

Imbalance in the budget

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A TOP priority in global change research is to improve our understanding of the global carbon cycle. Fossil fuel emissions and other anthropogenic activities have increased atmospheric carbon dioxide by almost 30 per cent in the past 200 years. For the past decade, on average about half of the estimated 6.6 gigatonnes of carbon released per year ($1 \text{ Gt} = 10^{15} \text{ g}$) has remained in the atmosphere. Less certain is how the remaining carbon is distributed between the other reservoirs. According to model estimates, about 2 Gt enters the ocean yearly, while the rest (about 1.2 Gt) is attributed to an unidentified terrestrial sink. Understanding just how the mechanisms for carbon uptake operate is crucial.

On page 201 of this issue¹, and in work presented at a conference last year², Hesshaimer, Heimann and Levin challenge our quantitative understanding of the global carbon cycle. They find that, using present estimates, they cannot balance the global budget of artificially produced radiocarbon. To correct this, they suggest that ocean uptake estimates based on observations made during the GEOSECS campaign³ must be revised downwards, and that a similar decrease should be fed into model-based estimates for ocean uptake of anthropogenic CO_2 .

Inadvertently, the atomic bomb tests of the late 1950s and early 1960s have yielded valuable geophysical information. The bomb tests added substantial amounts of radiocarbon to the natural background ($^{14}\text{C}/^{12}\text{C} \approx 10^{-12}$), leading to maximum tropospheric concentrations around 1964. Once test-ban treaties were set in place, stratospheric and tropospheric levels decreased as bomb radiocarbon became absorbed into the oceans and biosphere. Tracking the injection of bomb radiocarbon into the stratosphere and its subsequent spread into other carbon reservoirs allows one not only to study the global carbon cycle, but also to gain insight into the dynamics of the upper ocean and into tracer exchange between stratosphere and troposphere.

The ocean's radiocarbon distribution was mapped systematically, along with many other tracers, during the global GEOSECS campaign (1972–78). Today, these and many recent data serve as a standard to validate and calibrate ocean models, and estimates of ocean CO_2 uptake rely heavily on measurements of the penetration of bomb radiocarbon^{3,4}.

In their new study¹, Hesshaimer *et al.* investigate the global bomb-radiocarbon budget and point out a problem that, surprisingly, has been long overlooked. The problem involves two distinct time periods. First, in the late 1950s and early

1960s, bomb testing was at its highest: most of the bomb radiocarbon was still in the atmosphere. By combining atmospheric observations and bomb test statistics, they calculate a yield factor that allows them to convert estimates of explosive power into radiocarbon production. Second and more important, after the test ban atmospheric explosions were relatively rare, so the global radiocarbon budget should have remained roughly constant, an additional constraint that must be satisfied by carbon cycle models. Hesshaimer *et al.* find that an extra radiocarbon source equivalent to about 80% of the biospheric uptake or 25% of the oceanic uptake needs to be introduced to restore balance in their model.

Of the four important carbon reservoirs, global radiocarbon observations exist for three: the troposphere, the stratosphere and the ocean. The tropospheric concentration has been monitored since the onset of the bomb tests. Stratospheric data exist until 1969 and for 1989. For the

global ocean, observations exist only for the mid-1970s. Hesshaimer *et al.* derived the oceanic uptake history by using Siegenthaler and Oeschger's box-diffusion model⁵ as calibrated to match the observed bomb-radiocarbon distribution at the time of GEOSECS. To estimate the uptake of the remaining biospheric reservoir, a three-box model accounting for soil, short-lived and long-lived vegetation was used. The global biospheric uptake of bomb radiocarbon cannot be easily assessed by observation, but as it is of the same order as the imbalance, there seems to be no reasonable way to balance the budget purely by changing the model's biosphere structure.

How then can the imbalance in the bomb-radiocarbon budget be explained? Hesshaimer *et al.* provide substantial evidence suggesting that the accepted ocean inventory should be lowered by 25%. This, however, conflicts with a preliminary 15% upward revision of the inventory based on a more refined analysis of the GEOSECS observations^{3,6}. With that, balancing the budget becomes even harder.

Broecker and Peng⁶ have confirmed that in their model there is an imbalance in

Reservoir	Change in inventory mid-1965 to mid-1989 (10^{26} atoms)	Comments
Biosphere	$+75 \pm 30$	Average of 4 models in refs 1, 3, 5, 10. Model results: 60, 45, 89 and 99 units
Ocean	$+310 \pm 60$	Average of 3 models in refs 1, 6, 10. Error based on uncertainty in inventory estimates ^{3,6} . Model results: 299, 337 and 287 units
Troposphere	-150 ± 15	Derived from observations; assumed known within 10%
Stratosphere	-100 ± 30	Derived from observations ⁷ ; error of roughly 30% assumed because original estimate for 1965 has since been revised downwards ^{1, 11} by 17%
Changes in all reservoirs		$+135 \pm 75$
Sources and sinks	Cumulative production 1965 to 1989 (10^{26} atoms)	Comments
Nuclear industry	3 ± 2	Amount negligible
Radioactive decay	-1.7 ± 0.7	Amount negligible; calculated using global inventory of 6×10^{28} atoms and half-life 5,730 years
Bomb detonation	52 ± 20	See Hesshaimer <i>et al.</i> ¹ for calculation
Total production	53 ± 20	
Imbalance*	82 ± 78	
Data for production by nuclear industry and bomb detonation, and for atmospheric observations, courtesy of V. Hesshaimer. Model results for ocean and biosphere uptake courtesy of V. Hesshaimer and T. H. Peng.		
*Error obtained by quadratic error addition.		

bomb-radiocarbon budget for the post-test-ban period and, like Hesshaimer *et al.*, suspect that the reason lies in the ocean. However, they give a somewhat different explanation. Instead of lowering oceanic uptake estimates for each year, they propose an enhanced uptake for the bomb-test period, and a reduced uptake after 1963. This allows them both to fulfil the constraint of a roughly constant global ^{14}C -inventory for the post-test-ban period, and to match their GEOSECS inventory estimate^{3,6} for the mid-1970s. The initial enhanced oceanic uptake, which by 1963 accumulates to an increase in model inventory of roughly 100%, would probably require a substantially increased gas exchange rate (the uptake is largely limited by air-sea exchange). Increasing the gas exchange is not without its problems, as radiocarbon-based estimates of the global CO_2 gas exchange rate are already substantially higher than estimates based on wind tunnel and open lake experiments.

The uncertainties in all these figures are large. The tables list changes in bomb-radiocarbon inventories from 1965 to 1989, for which the budget imbalance amounts to $(82 \pm 78) \times 10^{26}$ atoms (82×10^{26} represents 10–15% of the global inventory). Most of the budget uncertainty stems from the ocean uptake estimate, because almost half of the bomb radiocarbon entered the ocean during that period. Although error estimates are somewhat arbitrary, the large uncertainty for this imbalance term implies that major revision of our picture of the global carbon cycle would be premature. But the effort to clarify the bomb-radiocarbon budget must be made if we are to refine our understanding of what controls the distribution of anthropogenic CO_2 .

What are the consequences of this imbalance? Hesshaimer *et al.* further suggest that the air-sea gas exchange, the bomb-radiocarbon penetration depth and thus the oceanic CO_2 uptake should also be lowered by 25%. However, bomb-radiocarbon and anthropogenic CO_2 do not behave identically. First of all, the equilibration time between surface water and air is about ten times longer for ^{14}C than it is for anthropogenic CO_2 , so the bomb-radiocarbon inventory strongly depends on gas exchange. In contrast, CO_2 uptake is more limited by mixing between surface and deep ocean waters. The bomb-radiocarbon penetration depth characterizes this downward transport of anthropogenic CO_2 to a large extent⁴, but not perfectly. The difference in the downward mixing of anthropogenic CO_2 and ^{14}C arises from the difference in time-scales: in surface water, CO_2 concentration has grown for the past 200 years with a 30–60 year *e*-folding timescale, whereas bomb radiocarbon increased rapidly in just two decades to reach its maximum in

the early 1970s.

The link between bomb-radiocarbon inventory and CO_2 -uptake estimates needs to be considered carefully. It is probable that there is a correlation between errors in the estimated bomb-radiocarbon inventory and in surface concentration (estimated as the difference between pre- and post-bomb measurements). So a simultaneous downward revision of bomb-radiocarbon surface concentration and inventory estimates does not necessarily require an equally large revision of their ratio, the penetration depth (defined as inventory in atoms m^{-2} divided by surface concentration in atoms m^{-3}). One would first need to quantify the relation between new estimates of ^{14}C inventory and penetration depth, before treating the bomb-radiocarbon penetration depth as a good measure for the ocean's anthropogenic CO_2 uptake. The bottom line is that a revision of CO_2 uptake estimates may be substantially smaller than the 25% suggested for the bomb-radiocarbon inventory.

Bomb radiocarbon, then, retains its usefulness as a benchmark for ocean models of CO_2 uptake, but it cannot be used alone. We need independent confirmation of mixing rates obtained by monitoring the penetration of CFCs and other transient tracers into the ocean. Also important are efforts to measure changes in atmospheric oxygen⁷ and atmospheric and oceanic ^{13}C (ref. 8). These two tracers are linked inextricably to the cycling of carbon, and their monitoring will help to distinguish carbon fluxes between atmosphere and ocean from those between atmosphere and biosphere. Combining all these pieces of the puzzle should produce a more detailed picture of carbon's pathway through the global climate system.

One last note. Uncertainties of the kind discussed above are thoroughly considered in the present scientific assessment of the Intergovernmental Panel on Climate Change⁹. It remains a fact that atmospheric CO_2 will continue to grow if carbon emissions are not lowered. □

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Draining away

MANY people, mostly women, seek to enhance their charms by having their excess fat surgically removed. Unlike dieting or exercise, liposuction is rapid, and can be directed at specific areas of fat. But it can also be expensive, crude and painful, and the results are not always pleasing. Daedalus now has a new idea.

Body fat, he points out, is an ester of glycerol and fatty acids. When the body needs energy, the fat is hydrolysed to glycerol and free fatty acid, which is released into the blood as a biological fuel. This fuelling system can react very rapidly. At any moment there is only about a gram of free fatty acid in the bloodstream, but if used up it can be replaced in a few minutes. So, says Daedalus, instead of removing fat surgically, why not extract it continuously from the blood? A gram of weight could be lost every few minutes. A few hours of the treatment every day could lose a pound of fat per week.

The obvious technology for the job is the dialysis treatment used to purify the blood of people with kidney failure. The patient would merely sit or lie down with a couple of transfusion needles in her. One would extract her blood and pass it through a fatty-acid separator; the other would reinject the defatted blood. No vigorous action or iron self-control would be required.

Compared to surgery, this simple and almost non-invasive process has one serious disadvantage. It gives no control over the region of fat to be lost. Women suffering from the dreaded pear-shaped syndrome, or men burdened with a spare tyre, could not be sure of losing fat from the afflicted region. But Daedalus recalls that the metabolism of fat rises with temperature, possibly because its viscosity drops. This may be why many figure-shaping programmes specifically exercise the muscles in the fatty regions. Sadly, the resulting muscular heat spreads all round the body and has no local effect. But Daedalus's blood-defatting process could easily be refined by warming the areas to be lost and cooling those to be retained. The body could be truly sculpted at last.

To attain the figure of her dreams, the subject would have to remain immobile and plumbed into the system for several hours a day. She would wear heating blankets over the regions to be lost, and water-cooled sheeting over those to be retained. This extended ordeal may seem daunting; but Daedalus points out that many people already stay still for at least four hours a day, watching television. The slight extra distress would probably go unnoticed.

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