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What makes sources sinks?

The uptake and release of carbon dioxide at land and sea is complicated by erratic phases of the global climate system.

Graeme O'Neill describes efforts to account for these climatic influences when balancing the carbon budget.

Like Wall Street's Dow Jones industrial index, for which it is a proxy, the graph of carbon dioxide concentration in the global atmosphere has been almost irrepressibly bullish for the past half century.

But closer analysis reveals an erratic pattern of peaks and troughs writ large upon this upward trend and the fine serrations of the seasons: the signature of the El Niño-Southern Oscillation (ENSO) climatic phenomenon.

Dr Ian Enting of CSIRO Atmospheric Research and Dr Peter Rayner of the Cooperative Research Centre for Southern Hemisphere Meteorology (CRCSHM) have made significant progress towards deciphering the influence of ENSO events on global carbon dioxide concentrations.

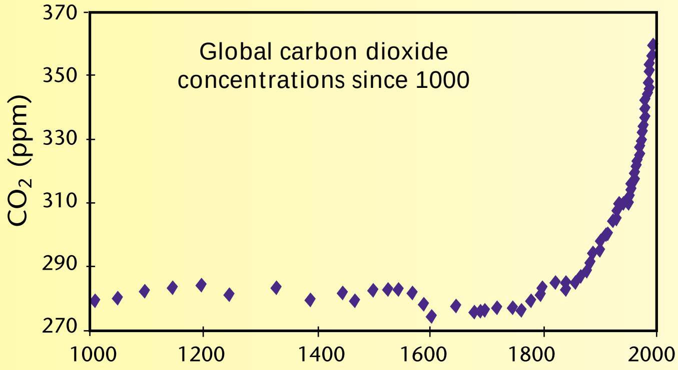
They believe they have discovered where most of extra carbon comes from during La Niña events, and where it goes – or remains – during ENSO events, as well as identifying the major mechanisms responsible for the striking variations in atmospheric CO_2 levels from year to year. Their tentative conclusion is that during ENSO events, when atmospheric CO_2 levels decline sharply, it's the tropical oceans that are mainly responsible: the release of CO_2 from the vast sink of the oceans is markedly reduced. But during La Niña events, tropical terrestrial sources – especially tropical rain forests – dominate the global picture, as litter decomposition and burning release more carbon dioxide into the atmosphere.

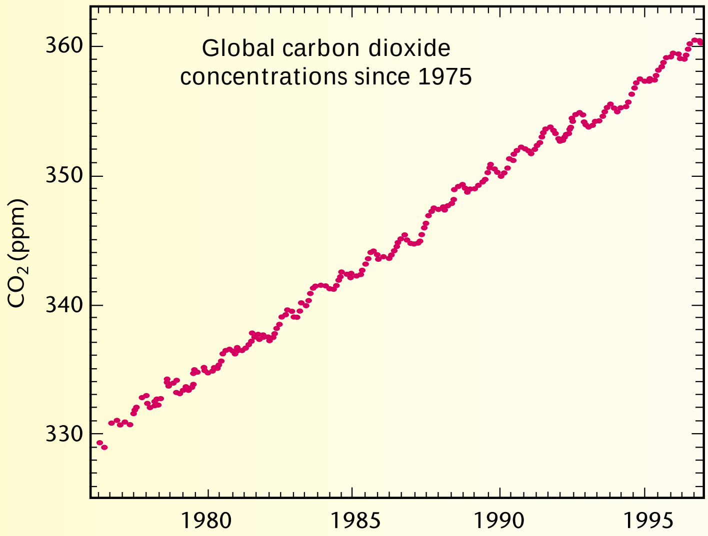
Understanding how carbon levels respond to natural climate variation is an essential step towards teasing out the simultaneous effects of human activities, such as the burning of fossil fuels. This knowledge will be needed to help determine whether nations comply with the Framework Convention on Climate Change and the Kyoto Protocol (the reduction of global greenhouse emissions to their 1990 levels by 2008–2012).

Scientists also need to understand how carbon fluxes varied before the time when,

Right: The influence of ENSO is refected in the erratic pattern of peaks and troughs overlying the steep rise in global CO_2 concentrations towards the end of the century.

Below: Evidence from Antarctic ice cores shows that CO_2 concentrations remained fairly stable until the industrial period.





two centuries ago, rampant population growth and the Industrial Revolution began perturbing natural systems by pouring CO_2 into the atmosphere.

Dr David Etheridge and Cathy Trudinger from CSIRO have reviewed historic CO_2 data from air trapped in Antarctic ice cores. Apart from predictably large deviations between glacial and interglacial periods, the system remained fairly stable until the industrial period, after which the signature of human-induced emissions becomes prominent.

Enting says that given time, the oceans could easily absorb 85% of the extra carbon entering the atmosphere as a result of human activity. But the current rate of uptake cannot cope with the sudden surge of CO_2 due to fossil fuel burning and environmental disturbances, and will only slow further as the surface layers of the oceans warm.

Understanding how the system responds to natural climate variation will provide a better understanding of how human-induced emissions could perturb natural feedback processes under a global warming regime.

A tour of the terminology

Sources are where the carbon comes from. For example, from human sources such as power stations, or methane from cattle, from decomposition of leaf litter in forests, or from the oceans off South America (as dealt with in this article) while sinks are where it goes.

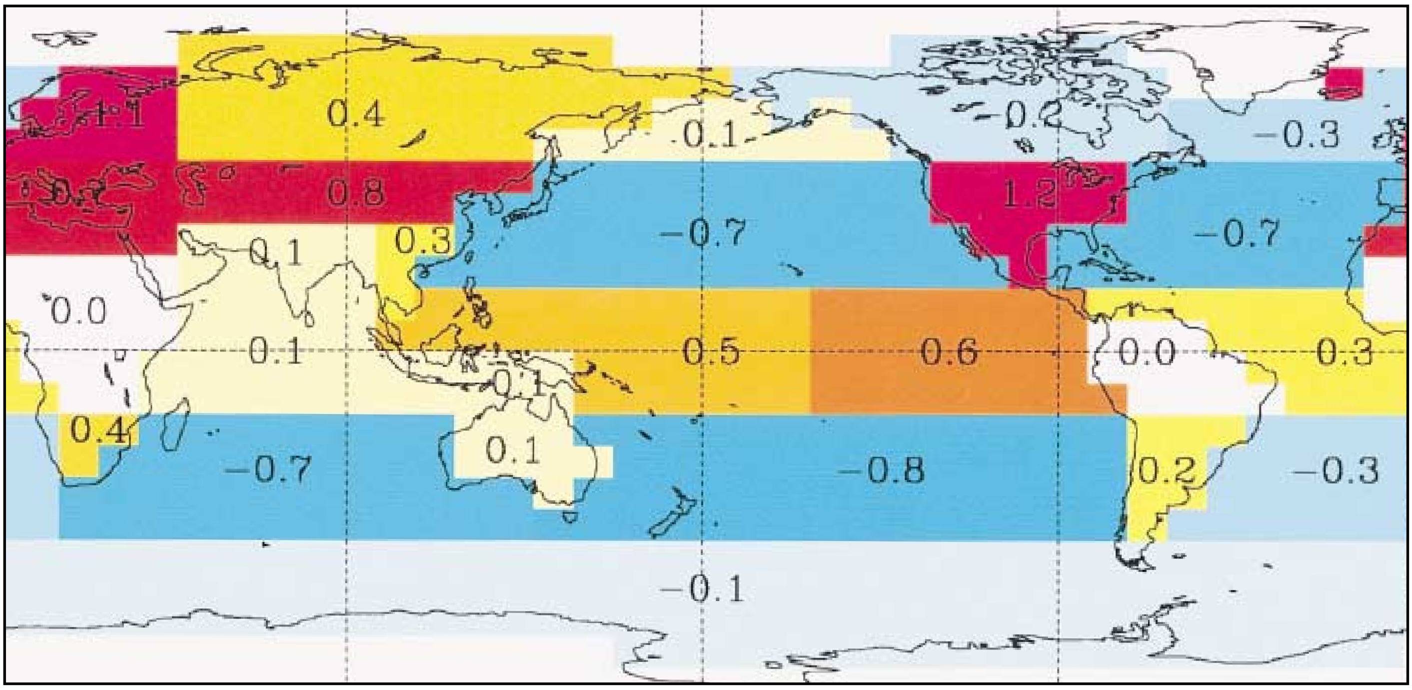
Sources and sinks are sometimes interchangeable: the oceans can absorb more or less carbon dioxide depending on their temperatures, with cold water absorbing more. That's why the cold Southern Ocean is thought to be a likely sink for atmospheric carbon dioxide.

Anomalies are pronounced deviations in normal carbon dioxide concentrations in particular regions of the atmosphere, due to proximity of major sources or sinks. An El Niño event produces an anomalously low carbon dioxide concentration off South America, because the suppression of normal upwelling prevents carbon-dioxide saturated water coming to the surface and diffusing into the atmosphere.

Flux is another term for flow, so carbon flux is basically the movement or flow or carbon, predominantly as carbon dioxide, between the various sources and sinks in nature.

Inter-annual carbon budget is the variation, from year to year, in carbon fluxes in either direction.

Carbon isotopes: Carbon atoms come in three different forms, according to the number of neutrons in their nuclei, and accordingly, have slightly different atomic masses. The lightest is carbon 12, followed by carbon 13 and radioactive carbon 14 (radiocarbon).



Estimated average annual sources (red) and sinks (blue) of CO_2 (in billions of tonnes) for 1980–1995. The land regions include CO_2 emissions due to fossil fuel burning. On average, out of the half of the fossil fuel input that is being removed from the atmosphere, three quarters (about two billion tonnes of carbon each year) is being absorbed by the ocean while 0.6 billion tonnes is being taken up by land plants. The uptake by land plants is a balance between deforestation and regrowth. If the estimates of deforestation are correct, the calculation suggests that most of the land uptake is occuring in the tropics.

The diagram shows that the tropical oceans are major natural sources because it is in these regions that ocean circulation causes upwelling of deep CO_2 enriched waters. The southern and northern oceans are sinks for atmospheric CO_2. As levels of CO_2 in the global atmosphere change, the balance of this natural cycle is changed. The tropical source is decreased while the non-tropical uptake of CO_2 is increased. During El Niño, years, the tropical source decreases almost to zero.

While predictions of a runaway greenhouse effect are in the realms of science fiction, Enting says human-induced global warming may cause changes in temperature and precipitation that could push the global carbon cycle permanently into a new regime.

Enting says terrestrial processes are the central issue, because terrestrial sources and sinks are far more susceptible to direct human disturbance than those of the oceans.

Global warming has a direct warming effect on the sea surface that reduces the solubility of CO_2, slowing the rate at which the oceans can absorb carbon and sequester it in the deep oceans as carbonate. Warming also makes the oceans more stable because the layering of warm surface water over frigid deep water inhibits the diffusion of carbon dioxide into the depths.

'If global warming due to human activity is superimposed on these long-term variations, and switches us into an ENSO-dominated cycle, the carbon cycle may look substantially different in 50 years' time,' Enting says.

'We need to understand any process involved in these variations that might be particularly sensitive to disturbance by human activity. It might not be the big things, but little things with feedback reactions that have the most dramatic long-term effects.'

Measuring change

Enting and Rayner are using three different data-sets to help unravel the effects of terrestrial processes: variations in carbon-isotope ratios, variations in the oxygen-nitrogen balance in the atmosphere, and spatial differences in atmospheric CO_2 concentration.

Changes in terrestrial carbon uptake can be inferred from localised changes in the ratio of the ^{12}C carbon isotope to the slightly heavier ^{13}C isotope.

While air-sea carbon exchanges have little net effect on atmospheric $^{12}C/^{13}C$ ratios, the photosynthesis reactions that fuel the growth of terrestrial vegetation have a slight bias towards carbon dioxide molecules containing the lighter ^{12}C atom. So the atmosphere becomes slightly enriched in ^{13}C during phases of increased vegetation growth. Enting hopes to make more use of extensive ^{13}C records in future.

Subtle variations in the atmospheric oxygen / nitrogen ratio have pointed to long-term trends in local carbon fluxes. When terrestrial plants absorb carbon dioxide from the atmosphere during photosynthesis, they emit oxygen, so the ratio of oxygen to nitrogen in the local atmosphere increases fractionally. In contrast, ocean-related photosynthesis has little effect on atmospheric oxygen concentration.

Measurements of atmospheric CO_2 concentration are coordinated by CSIRO's Dr Roger Francey, who ensures the same sampling protocols are used at a dozen sampling stations in Australia, France, Germany, the United States and Japan.

They are being analysed by Rayner and his colleagues – Dr Rachel Law, also with the CRCSHM, and Dr Roger Dargaville of the School of Earth Sciences at Melbourne University – using a technique called 'inversion'.

Instead of proceeding from known cause to specific effects, inversion infers causes from their known effects.

Above left: Terrestrial sources and sinks are far more susceptible to direct human disturbance than those of the oceans.

Left and below: Measurements of atmospheric CO_2 concentrations are taken from ships and at sampling stations in Australia, France, Germany, the United States and Japan. Pictured at left is the Atmospheric Baseline Monitoring Station at Cape Grim in north-west Tasmania.

In the real world, CO_2 fluxes between sources and sinks result in regional differences in atmospheric CO_2 concentrations; concentrations are higher near sources, lower near sinks.

'We are trying to work backwards from these spatial differences in concentrations to calculate the fluxes,' Enting says.

Many of the techniques are based on similar calculations used in seismology, where differences in the propagation speeds of earthquake-induced shock waves are used to infer details of the structure of the Earth's interior.

Inversion techniques become important when it becomes impractical to model systems involving numerous mechanisms that may work in concert or in opposition. There are many plausible influences on CO_2 variations: land clearance, logging and burning of forests, or changes in ocean temperature, to name a few.

Regional variations in atmospheric CO_2 levels are potentially informative about mechanisms, but Enting says it is only in the past decade that the tools have become available to map them at the resolution required to make inferences about particular sources and sinks.

The dynamics of the atmosphere complicate interpretation: air masses are in constant motion, smearing out anomalies caused by regional sources and sinks. A basic requirement is a reliable model of atmospheric transport.

When CSIRO and the National Oceans and Atmosphere Administration scientists attempted a similar exercise a decade ago, using globally-averaged CO_2 data as input for a simple two-dimensional model, the lack of any longitudinal detail added an unknown degree of uncertainty to the calculations.

Today's models represent the oceans and atmosphere in three dimensions, permitting more accurate simulations of atmospheric transport and mixing, and CO_2 flux.

For their study of the relationship between carbon dioxide fluxes and ENSO events published last February, Rayner, Law and Dargaville used two transport models – one developed by Dargaville's group at Melbourne University, the other by NASA researchers in New York – and used three different inversion techniques. Rayner's calculations included ^{13}C, which confirmed the other two estimates, derived from CO_2 alone.

Each inversion technique involves a degree of guesswork, and the estimated magnitude of the carbon flux varies with the technique used. But the researchers found that each technique independently reproduced the same broad pattern of real-world carbon-flux anomalies for the past 15 years.

That gives them some confidence that the inferences they have made about sources and sinks, and which mechanisms predominate as the global climate shifts from average conditions into an ENSO or La Niña pattern.

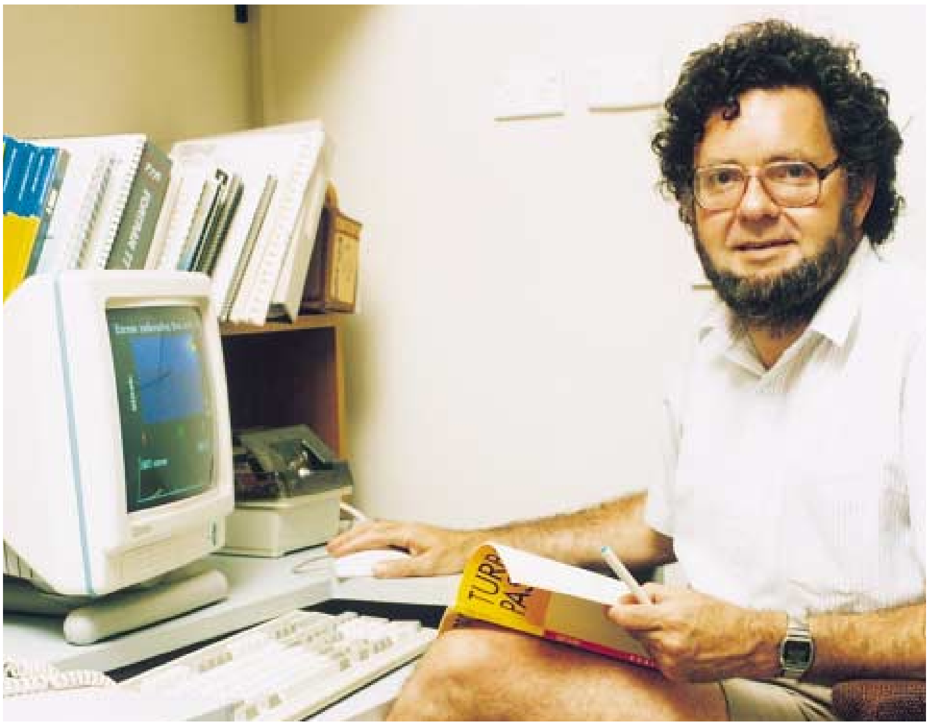
'As part of our evolving research program, we are focussing down from a global to a regional scale,' Rayner says. 'We want to try to measure what the biosphere is doing in the Australasian region.

'We're still in the design phase of the research, because we don't know yet what sort of measurements we need to constrain the background CO_2 flux so that we can detect human influences.'

This work on the behaviour of terrestrial sources and sinks in the Australasian region involves collaboration with Dr Dean Graetz's research team at the CSIRO Earth Observing Centre in Canberra, and with other CSIRO groups in Plant Industry, Land and Water, and Forestry and Forest Products. It will provide an atmospheric perspective that complements the studies of the CRC for Carbon Accounting. (See Accounting for carbon, *Ecos* 101).

Abstract: The El Niño-Southern Oscillation (ENSO) climatic phenomenon exerts a strong influence on global carbon dioxide concentrations. Understanding this link is vital to improving the accuracy of global carbon models, and to deciphering the climatic effects of human activities such as the burning of fossil fuels. Research so far suggests that during ENSO events, when atmospheric CO_2 levels decline sharply, it's the tropical oceans that are mainly responsible: the release of CO_2 from the vast sink of the oceans is markedly reduced. But during La Niña events, tropical terrestrial sources dominate the global picture, as litter decomposition and burning release more carbon dioxide into the atmosphere. It is not yet clear how ENSO or other climatic cycles affect CO_2 sources and sinks in the Southern Ocean. While local measurements suggest it should be a strong sink, but this is not confirmed by the atmospheric data.

Keywords: carbon dioxide, El Niño-Southern Oscillation (ENSO), carbon cycle La Niña, global warming, carbon-isotope ratios, inversion, carbon flux, ocean circulation.



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