Arctic Ocean. Combined with the warming of the surface ocean, these trends enhance the stratification within the top layers of the ocean, and are consequently expected to reduce the amount of vertical mixing[5].

Regionally intensified levels of vertical mixing, as observed by Rippeth and colleagues, result in large upward heat fluxes from the Atlantic layer. The largest dissipation rates are found at the entrance of the Arctic Ocean, north of Fram Strait, where the Atlantic Water layer is at its warmest and can be in direct contact with the atmosphere during years with low sea-ice cover. Rippeth and colleagues[2] infer vertical heat flux up to 50 W m^{-2} in this region. Although this heat loss occurs over a small region, it represents a very large fraction of the total heat lost by the Atlantic water mass during its entire transit through the Arctic Basin. The remaining heat is lost over a large area in the interior of the Arctic Basin through very small vertical heat fluxes[6], with very limited effect for the sea-ice pack.

The study by Rippeth and colleagues[2] identifies the important role of tides, compared with winds and sea ice, in controlling vertical mixing and associated heat fluxes in the Arctic basin. However, if we are to fully understand the influence of the ocean on current and future sea-ice loss, other processes such as the absorption of solar radiation in the surface layers of the Arctic Ocean will also have to be considered. ❐

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CARBON SEQUESTRATION

Biology's growing role


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The ocean is a remarkable sink for the increasing amount of carbon dioxide in the atmosphere. Carbon dioxide does not just diffuse into the ocean, it also reacts abiotically with seawater, producing bicarbonate and carbonate and thereby allowing more CO_2 to diffuse into the ocean. All in all, as a result of these reactions the oceans take up roughly a quarter of anthropogenic CO_2 emissions globally, and nearly all of this is converted to bicarbonate and carbonate.

In the Southern Ocean, biological production and decomposition also play an important role in regulating the CO_2 exchange between the ocean and the atmosphere. Although the Southern Ocean became a net CO_2 sink following the industrial revolution, CO_2 fluxes in this region are strongly seasonal. The Southern Ocean is a carbon dioxide sink in summer, when organisms use the dissolved inorganic carbon in the surrounding water — CO_2, bicarbonate, and carbonate — to grow. In winter, when organic material decomposes and releases CO_2 in the process, carbon dioxide is emitted back to the atmosphere.

In the 1950s, Roger Revelle and Hans Suess noticed that the efficiency of ocean uptake of atmospheric CO_2 can be quantified by a number that came to be known as the Revelle factor: a ratio relating changes in seawater CO_2 concentrations to changes in seawater concentrations of total dissolved inorganic carbon. But the equilibrium of the reaction between CO_2 concentration and dissolved inorganic carbon changes with pH. As oceans take up more CO_2, they become more acidic and the production of dissolved inorganic carbon becomes less favourable. Over time, the Revelle ratio increases, because a larger increase in the concentration of dissolved CO_2 is required to create a given amount of dissolved inorganic carbon. As a result, the oceans become less efficient at taking up CO_2.

Yet, as the oceans' chemical capacity to soak up CO_2 diminishes, biological activity could play an increasingly important role in regulating CO_2 uptake. Judith Hauck and Christoph Voelker simulated a scenario of large CO_2 emissions and climate change in the twenty-first century with a coupled ocean–ecosystem model (*Geophys. Res. Lett.* http://doi.org/zzc; 2014). Their approach allowed them to distinguish how CO_2 uptake is likely to change in the future in response to changes in the ocean's chemical capacity to take up CO_2 independent of the effects of changes in temperature, circulation, or resource availability.

It is no surprise that ocean uptake of CO_2 would increase alongside rising anthropogenic emissions of CO_2 over the twenty-first century. But as the ocean's ability to efficiently take up CO_2 diminished, the strength of the seasonal cycle in CO_2 uptake increased throughout the Southern Ocean. Late in the twenty-first century, the biological uptake of dissolved inorganic carbon caused a much larger decline in the amount of CO_2 in the Southern Ocean surface waters than it did early in the century, seawater CO_2 concentrations became more sensitive to changes in dissolved inorganic carbon concentrations: the change in the Revelle ratio means that a given decline in the levels of dissolved inorganic carbon will result in larger uptake of atmospheric CO_2 by the oceans. In total, CO_2 uptake from biological activity increased by roughly 2.5 times over the course of the twenty-first century, even though changes in biological activity were small.

With some effort, we can avoid the large increases in atmospheric CO_2 concentrations described in this high-emissions scenario. But even if emissions grow at a slower pace, CO_2 may eventually reach concentrations that shift the ocean system into a new chemical state, where marine organisms would play an increasingly important role in controlling CO_2 uptake.

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