tures, ~200 μm in diameter, surrounding a central blood vessel. Compact bone, solid to the naked eye, is modified in places to form trabecular bone, which consists of many struts; the spaces between the struts are filled with marrow (see the figure, right panel). These struts are not randomly arranged, but are related to the direction of loads on the bone. The mechanical and other properties of bone depend on the interaction of all levels of organization (*4*).

Two more examples of the structural hierarchy of biominerals are the teeth of sea urchins and the "crossed-lamellar" structure of many mollusk shells. The crossed-lamellar structure consists almost entirely of calcium carbonate in the crystalline form of aragonite, with a tiny amount of organic material between the crystals. It has five levels of organization, and the structures are arranged with high precision to prevent the traveling of cracks (*5*, *6*). Sea urchin teeth have fewer levels of hierarchy, but their structure is very similar to that of fiber-reinforced plastics. However, they consist of a composite in which fibers and matrix are chemically identical, being made of calcite, although the crystals differ greatly in size and orientation, with a layer of organic material surrounding the fibers (*7*). Furthermore, the magnesium content of the calcite increases toward the middle of the tooth, markedly increasing its hardness. The resulting differential wear produces a self-sharpened tooth.

The main mechanical function of these hierarchical arrangements, almost certainly, is to produce interfaces that will open up in the presence of potentially dangerous cracks, deflecting the cracks and making their travel energetically expensive. This makes biomineralized skeletons surprisingly tough, given that they are made almost entirely of mineral. Bone is a special case, having less mineral than most other biomineralized skeletons; it can be remarkably tough.

Apart from their hierarchical arrangement, two other features of biominerals contribute to the superior mechanical properties of skeletons made from them. First, at the lowest level, they are often made of tiny crystals that are smaller than the "Griffith length" necessary for cracks to spread (*8*). Second, the precision with which they can be laid down (changing their main orientation over a few micrometers, for instance) allows exquisite adaptations to the loads falling on the skeletons.

The particular mineral used in a skeleton—calcite, aragonite, apatite, silica, or others—is probably much less important than the precise way in which the mineral is arranged in space. Aizenberg *et al.* show this very clearly for the *Euplectella* skeleton, although the organic component is also crucial for providing clear interfaces between the layers.

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OCEAN SCIENCE

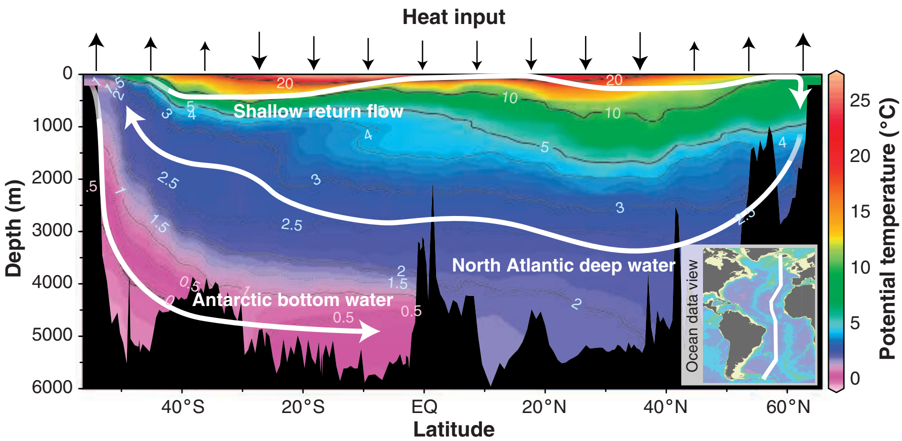
Warming the World's Oceans

Gabriele C. Hegerl and Nathaniel L. Bindoff

Rising greenhouse gas concentrations in the atmosphere are trapping more infrared radiation near Earth's surface. This extra radiation is expected to warm Earth's surface and lower atmosphere, but observations indicate that most of the heat is transported into the oceans (see the figure). On page 284 of this issue, Barnett *et al.* (*1*) substantially strengthen the evidence that human activities are indeed warming the world's oceans.

Observations have shown that 84% of the total heating of the Earth system since the 1950s is in the oceans (*2*). This increased ocean heat content has led to thermal expansion of the ocean, contributing at least 25% of the global sea-level rise observed over the same period (*3*). Ocean warming may also lead to greater stratification of the ocean, causing a weakening of the global overturning circulation in most model projections of future climates (*4*). Furthermore, the oceans are a key element in the global carbon cycle and are estimated to be storing roughly half of the total carbon released through human activities since preindustrial times (*5*). For all these reasons, the oceans are an important place to look for changes expected due to greenhouse warming ("fingerprints").

Many of the changes observed at Earth's surface and in the free atmosphere in the 20th century can be reproduced by climate models that account for the increase in greenhouse gases, aerosols associated with pollution, changes in solar radiation, and reflection by volcanic aerosols (*6*, *7*). Fingerprint methods use detailed information about the climate response to these external influences in order to separate them from each other and from natural variability within the climate system.



Heat transfer from atmosphere to ocean. This cross section of the Atlantic Ocean basin illustrates how atmospheric warming is transferred from the ocean surface to the ocean interior. The isolines show potential (that is, pressure-adjusted) temperature. The vertical black arrows show broadly where heat penetrates into the ocean surface layer and is then subducted into the upper ocean along surfaces of equal density. The combination of winds, sinking processes, and ocean circulation also leads to the meridional overturning circulation (and horizontal heat transport) (white arrows). Arrows pointing out of the ocean indicate net heat being transported from the oceans to the atmosphere. (**Inset**) Location of the cross section. [Adapted from (*9*)]

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Studies using such methods have shown with high confidence that much of the temperature change observed at Earth's surface and in the free atmosphere over the past 50 years has been caused by increases in greenhouse gas concentrations (*6*, *7*).

Barnett *et al*. (*1*) now apply a fingerprint method to the temperature history of the upper 700 m of each ocean basin since 1960. In this depth range, the greatest temperature changes are found (*1*, *2*); it is also where we have the best knowledge of ocean behavior. The authors compare the best available ocean observation data set to simulations using two different climate models. They find strong evidence that the anthropogenic fingerprint anticipated by the models is present in the observations. The results show that changes in solar radiation and volcanic forcing cannot explain the observed pattern of ocean changes. The fact that the findings are robust for two different climate models indicates that the results are not affected significantly by differences in model formulation.

The similar pattern of temperature change in the observations and in the simulations is strong evidence for a large-scale anthropogenic warming trend in the world's oceans. Barnett *et al.* thus add important information to the growing evidence that human-induced changes to the composition of the atmosphere are changing our climate (*7*).

Temperature changes in the oceans are important not only because they strengthen the evidence for anthropogenic climate change. They are also important for a reliable prediction of future warming at the Earth's surface. Climate feedbacks determine how strongly the atmosphere reacts to rising greenhouse gas concentrations. But the rate of warming at the Earth's surface also depends on how much of the excess energy trapped by greenhouse gases is transported into the ocean interior.

For example, if climate feedbacks are weak and little heat penetrates into the ocean, this would in the short term result in a surface climate change similar to one in which climate feedbacks are strong and a lot of heat penetrates into the ocean (*8*). However, as the ocean slowly comes into equilibrium with the atmosphere, these scenarios would diverge sharply, because stronger feedbacks would cause much stronger future warming. Therefore, the demonstration by Barnett *et al.* (*1*) that their two climate simulations are in quantitative agreement with the observed ocean warming improves our confidence in the simulated rate of ocean heat uptake and thus in projections of future climate.

The historical ocean data cover a relatively short time span (~50 years) and their spatial coverage is inhomogeneous, particularly in the less accessible Arctic and Southern Oceans. Therefore, it is still a challenge to validate more complex details of ocean physics in climate models than was done in (*1*). Further work is needed to determine more accurately and in more spatial detail how temperature and surface salinity changes penetrate into the ocean. We also need to better understand the ocean's major modes of climate variability, particularly on time scales of a decade or longer, and to quantify the likelihood of sudden ocean change [such as a collapse of the thermohaline circulation (*4*)]. Another question is how ocean biogeochemistry and ecosystems, and thus the global carbon cycle, will respond to global warming. Therefore, it is important that we keep probing the world's oceans.

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ANTHROPOLOGY

The Remaking of Australia's Ecology

Christopher N. Johnson

What was the impact of early human populations on pristine ecosystems? Studies of this question have focused on the possibility that humans caused extinctions of large mammals. For example, the arrival of modern humans in the Americas ~11,000 years ago coincided with the disappearance of mammoths, ground sloths, and many other large mammals (*1*). However, the role of humans is difficult to determine in this case because the climate was also changing rapidly as the last ice age came to an end; climate change, not human impact, may have caused the extinctions.

Modern humans reached Australia much earlier. Just when they did is still debated, but occupation was widespread by 45,000 years ago and may have begun several thousand years earlier (*2*)—well before the climatic upheavals at the end of the last glacial cycle. Australia should therefore provide a clear view of the ecological impacts of human arrival. But environmental changes following human arrival in Australia have been difficult to resolve, because very few precisely dated environmental records extend through the middle of the last glacial cycle. On page 287 of this issue, Miller *et al*. (*3*) provide such a record based on diet reconstructions of the continent's two largest bird species. The results indicate that human arrival resulted in a profound environmental shift.

Miller *et al*. studied past diets of the emu (*Dromaius novaehollandiae*) and an even larger flightless herbivorous bird, the extinct *Genyornis newtoni* (see the first figure), in the arid and semi-arid regions of the south Australian interior. By analyzing carbon isotopes in individually dated eggshells, they were able to compare the contributions of plants that use the C4 photosynthetic pathway (mainly tropical and arid-adapted grasses) and those that use the C3 pathway (most shrubs, trees, and nongrass herbs) to the diet of the birds that laid the eggs. Their collection of eggshells covers the past 140,000 years, encompassing the whole of the last glacial cycle.

Miller *et al.* found a sudden change in emu diet between 50,000 and 45,000 years ago. Before 50,000 years ago, emus had variable diets, with a strong contribution from C4 plants; after 45,000 years ago, they ate mostly C3 plants. *Genyornis* eggshells were common before 50,000 years ago, but they abruptly disappeared at the same time as the diet of the emu changed. Before then, *Genyornis* also ate a mixture of C3 and C4 plants, but its diet was much less variable than that of the emu through the same

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