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nia—ahead, making tidal currents the most predictable and reliable of all sustainable energy sources.

Marine turbines will enable hydro-lake water to be conserved, because they can be used as a base-load resource complementary to the country's hydro capacity. The predictability of tidal flow will allow blending of marine- and hydro-power outputs, so that hydro output will be maximised only during the short periods when the tide turns and the marine units swing from flow in one direction to flow in the other.

Furthermore, marine turbines are immune to the effects of weather extremes. A storm may turn the surface of the sea to foam, but in the depths it is hardly even detectable. Wave- and wind-power systems, on the other hand, require significant maintenance during extreme weather, and extreme weather is predicted to increase with global warming.

Marine turbines should eventually do away with the need for new fossil-fuel power stations. We should look on coal as a temporary energy source to tide us over until sufficient sustainable power generation can be brought into service, following which any increase in power demand should be met by expansion of sustainable generation. The ideal role for coal is as a source of carbon for the petrochemical industry.

A great deal of work has yet to be done before New Zealand can expect its first installation of marine turbines. But the Energy Efficiency and Conservation Authority is already addressing the processes involved in the establishment of sustainable generating systems, while a new industry association has been formed—the Aotearoa Wave And Tidal Energy Association (AWATEA: loosely translated = New Dawn)—which will coordinate the efforts of marine-power generation companies. The National Institute of Water and Atmospheric Research (NIWA) has amassed much essential information, but more research is needed to determine the best turbine locations and the operational parameters that will minimise the risk factors inherent in the establishment of a new industry. Nor can the possible influence on the marine environment be ignored. There is at present no knowledge of any ecological effects of wave- or tidal-power systems, either untoward or beneficial, and research into the possibilities will be necessary.

SMD-Hydrovision has been 60 per cent funded by the British Department of Trade and Industry, and is 40 per cent self-funded, to develop its TidEl design, benchmarked to the point of a test installation at a site in the Orkney Islands, north of the Scottish mainland, late in 2006. This will be followed by an extended test-and-development period, finishing in 2008, to acquire the knowledge needed to create a production design. One aspect of the testing will be to determine the effects of the turbines on marine mammals. The low speed at which the blades rotate should allow the likes of seals and whales, dependent on echolocation to navigate their way through the water, to detect and thus avoid them.

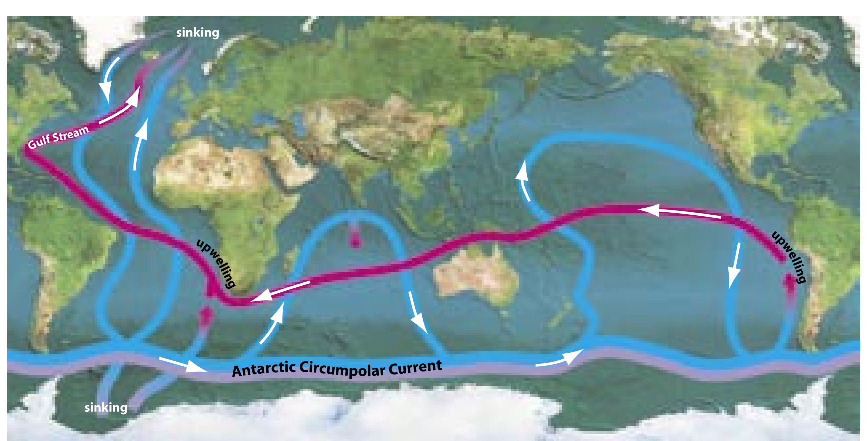
Of all the designs of marine turbine in development worldwide, the SMD-Hydrovision TidEl system appears to be the only one suited to operation in Cook Strait. Neptune Power anticipates the first units will be installed sometime in 2009–2010 and generating useful power immediately. Thereafter, installations will follow demand.

Neptune Power sees tidal-stream energy as just one source of electrical power in an integrated system of sustainable generation that also includes hydro, wind, wave and geothermal plants continuously controlled to match demand and that is expandible to meet all future needs. By 2020, New Zealand should be well on the way to acquiring such a system.

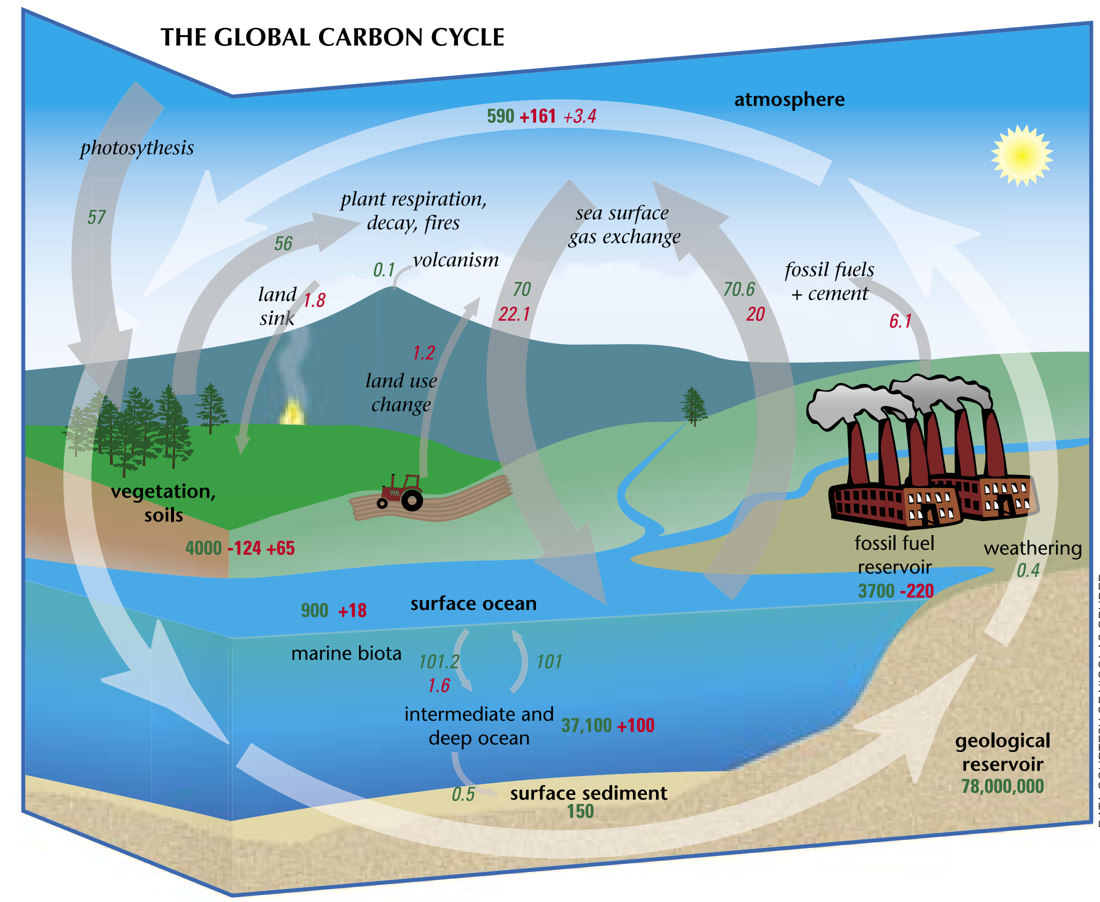
Ocean carbon

IRINA MARINOV & WARREN JUDD

ALTHOUGH THERE is a great deal of discussion and interest in the effects rising levels of atmospheric carbon dioxide (CO_2) are having on climate, little popular attention is given to CO_2 in the ocean. This is unfortunate because most of Earth's CO_2 is held there. Oxygen and carbon dioxide—the two atmospheric gases most essential to life—behave quite differently with respect to the atmosphere and ocean. Some 99.4 per cent of oxygen is in the atmosphere and



A series of interlinked currents, referred to as the ocean conveyor, steadily circulate water, nutrients—and dissolved carbon—through the world's oceans.



KEY

590 Pre-industrial total
70.6 Pre-industrial annual flux
161 Anthropogenic total
3.4 Anthropogenic annual flux
All units = gigatonnes of carbon

This diagram depicts how carbon moves between land, water and atmosphere, and how carbon produced as a result of man's recent intensive use of fossil fuels is impacting the cycle. The unit is the gigatonne which is 1 billion (10^9) tonnes of carbon (GtC). Green numbers represent amounts of carbon in natural reservoirs and green italics, natural annual fluxes. Red numbers give anthropogenic totals that have been added to or subtracted from these natural reservoirs over the last few hundred years. Red italicised numbers indicate annual fluxes of anthropogenic carbon. Hence it is estimated that there is a total of 3700 billion tonnes of carbon locked up in Earth's fossil fuels, from which we have released a total of 220 billion tonnes of carbon in the last two centuries. Annual use of fossil fuels is putting 6.1 billion tonnes of CO_2 into the atmosphere annually, though included in this total is CO_2 released during the manufacture of cement from limestone. Much of the 124 GtC lost from vegetation and soils is deforestation and the 65 added back represents an inferred terrestrial sink of uncertain origin.

only 0.6 per cent is dissolved in the sea. However, carbon dioxide is 30 times more soluble in the ocean than is oxygen and once dissolved it undergoes hydrolysis to carbonate and bicarbonate ions. As a result, some 98.5 per cent of carbon dioxide is in the ocean and only 1.5 per cent is in the atmosphere.

Small changes in how carbon dioxide dissolves in and is handled by the sea could have far-reaching consequences for CO_2 in the atmosphere and for climate change!

Carbon dioxide dissolves in water until it reaches an equilibrium with the amount in the air above it. Temperature changes this equilibrium, in that CO_2 is more soluble in cold water than warm. Hence there is more CO_2 dissolved in Arctic and Antarctic surface waters than there is in temperate or tropical surface water.

As ice forms in polar seas, salt is excluded and is forced into unfrozen water, which becomes saltier and therefore denser. The salt also depresses the freezing point so saltier-than-normal seawater around the fringes of Antarctica will not freeze until it is about –2°C. Because this super-cooled, hyper-saline seawater is the densest seawater around, it sinks to the seafloor and accumulates in the deep ocean near Antarctica, where it feeds deep water currents (in particular, the Antarctic Bottom Water), in a process known as "deep water formation". The sinking water also brings with it CO_2 from the ocean surface, resulting in an accumulation of CO_2 in the deep. This process by which carbon dioxide is transferred to the deep ocean and accumulates there in higher concentration than in shallower water is called the solubility pump.

There is a second "carbon pump" which transfers carbon to the deep sea—the biological pump. In the presence of sunlight and suitable molecular building blocks—carbon dioxide, phosphate, nitrogen and iron being the main ones—phytoplank-

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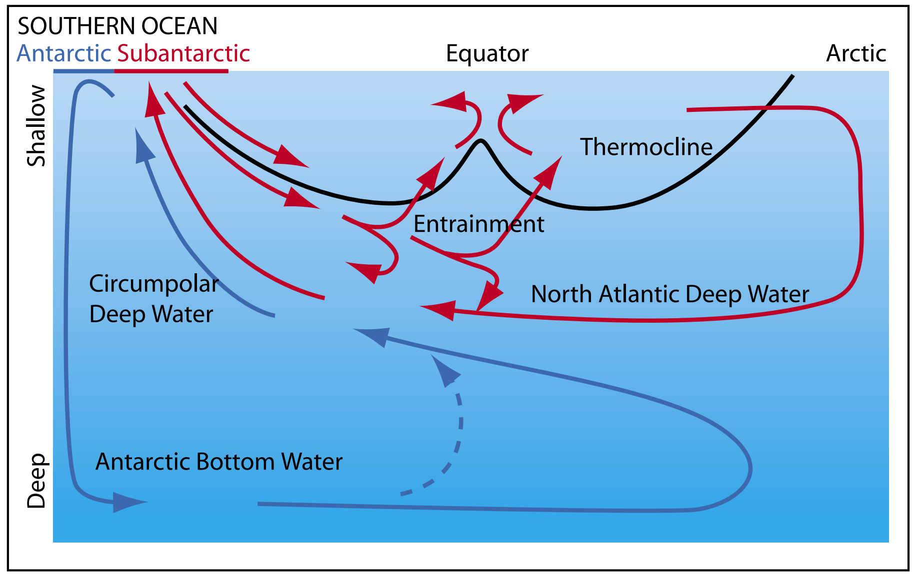


The biogeochemical divide between Antarctic waters south of 60° and those Subantarctic waters to the north can be clearly seen in this cross-section of the ocean. Under conditions of increased photosynthetic activity, the Antarctic Bottom Water captures CO_2 from the surface and effectively stores it in the deep ocean for a long time.

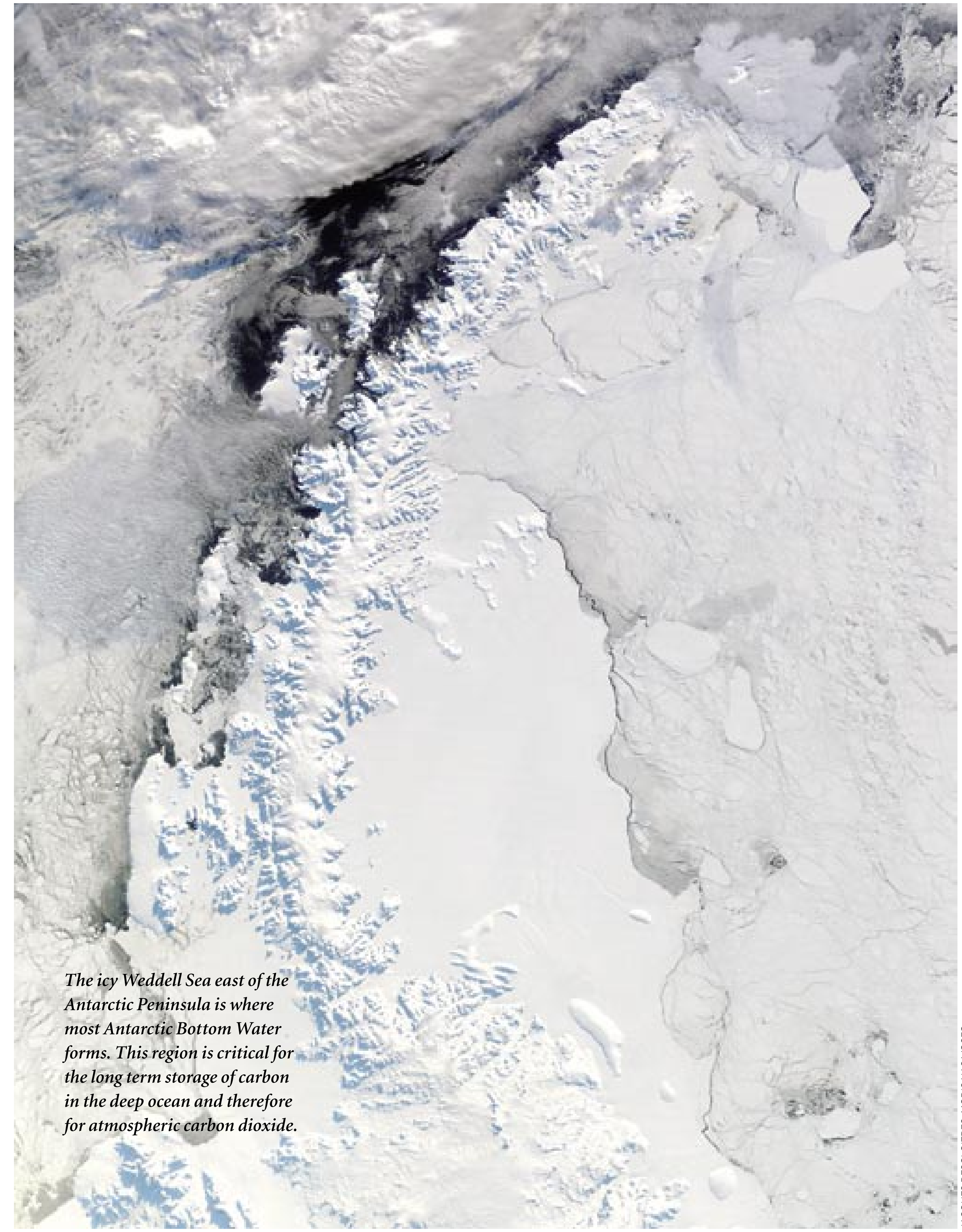
ton at the ocean surface carry out photosynthesis, incorporating carbon from CO_2 into living tissue. Phytoplankton are thought to remove some 60 billion tonnes of carbon from the upper layers of the sea annually! As organisms remove dissolved carbon dioxide from the water to grow, more carbon can enter the ocean from the atmosphere. Eventually all phytoplankton die and decompose back into CO_2, phosphate and nitrate, a process referred to as remineralisation. Because gravity ensures that decaying phytoplankton fall through the water column, the result of these biological processes—collectively known as the biological pump—is much higher carbon concentrations in deep water than in shallow. Many marine organisms also incorporate carbon in their calcium carbonate shells (e.g. molluscs, foraminifera, coccoliths), and sink to the seafloor after death. It is thought that about 10 billion tonnes of carbon (out of the 60 billion taken up by surface organisms) sinks into the deep ocean each year, remaining there for a good long time and escaping from the pool that is rapidly recycled within the surface layer.

The Southern Ocean constitutes 31 per cent of the world's sea surface, yet measurements and modelling suggest that it takes up 35–48 per cent of the anthropogenic carbon dioxide that is being dissolved in the world's oceans each year. Unfortunately, an inclement climate and remoteness combine to make the Southern Ocean a difficult and expensive place in which to take measurements and carry out experiments. However, there are remedies. Oceanographers have created sophisticated computer models which, given some initial conditions, reproduce well the observed circulation of the ocean. These models are tested against ocean measurements of salinity, temperature, currents, chemical components and are found to perform well. Models are a virtual laboratory, allowing us to perform experiments we cannot, or would not want to, perform in the real world.

The research group that one of us (I.M.) worked in at Princeton University, has recently published the result of modelling experiments to determine exactly how the Southern Ocean sequesters carbon dioxide and to learn more about how important that ocean might be in future and past climate change. In this exercise, the biological pump was set up to be much more efficient than it is in reality in the Southern Ocean, such that phytoplankton quickly sequestered the carbon that was available at the ocean surface. As a consequence, more CO_2 was drawn down from the atmosphere to replace the sequestered carbon. Oceans are vast beasts and take their time about things, so the model was run for some 5000 years to give ample time for equilibration.

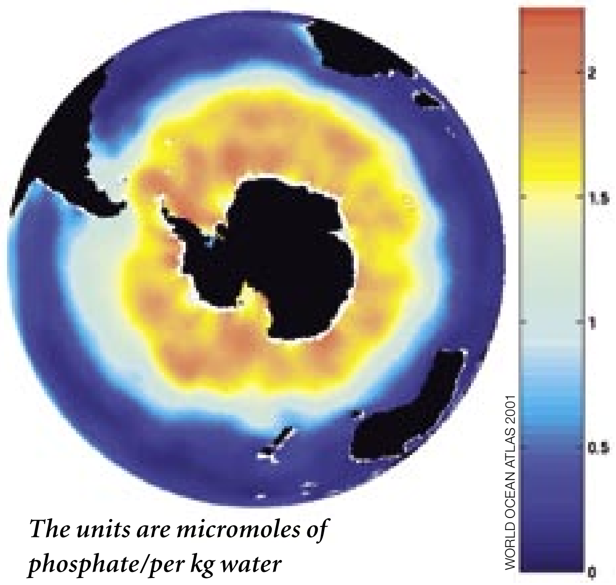
We have learned that the details of the Southern Ocean circulation and the amount of nutrients (such as phosphate) held there matter greatly for atmospheric carbon dioxide. The importance of the Southern Ocean as a sink for carbon dioxide was confirmed, and, most significantly, a previously unsuspected "biogeochemical divide" at about latitude 60° S was discovered. This divide separates the Antarctic region in the south, close to the Antarctic continent, from the Subantarctic region further north. Water and nutrients from north of this line are transported by various currents to enhance biological productivity in most of the world's oceans, particularly in the tropical ocean, and the CO_2 here cycles repeatedly between the upper layers of the ocean and the atmosphere.

From south of the line, water carries carbon down into the depths where it circulates as Antarctic Bottom Water. Although some of this water reaches the Northern hemisphere, it never mixes with shallower water, so the carbon it carries is effectively locked up in the deep ocean for a long time. These waters seem to re-surface (after about 1000 years!) close to latitude 60° south. At this stage they will release some of the excess CO_2 they have accumulated from the carbon pumps to the atmosphere in the process of re-equi-



The icy Weddell Sea east of the Antarctic Peninsula is where most Antarctic Bottom Water forms. This region is critical for the long term storage of carbon in the deep ocean and therefore for atmospheric carbon dioxide.

JACQUES DESCLOITRES, MODIS NASA/GSFC



The units are micromoles of phosphate/per kg water

The separation between the Antarctic and Subantarctic waters can also be seen in nutrients, such as phosphate (above), with much more in the Antarctic than the Subantarctic. Low iron, lack of light and cold are thought to make photosynthesis less efficient in Antarctic waters so nutrients like phosphate are not depleted as thoroughly.

libration. Some of the remaining CO_2 in water will be converted back into living organisms, and some will just return to the depths again—where it will be further enriched by the biological and solubility pumps.

Furthermore, when the model depleted nutrients south of 60°, that section of the ocean was 5–12 times as effective at reducing atmospheric carbon dioxide than when nutrients were depleted north of that latitude! Hence the remote waters south of 60°—especially the Antarctic Bottom Water originating mainly in the Weddell Sea east of the Antarctic Peninsula—seem to play a much more important role than was previously suspected in regulating atmospheric carbon levels. Waters north of that latitude—subantarctic waters—seem to be much less important for atmospheric CO_2—although they are vital for maintaining the biological productivity of the oceans. The divide separating the Antarctic from the subantarctic suggests that one region could be modified—by climate change or human intervention—without greatly altering the other.

These findings may also shed light on past climate mysteries.

Over the last million years there have been seven ice ages, each lasting for about 100,000 years and separated by warmer interglacials, one of which we enjoy at present. During the cold glacial periods, atmospheric CO_2 fell considerably, primarily because of increased storage of CO_2 in the ocean. These cycles show that there is a very tight link between changes in CO_2 and changes in climate. This is particularly important in light of the effects of recent human industrial activity on the global climate. Over the past 200 years, burning of fossil fuels has returned vast amounts of carbon dioxide—once securely locked away in coal and oil—to the atmosphere. Levels of atmospheric CO_2 are thought to be the highest they have been in 20 million years. We have forced atmospheric CO_2 to increase by about 80 parts per million volume in only 200 years. By comparison, a similar increase in atmospheric CO_2 took place over tens of thousands of years going from glacial periods to interglacials! Scientists are worried about the repercussion of this CO_2 increase on climate and the future of our planet. Are we producing change to our planet and climate that cannot be reversed?

The present work highlights the critical role of the Antarctic in the global carbon cycle. The decrease in atmospheric CO_2 during the ice ages was probably due to a combination of factors which increased ocean CO_2 uptake, such as perturbation of currents (e.g., the Antarctic Bottom Water) around Antarctica, change in Southern Ocean biological production or increased coverage of the sea by ice.

In the last two decades, there has been interest in the notion of reducing levels of carbon dioxide in the atmosphere by stimulating the growth of marine phytoplankton. Iron is often the limiting nutrient in the ocean, so by adding small amounts, algal growth might be stimulated. When the phytoplankton perish, it is hoped a reasonable percentage of their carbon will remain tied up in the deep ocean and out of the atmosphere. Glacial-interglacial science provided the inspiration. One possible explanation for the extra carbon held in the oceans during the glaciations is that increased amounts of iron-rich dust from the land stimulated phytoplankton growth.

New Zealand's National Institute of Water and Atmosphere (NIWA) has been involved in some of these iron fertilisation experiments. The Princeton results suggest that deep water formation areas such as the Antarctic seas south of 60° should be the most worthwhile part of the world's oceans in which to indulge in such experimentation.

The study also reinforces the interconnectedness of all parts of the natural realm. Changing the amount of nutrients in the surface waters of the Southern Ocean will affect the biological productivity of oceans everywhere as well as atmospheric CO_2. Similarly, if Southern Ocean winds change, this is likely to affect ocean circulation worldwide and also ocean biology, atmospheric CO_2 and global climate.

And by the way, with global warming, Southern Ocean westerlies are expected to move poleward and increase in strength. Something to look forward to in southern New Zealand? ■