

CLIMATE SCIENCE

We should also expect it to be much more difficult to grow more-complex organs such as the kidney or the heart using this strategy. Unlike the pancreas, these organs arise from several progenitor cell types controlled by separate biological pathways^{7,8}. Suppressing the growth of the entire host kidney or heart is unlikely to be as simple as deleting a few genes, meaning that more-elaborate strategies will probably be required.

Mice and rats are distinct species, but share much of their genetic make-up. Nevertheless, there seem to be as-yet-undefined molecular barriers to rat cell growth or integration into mouse tissues⁴. Would it be possible, then, to use a similar strategy to grow organs in more-distantly related species, in which such problems would presumably be amplified? The eventual aim would be to grow human organs in pigs or sheep, whose organs are of comparable size to those of humans. But major technical challenges probably lie ahead, including poor contribution of human cells to animal embryos and rejection of human organs by the host animal's immune system.

After organ transplants between humans, immunosuppressive drugs must be taken for life to prevent organ rejection. Such drugs are toxic and have serious side effects. But, theoretically, immune-compatible organs could be produced with the interspecies approach using patient-specific induced pluripotent stem (iPS) cells — a type of pluripotent cell generated by taking a patient's skin or blood cells and engineering them to acquire a pluripotent state *in vitro*. Human endocrine islets derived from iPS cells, for instance, will be immunologically matched with the cell donor. In their experiments, Yamaguchi *et al.* used mouse iPS cells as well as embryo-derived pluripotent stem cells, demonstrating that both techniques are feasible in rodents.

Before human organs can be grown in animals, many technical challenges will need to be overcome, and ethical and legal questions addressed. But given the pressing clinical need for organs for transplantation, and the lack of good options available, this line of research must continue. ■

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Ocean circulation drove increase in CO₂ uptake

The ocean's uptake of carbon dioxide increased during the 2000s. Models reveal that this was driven primarily by weak circulation in the upper ocean, solving a mystery of ocean science. [SEE LETTER P.215](#)

SARA E. MIKALOFF FLETCHER

The ocean has absorbed approximately 40% of the carbon dioxide emitted to the atmosphere by the burning of fossil fuels and cement production during the industrial era^{1,2}. This uptake is variable: the amount of CO₂ absorbed declined in the 1990s, but increased sharply during the 2000s (refs 3, 4). However, the processes controlling this reinvigoration of ocean carbon uptake remain a puzzle. On page 215, DeVries *et al.*⁵ report that most of the increase that occurred in the 2000s can be explained by changes in ocean overturning circulation — the sinking of cold, dense surface waters to the deep ocean, and the compensatory rising of deep waters. This suggests that biological processes and temperature-driven changes in solubility have relatively minor roles.

Ocean carbon uptake is proportional to a quantity known as Δp_{CO_2} , which is a measure of the difference between the amount of CO₂ in the atmosphere and that in the ocean surface⁶. If there were no changes in ocean temperature, biology or circulation, one would expect ocean carbon uptake to increase in proportion to atmospheric CO₂ levels. Ocean models and

estimates based on atmospheric and ocean-surface data suggest that ocean CO₂ uptake declined during the 1990s, relative to what might have been expected from atmospheric CO₂ concentrations, and that this decline occurred primarily in the Southern Ocean^{3,4,7}. This reduction was linked^{7,8} to intensification of the westerly winds over the Southern Ocean, which brought carbon-rich deep waters to the surface and so decreased Δp_{CO_2} .

Observations of CO₂ levels in the atmosphere and ocean surface suggest that this trend reversed in the early 2000s (refs 4, 9). The Southern Ocean again played a crucial part in this increase in ocean carbon uptake^{3,10}, but uptake also increased at northern mid-latitudes during this period⁴. The post-2000 increase in ocean carbon uptake cannot be explained by a simple reversal of the mechanism that caused the slowdown during the 1990s, because westerly winds continued to strengthen during the 2000s. An analysis of temperature-driven effects on the solubility of CO₂ suggested that these have a substantial role in the uptake of CO₂ in some regions^{3,4}, but cannot explain it entirely. Other processes are needed to fully explain the observed changes^{3,4}. DeVries and colleagues' paper is the first to

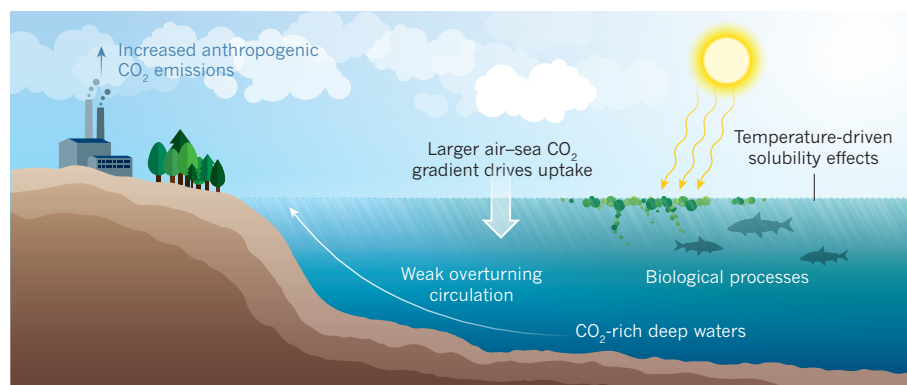


Figure 1 | Factors affecting the ocean carbon sink. The amount of carbon dioxide absorbed by the ocean during the 2000s increased compared with that absorbed during the 1990s. DeVries *et al.*⁵ report that the large-scale circulation of the ocean (the overturning circulation) was weaker during the 2000s than during the 1990s, especially in the upper ocean, and therefore brought less CO₂-rich water from the ocean depths to the surface. This effect, taken together with increases in anthropogenic CO₂ emissions, increased the CO₂ gradient between the atmosphere and the ocean, driving CO₂ uptake by the ocean. Temperature-driven solubility effects were about tenfold smaller than circulation-driven changes. Because most of the observed change in ocean CO₂ uptake during the 2000s can be explained by changes in circulation and atmospheric CO₂, it is likely that ocean biology had only a modest role.

robustly quantify the role of circulation change in the recent decadal shift in CO₂ uptake, providing the missing piece of this puzzle.

DeVries *et al.* used a new ocean inverse-modelling approach to quantify changes in circulation. Inverse models use observations of the state of a system to estimate the combination of parameters most likely to explain the observed conditions. The authors estimated parameters that drive ocean circulation using observations of ocean temperature, salinity and the concentrations of trace chemicals such as chlorofluorocarbons and radiocarbon, which are strongly affected by ocean circulation but not by ocean biology. This approach revealed decadal variability in upper ocean circulation of up to 50%. Changes between the 1980s and 1990s occurred primarily in the Southern Hemisphere, whereas changes between the 1990s and 2000s involved many regions of the ocean.

The authors then coupled their ocean inverse model to an ocean carbon-cycle model to quantify how these changes in circulation would have affected ocean carbon uptake. The results suggest that upper ocean circulation slowed during the 2000s, reducing the upwelling of carbon-rich deep waters and increasing Δp_{CO_2} , and therefore also increasing ocean CO₂ uptake (Fig. 1). To estimate the total increase in uptake, the authors used data from the Surface Ocean pCO₂ Mapping (SOCOM) project⁹, which reconstructs the ocean CO₂ sink around the world. By selecting the subset of SOCOM models that best match observations of Δp_{CO_2} , the authors conclude that the total increase in uptake between 2001 and 2011 was approximately 0.8 petagrams of carbon (PgC; 1 Pg is 10¹⁵ g) per year per decade. About half of this change can be explained by the increase in atmospheric CO₂ from human activities during this period, and the researchers estimate that the remaining trend of 0.4 PgC yr⁻¹ decade⁻¹ is due to ocean circulation alone.

These findings suggest that biological processes are unlikely to have had a major role in the post-2000 increase in ocean carbon uptake. This does not imply that ocean biology has remained constant in response to circulation changes, only that the changes have probably had a relatively modest net impact on carbon uptake. For example, a reduction in upper ocean circulation might lead to a reduced nutrient supply at the ocean surface, lowering biological CO₂ uptake, whereas temperature-driven changes in the depth of the mixed layer (the depth to which the ocean surface is well mixed by winds) might affect light availability, potentially increasing biological CO₂ uptake. The net effect of such changes on the ocean carbon sink might have been limited during the past decade, but the changes might have affected the structure of ocean biological communities. Furthermore, the ability to represent these biological processes accurately in models might be important for predicting other

ocean–climate feedbacks¹¹ and future carbon uptake.

The current generation of models — used to estimate global carbon uptake during recent decades and to simulate Earth's response to climate change — do not fully capture the observed decadal-scale variability⁴. This represents a considerable gap in our ability to assess contemporary carbon budgets and predict future change. Inverse methods such as that used by the authors are currently among the best tools with which to infer how parameters must have varied to match observations, but provide limited insight as to why. So, although DeVries and colleagues' work is a major advance in our understanding of these trends in ocean carbon uptake, it remains unclear for how long the increased carbon uptake observed during the 2000s will persist. More detailed mechanistic studies are needed to tell us what the future holds. ■

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PALAEONTOLOGY

Tiny fossils in the animal family tree

Newly discovered microscopic fossils might shed light on the early evolution of the deuterostomes, the animal group that includes vertebrates. But more work is needed to resolve the fossils' place in the deuterostome tree. [SEE LETTER P.228](#)

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One of the main divisions of the animal kingdom is the superphylum Deuterostomia, which includes organisms such as starfish, acorn worms and vertebrates. The evolutionary relationships of the living deuterostome groups, or phyla, are well established on the basis of genetic data¹, but because these phyla have strikingly different adult body plans, the nature of their most recent common ancestor and the initial steps in deuterostome evolution are poorly understood. On page 228, Han *et al.*² report fossils from China that date to the Cambrian period (around 541 million to 485 million years ago). The authors interpret these fossils as being primitive deuterostomes, and this discovery could improve our understanding of the origin and early evolution of this key animal group.

Living deuterostomes are classified into three main phyla: echinoderms (such as starfish), hemichordates (such as acorn worms) and chordates (such as fish and humans). The fossil record preserves an assortment of extinct forms that could help to bridge the

gaps between the living deuterostomes and their earlier ancestors, potentially illuminating the ancient evolutionary history of deuterostomes. However, most of the fossils identified as deuterostomes have been interpreted as early chordates³, echinoderms⁴ or hemichordates⁵, and therefore cannot provide insight into the evolutionary steps before the divergence of the living deuterostome groups.

Han and colleagues identified fossils that have the potential to fill in some gaps in our understanding of deuterostome evolution. The samples were collected in central China from a site of exceptionally well-preserved fossils called a lagerstätte. The specimens are at least 529 million years old, dating to the earliest part of the Cambrian. From study of the fossil record, we know that the Cambrian was the period when diverse animals appeared for the first time in Earth's history, in what is known as the Cambrian explosion. Early fossil representatives of nearly all animal phyla have been reported from the Cambrian, often from lagerstätten such as the Burgess Shale in Canada and Chengjiang in China⁶. These