Budgeting sinks and sources of CO_2 in the coastal ocean: Diversity of ecosystems counts

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[1] Air-water CO_2 fluxes were up-scaled to take into account the latitudinal and ecosystem diversity of the coastal ocean, based on an exhaustive literature survey. Marginal seas at high and temperate latitudes act as sinks of CO_2 from the atmosphere, in contrast to subtropical and tropical marginal seas that act as sources of CO_2 to the atmosphere. Overall, marginal seas act as a strong sink of CO_2 of about -0.45 Pg C yr^{-1}. This sink could be almost fully compensated by the emission of CO_2 from the ensemble of near-shore coastal ecosystems of about 0.40 Pg C yr^{-1}. Although this value is subject to large uncertainty, it stresses the importance of the diversity of ecosystems, in particular near-shore systems, when integrating CO_2 fluxes at global scale in the coastal ocean.

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1. Introduction

[2] The coastal ocean has been to a large extent ignored in global carbon budgets, even if the related flows of carbon and nutrients are disproportionately high in comparison with its surface area. It receives massive inputs of organic matter and nutrients from land, exchanges large amounts of matter and energy with the open ocean across continental slopes and constitutes one of the most biogeochemically active areas of the biosphere. Hence, intense air-water CO_2 exchanges can be expected in the coastal ocean that could lead to a major re-evaluation of CO_2 flux budgets at regional [*Frankignoulle and Borges*, 2001] or global scales [*Tsunogai et al.*, 1999; *Thomas et al.*, 2004a]. However, the direction, magnitude and latitudinal variability of air-sea CO_2 fluxes in marginal seas has been recently debated [*Cai and Dai*, 2004; *Thomas et al.*, 2004b] although it has been overlooked that the coastal ocean is an ensemble of multiple diverse ecosystems and is not solely composed of marginal seas. A climatological approach is not possible at present time to evaluate sinks and sources of CO_2 in the coastal ocean, due to the strong temporal and spatial heterogeneity of coastal environments and relative paucity of data. We adopted in the present paper an up-scaling approach (i.e. reasonable flux value for a given ecosystem multiplied by its respective surface area) to attempt to assess the relative importance and potential impact of near-shore systems on the overall budget of CO_2 in the coastal ocean.

2. Results and Discussion

[3] An exhaustive literature survey of air-water CO_2 fluxes was conducted (Table A1[1]) and data in 44 coastal environments were gathered in 6 major ecosystems (marginal seas, upwelling systems, estuaries, mangrove and salt-marsh waters, and coral reefs). We updated the recent compilation by *Borges* [2005] by: 1 - adding data that was overlooked or recently published (Ross Sea, South China Sea, Southwest Brazilian coast, Vancouver Island coast); 2 - homogenizing for upwelling systems and marginal seas the fluxes computed using different gas transfer velocity parameterizations; 3 - accounting for the relative occurrence of El Niño/La Niña events for upwelling systems; 4 - computing the fluxes using daily wind speeds rather than using a constant gas transfer velocity, for sites where fluxes were not given in the original publications; 5 - using the most recent estimates of the surface areas of coastal ecosystems (in particular mangroves and coral reefs).

[4] Marginal seas at high (Barents Sea, Bristol Bay, Pryzd Bay, and Ross Sea) and temperate (Baltic Sea, North Sea, Gulf of Biscay, US Middle Atlantic Bight, and East China Sea) latitudes are net annual sinks of atmospheric CO_2 but at sub-tropical and tropical latitudes they are net annual sources of CO_2 to the atmosphere (US South Atlantic Bight, South China Sea, and Southwest Brazilian coast) (Table A1). This contrasted behavior is partly related to the fact that the open oceanic waters that circulate over continental shelves tend to be on annual scale undersaturated in CO_2 at high and temperate latitudes and oversaturated in CO_2 at subtropical and tropical latitudes (Table 1). Biogeochemical processes over continental shelves further amplify or dampen this background signal imposed by the open oceanic waters. At high latitudes, important CO_2 absorption from the atmosphere occurs during the ice free periods when primary production is high, and sea ice extensively present during most of the year is assumed to block CO_2 exchanges with the atmosphere [e.g., *Gibson and Trull*, 1999]. At temperate and subtropical latitudes the most comprehensive studies of carbon flows including air-water CO_2 fluxes are, respectively, in the North Sea (NS [*Thomas et al.*, 2005]) and the US South Atlantic Bight (SAB [*Cai et al.*, 2003]). The comparison of

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023053.

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Table 1. Tentative Budget of Air-Water CO_2 Fluxes in the Coastal, Open and Global Oceans

	Surface (10^6 km^2)	Air-Water CO_2 Flux mol C m^{-2} yr^{-1}		Pg C yr^{-1}
60°–90° (high latitude)				
Open	30.77	−0.61[f]		−0.22
Marginal seas	7.08[a]	−1.94[g]	−1.21	−0.10
Estuaries	0.11[b]	46.00[h]		
Sub-total	37.96	−0.72		−0.33
30°–60° (temperate)				
Open	122.44	−1.40[f]		−2.06
Marginal seas	14.49[a]	−1.84[i]		
Coastal upwelling	0.24[a]	0.11[j]	−0.73	−0.13
Estuaries	0.27[b]	46.00[h]		
Marsh waters	0.14[c]	21.40[k]		
Sub-total	137.58	−1.33		−2.19
0°–30° (subtropical and tropical)				
Open	182.77	0.32[f]		0.71
Marginal seas	1.46[a]	1.84[l]		
Coastal upwelling	1.25[a]	0.11[j]		
Coral reefs	0.28[d]	1.51[m]	4.19	0.18
Mangrove waters	0.15[e]	18.66[n]		
Estuaries	0.56[b]	16.83[o]		
Sub-total	186.44	0.40		0.90
Total				
Open ocean	336.0	−0.39		−1.57
Coastal ocean	26.0[a]	−0.15		−0.05
Global ocean	362.0	−0.37		−1.61

[a]From *Walsh* [1988].
[b]Based on the global surface area estimate of 0.9433 10^6 km^2 from *Woodwell et al.* [1973] partitioned into latitudinal bands assuming a linear dependence with freshwater discharge.
[c]Assuming that non-estuarine marshes correspond to half of the global surface area estimate of 0.2787 10^6 km^2 given by *Woodwell et al.* [1973].
[d]*Spalding et al.* [2001].
[e]*Food and Agriculture Organization of the United Nations* [2003].
[f]*Takahashi et al.* [2002] and http://www.ldeo.columbia.edu/res/pi/CO2/.
[g]Average of data for Barents Sea, Bristol Bay, Pryzd Bay and Ross Sea.
[h]Surface area weighted average of data for estuaries located north of 31°N.
[i]Surface area weighted average of data for marginal seas located between 32°N and 57°N.
[j]Surface area weighted average of data for coastal upwelling systems.
[k]Data from Duplin River.
[l]Average of data for US South Atlantic Bight, South China Sea and Southwest Brazilian coast.
[m]Average of data for coral reefs.
[n]Average of data for mangrove waters.
[o]Average of data for estuaries located south of 32°N.

these two marginal seas by *Borges* [2005] shows that the NS receives less dissolved inorganic (DIC) and organic carbon (DOC) of terrestrial origin and exports more efficiently DIC to the adjacent Atlantic Ocean than the SAB. This is due to the seasonal stratification in the NS that allows a decoupling of primary production in the mixed layer and the degradation below the pycnocline of sedimented organic matter, enriching in DIC the bottom waters that are advected out of the system (the so called "continental shelf pump"). In the permanently well mixed waters of the SAB, the decoupling of organic carbon production and degradation occurs in time but does not occur across the water column, thus, the CO_2 produced by organic carbon degradation can be readily exchanged with the atmosphere. It remains to be established if the modes of carbon cycling in the NS and the SAB are representative of the majority of marginal seas at, respectively, temperate and subtropical/tropical latitudes.

[5] Near-shore ecosystems (estuaries, saltmarsh waters, mangrove waters, coral reefs, and coastal upwelling systems) are net annual sources of CO_2 (Table A1). The most intense fluxes are located at the land-aquatic interface (estuaries, saltmarsh waters, and mangrove waters) due to inputs of terrestrial organic carbon that fuel the net heterotrophy of the aquatic compartment (refer to *Frankignoulle et al.* [1998], *Wang and Cai* [2004], and *Borges et al.* [2003], respectively). Coral reefs act as sources of CO_2 due intense calcification and a low net organic carbon production [e.g., *Gattuso et al.*, 1998]. Coastal upwelling systems characterized by high upwelling index (UI) values (Oman and California coasts) tend to be sources of CO_2 in contrast to those with low UI values (Galician coast, Vancouver Island) (Table A1). This could be related to the fact that the residence time of the water mass is so short and the inputs of nutrients and DIC so intense that exhaustion of nutrients and under-saturation of CO_2 do not occur over the continental shelf in high UI systems, although probably occurring in upwelling filaments [*Borges*, 2005].

[6] Table 1 shows the up-scaled CO_2 fluxes in the coastal ocean by latitudinal bands of 30°, taking into account its geographical and ecosystem diversity. Systems close to a latitudinal band border were also classified according to general climatic features (for instance Bristol Bay is included in the 60°–90° band due to extensive yearly presence of sea-ice). An overall integration of CO_2 fluxes (global ocean in Table 1) was carried out using the recent climatology for open oceanic waters from *Takahashi et al.* [2002] (open ocean in Table 1). The coastal ocean would act as a net CO_2 sink at high and temperate latitudes and as a net CO_2 source at tropical latitudes. The inclusion of coastal air-water CO_2 fluxes would strongly increase the overall CO_2 sink at high latitudes (−0.22 versus −0.33 Pg C yr^{-1}, 50%) and temperate latitudes (−2.06 versus −2.19 Pg C yr^{-1}, 6%), but would significantly increase the overall CO_2 source at subtropical and tropical latitudes (+0.71 versus +0.90 Pg C yr^{-1}, 27%). Marginal seas act as a significant CO_2 sink (−1.62 mol C m^{-2} yr^{-1}; −0.45 Pg C yr^{-1}) in agreement with previous estimates based on the extrapolation to worldwide continental shelves of data from the East China Sea [*Tsunogai et al.*, 1999] or the North Sea [*Thomas et al.*, 2004a]. This agreement is due to the fact that although tropical and subtropical marginal seas are CO_2 sources (Tables A1 and 1) they only represent 5.6% of the total surface area of the coastal ocean compared to 55.7% and 27.2% for, respectively, temperate and high latitude marginal seas (Table 1). However, the global sink of CO_2 in marginal seas could be almost fully compensated by the emission of CO_2 (+11.09 mol C m^{-2} yr^{-1}; +0.40 Pg C yr^{-1}) from the ensemble of near-shore coastal ecosystems, mostly related to the emission of CO_2 from estuaries (0.34 Pg C yr^{-1}). On the whole, the coastal ocean would act as a small CO_2 sink (−0.05 Pg C yr^{-1}) and would lead to a modest increase of the CO_2 sink from the global ocean (−1.57 versus −1.62 Pg C yr^{-1}, 3%).

[7] Although it cannot be denied that the estuaries studied so far are sources of CO_2 (Table A1), our global up-scaled CO_2 emission estimate can be biased for at least two reasons. Eleven of the 16 estuaries in Table A1 are located in Europe among which most are highly impacted by human activities. But the largest bias in the up-scaling is probably related to the surface area estimate from *Woodwell et al.* [1973] and its portioning into latitudinal bands. Here, we

partitioned by latitude assuming a linear dependence of the surface area with freshwater discharge while *Borges* [2005] assumed a linear dependence with coastline length and obtained a slightly higher global CO_2 emission (0.43 Pg C yr^{-1}). Also, *Woodwell et al.* [1973] state that their estimate is prone to an uncertainty of at least ±50%. Using the lower bound global surface area estimate of estuaries (0.47 10^6 km^2) would bring the global CO_2 emission to 0.16 Pg C yr^{-1} from estuaries and to 0.24 Pg C yr^{-1} from the ensemble of near-shore coastal ecosystems. Note also that the surface area of *Woodwell et al.* [1973] relates to inland (or inner) estuaries (from the mouth to the uppermost limit of the tide) and does not cover the areas of salinity mixing at sea (outer estuaries or river plumes).

[8] The isotope signature of organic matter in sediments suggests that less than 10% of particulate organic carbon (POC) of terrestrial origin is preserved over continental shelf sediments [e.g., *Hedges et al.*, 1997]. This implies that the degradation of most of terrestrial POC could occur in estuaries in accordance with the strong net heterotrophic nature of these ecosystems [e.g., *Gattuso et al.*, 1998; *Hopkinson and Smith*, 2005]. The degradation within estuaries of riverborne POC has been estimated to range between 50 and 70% (*Abril et al.* [2002] and *Keil et al.* [1997], respectively). Assuming that the produced CO_2 is ventilated back to the atmosphere within estuaries, these systems would emit between 0.25 and 0.35 Pg C yr^{-1} based on the provocative riverborne POC input of 0.50 Pg C yr^{-1} proposed by *Richey* [2004]. Isotopic signatures also show that most of the terrestrial DOC is removed before reaching the deep ocean [e.g., *Hedges et al.*, 1997]. Isotopic signatures of DOC within estuaries further suggest that it is partly removed during estuarine mixing and that the canonical conservative behavior of DOC in these systems is related to the balance of removal and production terms [e.g., *Peterson et al.*, 1994]. However, the fraction of DOC that is removed by degradation (contributing to the emission of CO_2 from estuaries) compared to flocculation and adsorption remains to be established [e.g., *Hedges et al.*, 1997]. Nevertheless, the degradation of riverborne organic carbon could in theory sustain in estuarine environments a CO_2 emission of about 0.3–0.4 Pg C yr^{-1} in accordance with the estimate we derived from up-scaled air-water CO_2 fluxes in estuaries. Furthermore, there is increasing evidence that a significant fraction of the CO_2 emission from estuaries is sustained by lateral inputs of organic carbon and DIC although not estimated at global scale.

3. Concluding Remarks

[9] The present up-scaling of air-water CO_2 fluxes shows the contrasted behavior of the proximal coastal ocean (ensemble of near-shore ecosystems) strongly influenced by terrestrial inputs and the distal coastal ocean (marginal seas) that exports carbon to the adjacent deep ocean as DIC [*Tsunogai et al.*, 1999; *Cai et al.*, 2003; *Thomas et al.*, 2004a] and as organic carbon [e.g., *Wollast*, 1998]. This up-scaling also clearly illustrates the importance of the diversity of ecosystems and latitudinal variability in the overall role of the coastal ocean as a sink or a source of CO_2. This has significant consequences on our understanding of global cycles of carbon and CO_2. For instance, 80% of the surface area of the coastal ocean is located in the Northern Hemisphere, with possible consequences for global atmospheric CO_2 inversion models and inter-hemisphere carbon transport estimates.

[10] Several caveats remain in the present up-scaling that should be the focus of future research: 1 - a more complete description of the latitudinal and temporal variability of air-water CO_2 fluxes in marginal seas and near-shore ecosystems; 2 - the uncertainty of surface area estimates of near-shore systems, in particular estuaries and the aquatic compartment associated to intertidal habitats (mangroves and marshes); 3 - the neglect of river plume data characterized by large fluxes and surface areas [*Borges and Frankignoulle*, 2002; *Körtzinger*, 2003], although under-sampled and for which no global surface area estimate is available; 4 - the lack of data in high-latitude estuaries and river plumes; 5 - the assumption of a zero atmosphere-ice CO_2 flux at high latitudes that is inconsistent with recent data in the Artic [*Semiletov et al.*, 2004] and in Antarctica [*Delille et al.*, 2004]; 6 - the lack of data in certain coastal ecosystems such as highly productive seagrass and macrophyte dominated communities, systems mainly influenced by ground water inputs, and tidal and non-tidal lagoons.

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Table A1: Longitude (°E), Latitude (°N), range of partial pressure of CO_2 (pCO_2 in ppm) and air-water CO_2 fluxes (FCO_2 in mol m^{-2} y^{-1}) in 44 coastal ecosystems. The last column mentions the method to derive the flux values (direct method or computed from a gas transfer velocity (k) parameterization) and origin of data.

Ecosystem/site	°E	°N	pCO_2 range	FCO_2	Notes and references
Inner estuaries					
Randers Fjord	10.3	56.6	220-3440	2.2	based on floating dome measurements, from Gazeau et al. [2005]
Elbe	8.8	53.9	580-1100	53.0	based on floating dome measurements, from Frankignoulle et al. [1998]
Ems	6.9	53.4	560-3755	67.3	based on floating dome measurements, from Frankignoulle et al. [1998]
Rhine	4.1	52.0	545-1990	39.7	based on floating dome measurements, from Frankignoulle et al. [1998]
Thames	0.9	51.5	505-5200	73.6	based on floating dome measurements, from Frankignoulle et al. [1998]
Scheldt	3.5	51.4	125-9425	63.0	based on floating dome measurements, from Frankignoulle et al. [1998]
Tamar	-4.2	50.4	380-2200	74.8	based on floating dome measurements, from Frankignoulle et al. [1998]
Loire	-2.2	47.2	630-2910	64.4	using a constant k of 13 cm/h, from Abril et al. [2003]
Gironde	-1.1	45.6	465-2860	30.8	based on floating dome measurements, from Frankignoulle et al. [1998]
Douro	-8.7	41.1	1330-2200	76.0	based on floating dome measurements, from Frankignoulle et al. [1998]
Sado	-8.9	38.5	575-5700	31.3	based on floating dome measurements, from Frankignoulle et al. [1998]
York River	-76.4	37.2	350-1900	6.2	using the k parameterization of Raymond et al. [2000], from Raymond et al. [2000]
Satilla River	-81.5	31.0	360-8200	42.5	using a constant k of 12.5 cm/h, from Cai and Wang [1998]
Hooghly	88.0	22.0	80-1520	5.1	using the k parameterization of Wanninkhof [1992], from Mukhopadhyay et al. [2002]
Godavari	82.3	16.7	220-500	5.5	using the k parameterization of Raymond and Cole [2001], from Bouillon et al. [2004]
Mandovi-Zuari	73.5	15.3	500-3500	14.2	using the k parameterization of Wanninkhof [1992], from Sarma et al. [2001]
Salt-marsh waters					
Duplin River	-81.3	31.5	500-3000	21.4	using the k parameterization of Wanninkhof [1992], from Wang and Cai [2004]
Mangrove waters					
Norman's Pond	-76.1	23.8	385-750	5.0	using the k parameterization of Carini et al. [1996], from Borges et al. [2003]
Mooringanga Creek	89.0	22.0	800-1530	8.5	using the k parameterization of Carini et al. [1996], from Borges et al. [2003]
Saptamukhi Creek	89.0	22.0	1080-4000	20.7	using a constant k of 4 cm/h, from Borges et al. [2003] based on Ghosh et al. [1987]
Gaderu Creek	82.3	16.8	1380-4770	20.4	using the k parameterization of Carini et al. [1996], from Borges et al. [2003]
Nagada Creek	145.8	-5.2	540-1680	15.9	using the k parameterization of Carini et al. [1996], from Borges et al. [2003]
Itacuraça Creek	-44.0	-23.0	660-7700	41.4	using a constant k of 4 cm/h, from Borges et al. [2003] based on Ovalle et al. [1990]
Coral Reefs					
Hog Reef	-64.8	32.3	340-480	1.2	using the k parameterization of Wanninkhof [1992], from Bates et al. (2001)
Okinawa Reef	127.5	26.0	95-950	3.2	flux values converted to the k parameterization of Wanninkhof [1992] using conversion factors determined from the Rayleigh frequency distribution from values originally computed from the k parameterization of Liss and Merlivat [1986], from Ohde and van Woesik [1999]
Yonge Reef	145.6	-14.6	250-700	1.5	based on floating dome measurements, Frankignoulle et al. [1996]
Moorea	-149.8	-17.5	240-580	0.1	based on floating dome measurements, from Gattuso et al. [1993, 1997] and Frankignoulle et al. [1996]
Coastal upwelling systems					
Vancouver Island coast	-126.0	49.0	200-550	-1.2	using the k parameterization of Wanninkhof [1992], from Ianson and Allen [2002], and assuming an occurrence of El Niño and La Niña events with a frequency of, respectively, 0.56 and 0.44 based on Southern Oscillation Index for the 1983-2003 period from Climatic Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/)
Galician coast	-9.2	42.5	265-415	-2.2	using the k parameterization of Wanninkhof [1992], from Borges and Frankignoulle [2002]
Californian Coast	-122.0	36.8	100-850	0.5	flux values converted to the k parameterization of Wanninkhof [1992] using conversion factors determined from the Rayleigh frequency distribution from values originally computed from the k parameterization of Wanninkhof and McGillis [1999], from Friederich et al. [2002], and assuming an occurrence of El Niño and La Niña events with a frequency of, respectively, 0.56 and 0.44 based on Southern Oscillation Index for the 1983-2003 period from Climatic Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/)
Oman coast	59.0	20.0	365-660	0.9	using the k parameterization of Wanninkhof [1992], from Goyet et al. [1998]
Marginal seas					
Barents Sea	30.0	75.0	168-352	-3.6	using the k parameterization of Wanninkhof [1992], based on data compiled from Kaltin et al. [2002] and Omar et al. [2003], using NCEP daily wind speeds for the 1993-2003 period obtained from National Oceanic and Atmospheric Administration Climate Diagnostics Center (http://www.cdc.noaa.gov/), and assuming a zero air-ice CO2 flux (ice coverage based on data from the National Snow and Ice Data Center downloaded from http://nsidc.org/)
Bristol Bay	-164.0	58.0	111-450	-0.2	using the k parameterization of Wanninkhof [1992], based on data compiled from Kelly and Hood [1971], Codispoti et al. [1986], Chen [1993], and Murata and Takiwaza [2002], using NCEP daily wind speeds for the 1993-2003 period obtained from National Oceanic and Atmospheric Administration Climate Diagnostics Center (http://www.cdc.noaa.gov/), and assuming a zero air-ice CO_2 flux (ice coverage based on Walsh and Dieterle [1994])
Baltic Sea	20.0	57.0	156-475	-0.8	using the k parameterization of Wanninkhof [1992], from Thomas and Schneider [1999]
North Sea	2.6	56.7	145-495	-1.4	flux values converted to the k parameterization of Wanninkhof [1992] using conversion factors determined from the Rayleigh frequency distribution from values originally computed from the k parameterization of Wanninkhof and McGillis [1999], fromThomas et al. [2004]
English Channel	-1.2	50.2	200-500	0.0	using the k parameterization of Wanninkhof [1992], from Borges and Frankignoulle [2003]
Gulf of Biscay	-7.9	49.0	260-460	-2.9	using the k parameterization of Wanninkhof [1992], from Frankignoulle and Borges [2001]
US Middle Atlantic Bight	-74.5	38.5	200-660	-1.2	using the k parameterization of Wanninkhof [1992], from DeGranpre et al. [2002]
East China Sea	125.0	32.0	200-390	-2.1	flux values converted to the k parameterization of Wanninkhof [1992] using conversion factors determined from the Rayleigh frequency distribution from values originally computed from the k parameterization of Liss and Merlivat [1986], from Wang et al. [2000]
US South Atlantic Bight	-80.6	31.0	300-1200	2.5	using the k parameterization of Wanninkhof [1992], from Cai et al. [2003]
South China Sea	115.0	22.0	290-450	1.3	using the k parameterization of Wanninkhof [1992], from Zhai et al. [2005]
Southwest Brazilian coast	-45.5	-25.0	350-475	1.8	using the k parameterization of Wanninkhof [1992], from Ito et al. [2005]
Pryzd Bay	78.9	-68.6	50-325	-2.2	using the k parameterization of Wanninkhof [1992], from Gibson and Trull [1999], and assuming a zero air-ice CO_2 flux during 297 d per year
Ross Sea	180.0	-75.0	130-425	-1.5	using the k parameterization of Wanninkhof [1992], from Sweeney [2003], and assuming a zero air-ice CO_2 flux during 200 d per year

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