

Ups and Downs of CO₂ Uptake

Paul Quay

“Models come and go, but a good data set lasts forever.” This message was often repeated by my postdoctoral advisor while he was busy making high-precision radiocarbon measurements, and I was using a model to interpret them. I have since learnt to appreciate how much a unique data set can

Enhanced online at
www.sciencemag.org/cgi/content/full/298/5602/2344

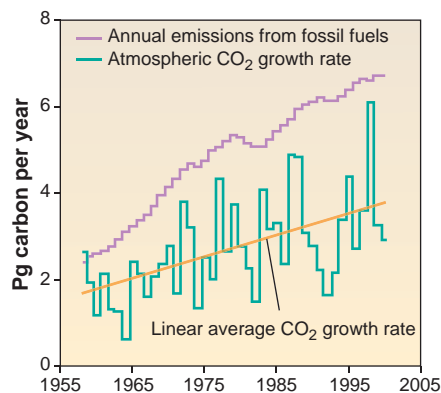
influence scientific progress. One of the most widely recognized data sets in the field of climate change is the increase in atmospheric CO₂ concentration measured by Dave Keeling since 1958 at the Mauna Loa observatory in Hawaii. This single time series spawned today's atmospheric CO₂ monitoring program at ~100 sites worldwide.

On page 2374 of this issue, Gruber *et al.* (1) present an 18-year record of surface ocean CO₂ concentrations near Bermuda. The record is derived from measurements of dissolved inorganic carbon and alkalinity. The authors use this record to estimate the interannual variability of anthropogenic CO₂ uptake in the North Atlantic Ocean. In stark contrast to the monitoring network for atmospheric CO₂, such decade-long ocean CO₂ records exist at only two other sites: one in the equatorial Pacific and one in the subtropical North Pacific.

Over the past 25 years, on average about 3 Pg C (1 Pg = 10¹⁵ g) of CO₂ accumulate each year in the atmosphere from fossil fuel combustion and deforestation. But over the same time period, the annual rate of atmospheric CO₂ increase has varied substantially (by about ±2 Pg C) about this average (see the figure) (2). The amount of CO₂ produced by fossil fuel combustion shows little interannual variability, despite its long-term increase (see the figure). The yearly variations in atmospheric CO₂ accumulation rate must therefore result from changes in the rate of CO₂ uptake by the terrestrial biosphere and the ocean.

However, quantifying the interannual variability in terrestrial and oceanic CO₂ uptake rates has not been easy. Annual carbon accumulation rates on land at global scales are difficult to measure directly with sufficient accuracy. The lack of ocean CO₂ time-series sites severely limits our ability to estimate interannual changes in oceanic CO₂ uptake.

The author is in the School of Oceanography, University of Washington, Seattle, WA 98195, USA. E-mail: pdquay@u.washington.edu



Going up. Annual global rates of CO₂ accumulation in the atmosphere and CO₂ emission from fossil fuel burning since 1958 (2).

Researchers have therefore relied on atmospheric budgets of CO₂, ¹³CO₂, and O₂ derived from atmospheric time series (3–5) to infer interannual changes in the oceanic and terrestrial CO₂ uptake. These budgets indicate that oceanic CO₂ uptake has varied by ±1 to 2 Pg C per year, but unfortunately, the uncertainties are of similar magnitude (5, 6). In contrast, an ocean model (7) and a correlation between CO₂ concentrations in the surface ocean and sea surface temperature (8) predict the interannual variability of oceanic CO₂ uptake to be three to five times lower. These results imply that most of the interannual variability in atmospheric CO₂ is driven by changes in uptake by terrestrial biota.

Until now, these estimated changes in oceanic CO₂ uptake could only be compared with data from the equatorial Pacific, where seasonally and interannually resolved records of surface CO₂ concentrations exist for the past decade. In this part of the ocean, winds and currents are strong and variable, and the magnitude of the air-sea CO₂ flux correlates well with El Niño events, varying by ±0.6 Pg C per year (9). Now, thanks to the CO₂ time series near Bermuda, one more ocean region has been analyzed. Gruber *et al.* report that interannual variability in the entire North Atlantic could be as high as ±0.3 Pg C per year if the Bermuda record is representative.

Gruber *et al.* find that the interannual variability in the surface-ocean CO₂ concentration near Bermuda correlates strongly with changes in the mixing depth of the ocean's surface layer during winter. When atmospheric conditions favor the forma-

tion of deep surface-mixed layers in the North Atlantic during winter, the surface ocean remains colder, takes up more CO₂, and has higher levels of photosynthesis than during normal years.

The interannual variability in ocean CO₂ uptake in this part of the ocean is thus mainly determined by physical processes, which may in turn be linked to decadal shifts in climate known as the North Atlantic Oscillation. The other key process controlling surface-ocean CO₂ concentrations is the rate of marine photosynthesis, which reduces CO₂ concentrations by converting CO₂ to organic carbon. Gruber *et al.* also measured the ¹³C/¹²C ratio of the ocean CO₂ during this period and used the sensitivity of ¹³C/¹²C to photosynthesis rates to determine the effects of biological organic carbon production rates on CO₂ uptake. They compared their observational record of annual changes in oceanic CO₂ uptake with an independent prediction from an atmospheric circulation model, which uses measured CO₂ gradients in the atmosphere to calculate CO₂ sources and sinks on the ocean and land surfaces (10). The agreement between the two records is striking [see Fig. 4 in (1)].

Such model tests are needed to gain confidence in model predictions, but are limited by the lack of decade-long ocean CO₂ time series. Potentially important regions like the Southern Ocean, where ocean models predict substantial interannual variations in CO₂ uptake (7), remain chronically undersampled. Impressive ocean-wide CO₂ data sets (11) provide a reasonably clear picture of the mean surface ocean CO₂ concentrations by integrating over many years of CO₂ measurements, but we know little about interannual variability.

To improve the detection of the anthropogenic CO₂ uptake by the ocean, we must establish additional sites for oceanic CO₂ time series and augment them with measurements obtained with CO₂ sensors deployed on unattended moorings, drifting floats, and ships that routinely criss-cross the ocean. Although they may come and go, we must rely on models to predict future atmospheric CO₂ levels. Confidence in these predictions should not be limited by our ability to test the models with key data sets.

References

1. N. Gruber, C. D. Keeling, N. R. Bates, *Science* **298**, 2374 (2002).
2. P. Tans *et al.*, *CMDL Rep.* **26**, 28 (2002).
3. R. Francey *et al.*, *Nature* **373**, 326 (1995).
4. P. Rayner *et al.*, *Tellus* **51B**, 213 (1999).
5. M. Battle *et al.*, *Science* **287**, 2467 (2000).
6. P. Ciais *et al.*, *Science* **269**, 1098 (1995).
7. C. LeQuere *et al.*, *Global Biogeochem. Cycles* **14**, 1247 (2000).
8. K. Lee *et al.*, *Nature* **396**, 155 (1998).
9. R. Feely *et al.*, *Nature* **398**, 597 (1999).
10. P. Bousquet *et al.*, *Science* **290**, 1342 (2000).
11. T. Takahashi *et al.*, *Deep-Sea Res.* **49**, 1601 (2002).

CREDIT: ADAPTED FROM (2)