

## Response to Comment on “Enhanced Open Ocean Storage of CO<sub>2</sub> from Shelf Sea Pumping”

The comment by Cai and Dai (1) recognizes the good design of our high-resolution carbon cycle study in the North Sea (2) but purports to caution against the common practice of extrapolating regional results to a global scale. We argue that the comment (1) is invalid on all counts and is a misleading representation of previous work (2–5). Indeed, in the comment, Cai and Dai target not only our *Science* paper (2) but also earlier work in another journal by Tsunogai *et al.* (6)—a 5-year-old study whose authors lack the opportunity to respond in this forum.

We surveyed the North Sea for four consecutive seasons (2). During each of the four cruises, we obtained ~23,000 measurements of the partial pressure of CO<sub>2</sub> (*p*CO<sub>2</sub>) in surface waters and the atmosphere, and vertical profiles of dissolved inorganic carbon (DIC) at 97 stations. This high spatial resolution allowed for the most accurate estimate of the net annual air-sea flux of CO<sub>2</sub> for a coastal sea to date. Extrapolating from the North Sea (1.89% of all coastal seas), the net annual influx of CO<sub>2</sub> in worldwide coastal seas would be on the order of 20% of the overall net uptake by the oceans (assuming that all coastal seas behave like the North Sea). Similar global extrapolations have been made from studies in the Gulf of Biscay (4), East China Sea (ECS) (6, 7), and the salt-marsh-dominated margin system of the South Atlantic Bight (SAB) (5). All of these studies demonstrate a net annual uptake of atmospheric CO<sub>2</sub> and transport into the open ocean and therefore provide strong support for the continental shelf CO<sub>2</sub> pump hypothesis. They also demonstrate that it is common practice to place a regional study in wider (4) or global (5–7) context. In addition, the overview references provided in our study [notes 3 to 5 in (2)] allow the reader to assess our extrapolation.

The North Sea study (2) did not confirm preliminary observations in the same area (3, 4), as mistakenly stated in (1). The extrapolation of the Gulf of Biscay Study (4) to all European continental shelves ignored the undersampled North Sea. The pioneering North Sea study (3) in May to June 1986 used ~1000 calculated *p*CO<sub>2</sub> values [substantially fewer, as well as with considerably different *p*CO<sub>2</sub> values, than our May 2002 survey (2)],

and yielded a 6-week flux estimate, which differs greatly from the May 2002 survey and which has been extrapolated (3) to six warm months but not to an annual net flux value.

The concerns raised by Cai and Dai (1) about extrapolating a regional study to the global scale (1) contradict similar extrapolations made in previous work (6, 7), including the SAB study by the lead author of the current comment (5). The SAB study by Cai *et al.* (5) involved five repeats of only one shelf transect, which had first been extrapolated along the margin. It is important to note that there is inherent uncertainty in assumed along-margin uniformity. Next, the extrapolated shelf-wide DIC export rate (2.6 Mt C year<sup>-1</sup>) was combined with rates somehow obtained in the salt marshes, into an overall budget [figure 3 in (5)] and then again extrapolated at a global scale to an annual net export rate of DIC into the deep ocean of 0.6 Gt C year<sup>-1</sup>. This value was compared with the annual net value of 1.5 Gt C year<sup>-1</sup> extrapolated from another coastal sea (ECS) (6) and with the overall net annual uptake by the world oceans of 2 Gt C year<sup>-1</sup>. Cai *et al.* (5) admitted that large uncertainty may be involved in the global extrapolation (their study was based on two successive extrapolations) but in the end suggested that “ocean carbon sequestration can proceed effectively through the absorption of atmospheric CO<sub>2</sub> by marsh grasses and the subsequent export to the open ocean.”

Cai and Dai (1) also mistakenly isolate the shelf part of the overall salt-marsh-dominated margin system as the first published example of a coastal margin acting as a net source of atmospheric CO<sub>2</sub>. [It is not the first example; see (8)]. The SAB is obviously one system in which intense CO<sub>2</sub> fixation in the salt marsh causes massive organic loading of the shelf, which in turn drives net annual CO<sub>2</sub> outgassing from the open shelf. Despite loss of CO<sub>2</sub> to the atmosphere, the overall system still acts as a net annual sink of CO<sub>2</sub> and exports DIC into the deep ocean. Thus, the high *p*CO<sub>2</sub> values at the shelf [up to 1200 parts per million (ppm); see figure 1 in (5)] are intrinsic to this salt-marsh-dominated margin system and akin to the *p*CO<sub>2</sub> (up to 750 ppm) observed in the Scheldt River plume (8). Only if all the salt marshes were dammed off could the SAB shelf component be presented as a system on its own. If that were the case, however, the

high *p*CO<sub>2</sub> values at the shelf would disappear immediately. In due course, the modest autotrophic CO<sub>2</sub> fixation on the open shelf would drive a continental shelf pump, albeit at a more modest pace than nowadays.

Classical upwelling systems initially show CO<sub>2</sub> supersaturation in the newly upwelled waters and later act as strong CO<sub>2</sub> exporters to the deep ocean through the biological pump supported by upwelled nutrients (9–12). Depending on the balance between the CO<sub>2</sub> upwelling supply and the biological pump, these upwelling systems may act as either an annual source or an annual sink of CO<sub>2</sub>. This is not dependent on latitude as suggested in (1); indeed, the largest upwelling system in the world is the Southern Ocean at high latitude (13). In a well-known study of mangrove systems in Papua New Guinea, the Bahamas, and India (14), the usual global extrapolation was made, which implied a global annual CO<sub>2</sub> release of 0.05 Pg C year<sup>-1</sup>. Although this is a substantial amount, it is still an order of magnitude lower than the extrapolated global continental shelf uptake of 0.4 Pg C year<sup>-1</sup> from our North Sea study (2).

In conclusion, we believe that the comment by Cai and Dai (1) raises a non-issue, has made several invalid claims and wrongly cites previous studies of ocean uptake of atmospheric CO<sub>2</sub>, and purports to caution about the common practice of global extrapolation. (2–5). Moreover, it confuses classical upwelling systems with a speculative latitudinal dependence of the CO<sub>2</sub> gas exchange in marginal seas and the enhanced open ocean storage of CO<sub>2</sub> from shelf sea pumping.

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### References and Notes

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## TECHNICAL COMMENT

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