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.

References and Notes

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2. This paragraph reflects the author's view of the levels of hierarchy in *Euplectella*; the levels do not quite agree with those specified in (*1*).
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OCEAN SCIENCE

Warming the World's Oceans

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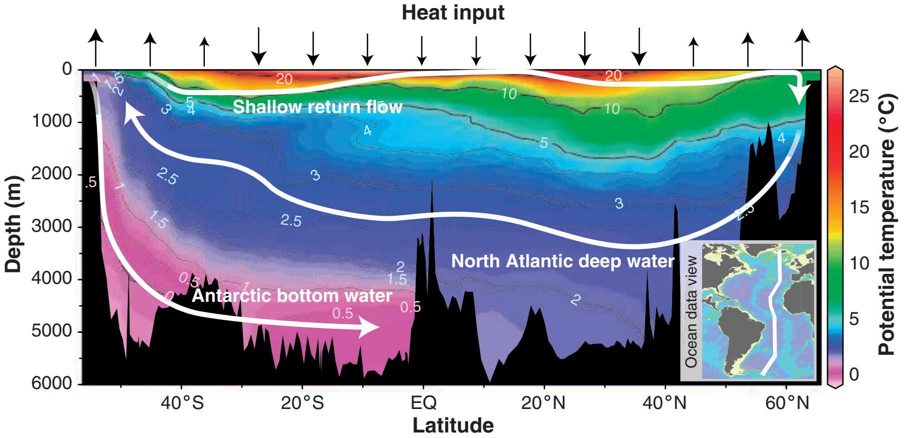
Rising greenhouse gas concentrations in the atmosphere are trapping more infrared radiation near Earth's surface. This extra radiation is expected to warm Earth's surface and lower atmosphere, but observations indicate that most of the heat is transported into the oceans (see the figure). On page 284 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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