlantic that accompanied the ice buildup on the nearby North American continent. Today the only continental ice in the Northern Hemisphere is found on Greenland, but during the maximum extent of the last glaciation, the Laurentide Ice Sheet penetrated southward on the North American continent to nearly 38°N. The effect of this large ice mass on the surface climate of the North Atlantic was extreme. Surface-water temperatures were cooled by as much as 10° C in the temperate latitudes, oceanic fronts like the polar front moved southward by 30 degrees of latitude, and the wind distribution became more zonal. The net effect of these changes was to decrease northward heat transport in the North Atlantic and to shut down the thermohaline circulation system that produces deep water in the Atlantic.

In addition, there was a change in the distribution of surface- water properties in the zone where thermocline waters were entrained. Thermal gradients in the mid-latitudes were much stronger than they are today, and these gradients control the distribution and intensity of surface winds in the region of westerly winds (at about 40°N during the last glacial maximum). South of the zone of the line separating upwelling from downwelling (the dashed line in the lower figure on page 12), surface-water properties were at least 2˚ to 4° C cooler than today. North of the dashed line, the ocean surface was extremely cold and covered with sea ice during much of the winter. These two differences combined to create the distribution of carbon isotopes and temperature we observed in glacial sediment samples. The increase in wind stress during the glaciation and the increased cooling of surface water combined to increase the rate of subduction of surface waters into the subtropical-gyre thermocline. As a result, the thermocline was well ventilated over its entire depth.

This research leaves several unanswered questions. First of all, how widespread was this change in gyre circulation? Was the oxygen minimum absent from the eastern subtropical gyre as well? Today the oxygen minimum is much more developed in the eastern Atlantic along the upwelling region off Northwest Africa than it is in the western subtropical gyre. Thus it would take a greater increase in dissolved-oxygen delivery to eliminate the oxygen minimum there. How about other ocean basins? The Pacific Ocean is generally lower in dissolved oxygen than the Atlantic, and has a well-developed oxygen minimum today. Again, it would take a large increase in circulation rate to eliminate the oxygen minimum in the Pacific. Since glacial-interglacial changes in atmospheric circulation were most pronounced in the North Atlantic because of the effects of the nearby ice sheet on North America, it is likely that the changes in ocean circulation were also greatest in the North Atlantic.

Our research strategy can be applied to several other shallow carbonate banks around the world, but as yet we have little data from other regions with the same resolution of the upper water column as we have at the Bahamas. Our strategy for the next several years will be to core these regions to evaluate the effects of the last glaciation on subtropical-gyre circulation in the Indian and Pacific oceans. ■



A comparison of the present water column profile of carbon isotopes (left figure, dashed line) and the record from the benthic foraminiferal shells living in the tops of Bahamian sediment cores (right figure, open symbols). The benthic organisms show a prominent minimum in carbon isotopic composition at the depth of the oxygen minimum. But during the maximum of the last glaciation (right figure, closed symbols) no minimum is present. The absence of this carbon isotopic minimum suggests that no dissolved oxygen minimum was present in the thermocline of the glacial North Atlantic.