Evaluation of sinks and sources of CO_2 in the global coastal ocean using a spatially-explicit typology of estuaries and continental shelves

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[1] The exchange of CO_2 between the atmosphere and the global coastal ocean was evaluated from a compilation of air-water CO_2 fluxes scaled using a spatially-explicit global typology of inner estuaries (excluding outer estuaries such as large river deltas) and continental shelves. The computed emission of CO_2 to the atmosphere from estuaries (+0.27 ± 0.23 PgC yr^{-1}) is ~26% to ~55% lower than previous estimates while the sink of atmospheric CO_2 over continental shelf seas (−0.21 ± 0.36 PgC yr^{-1}) is at the low end of the range of previous estimates (−0.22 to −1.00 PgC yr^{-1}). The air-sea CO_2 flux per surface area over continental shelf seas (−0.7 ± 1.2 molC m^{-2} yr^{-1}) is the double of the value in the open ocean based on the most recent CO_2 climatology. The largest uncertainty of scaling approaches remains in the availability of CO_2 data to describe the spatial variability, and to capture relevant temporal scales of variability. **Citation:** Laruelle, G. G., H. H. Dürr, C. P. Slomp, and A. V. Borges (2010), Evaluation of sinks and sources of CO_2 in the global coastal ocean using a spatially-explicit typology of estuaries and continental shelves, *Geophys. Res. Lett.*, *37*, L15607, doi:10.1029/2010GL043691.

1. Introduction

[2] While the atmospheric CO_2 sink is reasonably well-constrained for the open ocean, with estimates ranging between −1.4 PgC yr^{-1} and −2.2 PgC yr^{-1} [e.g., *Gruber et al.*, 2009; *Takahashi et al.*, 2009], CO_2 flux estimates for the coastal ocean are subject to large uncertainties [*Borges*, 2005; *Borges et al.*, 2005; *Cai et al.*, 2006; *Chen and Borges*, 2009]. The global CO_2 uptake by continental shelf seas has been evaluated by several authors based on the global extrapolation of a flux value from a single continental shelf sea [*Tsunogai et al.*, 1999; *Thomas et al.*, 2004] or from the compilation of literature data in several continental shelf seas [*Borges*, 2005; *Borges et al.*, 2005; *Cai et al.*, 2006; *Chen and Borges*, 2009], and values range between −0.22 PgC yr^{-1} and −1.00 PgC yr^{-1}.

[3] Inner estuaries and other near-shore ecosystems are net sources of CO_2 to the atmosphere [e.g., *Frankignoulle et al.*, 1998; *Borges et al.*, 2003] and may account for a global emission of CO_2 of a similar order of magnitude as the CO_2 sink from continental shelf seas, ranging between +0.4 PgC yr^{-1} and +0.6 PgC yr^{-1} [*Abril and Borges*, 2004; *Borges*, 2005; *Borges et al.*, 2005; *Chen and Borges*, 2009]. This range of flux values reflects the heterogeneity and complexity of these highly active biogeochemical environments at the interface between the land and the ocean, but also demonstrates the insufficient data coverage both in time and space, and the lack of appropriate spatially-explicit numerical models for carbon cycling in the global coastal ocean.

[4] As an alternative, scaling approaches can be used where a reasonable flux value for a coastal system is multiplied by the respective surface area [*Abril and Borges*, 2004; *Borges*, 2005; *Borges et al.*, 2005; *Cai et al.*, 2006; *Chen and Borges*, 2009]. The success of such scaling approaches not only depends on the quality and quantity of the measurements and how representative they are for a given coastal environment, but also on the accurate determination of the respective surface area. In this study, we evaluate sources and sinks of CO_2 in the global coastal ocean using a scaling approach, based on surface areas from a spatially-explicit coastal typology of both estuaries and continental shelf seas.

2. Budget Calculations

[5] We calculated the exchange of CO_2 between inner estuaries and the atmosphere based on a compilation of 62 published annual air-water CO_2 fluxes based on pCO_2 measurements (Table S1 of the auxiliary material), and the surface areas of four estuarine types, based on morphological differences [*Dürr et al.*, 2010]: I – small deltas and small estuaries, II – tidal systems and embayments, III – lagoons, IV – fjords and fjärds.[1] Note that outer estuarine plumes protruding onto continental shelves were not considered as estuaries. This is the case for large-river deltaic estuaries (LDE) [*Bianchi and Allison*, 2009] such as the Amazon and the Changjiang. Average air-water CO_2 fluxes were calculated for each estuarine type and extrapolated globally, based on the type-specific surface areas (Table 1). The air-water CO_2 fluxes representative for each type are based on 19, 36, 6 and 1 estimates for Types I, II, III, IV, respectively.

[6] The typology of continental shelf seas relies on 138 units with surface areas calculated using a geographical information system. The off-shore limit of the continental shelf is set to 200 m depth [*Walsh*, 1988; *Wollast*, 1998] and the related isobath was extracted from the 1' resolution global bathymetry of *Smith and Sandwell* [1997]. Each shelf unit was defined by extrapolating perpendicularly the limits

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Table 1. Air-Water CO_2 Fluxes per Surface Area and Scaled Globally for Four Estuarine Types[a]

	Surface Area (10^6 km^2)	Air-Water CO_2 Flux (molC m^{-2} yr^{-1})	Air-Water CO_2 Flux (PgC yr^{-1})
Small deltas and estuaries (Type I)	0.084	25.7 ± 15.8	0.026 ± 0.016
Tidal systems and embayments (Type II)	0.276	28.5 ± 24.9	0.094 ± 0.082
Lagoons (Type III)	0.252	17.3 ± 16.6	0.052 ± 0.050
Fjords and fjärds (Type IV)	0.456	17.5 ± 14.0[b]	0.096 ± 0.077
Total	1.067	21.0 ± 17.6	0.268 ± 0.225

[a]Air-water CO_2 fluxes per surface area in molC m^{-2} yr^{-1} and scaled globally in PgC yr^{-1} based on averages of individual estimates given in Table S1, A positive value represents a source of CO_2 to the atmosphere.
[b]The standard deviation was estimated as ±80% based on the values of the other 3 types.

of coastal segments from the shoreline [*Meybeck et al.*, 2006]. These segments were designed by identifying homogeneous stretches of coast according to a set of parameters such as morphology, lithology, oceanic currents and climate, not biased by national or political boundaries. A type was attributed to each continental shelf sea unit: Type 1 corresponds to enclosed shelves; Type 2 includes Western and Eastern boundary currents characterized by coastal upwelling and are separated according to the oceanic basin (Pacific, Atlantic and Indian); Type 3 consists of all other open continental shelf areas, ranked by climatic zones (Type 3a (tropical): 0–30°, Type 3b (temperate): 30–60°, Type 3c (polar): 60–90°). A total of 37 published air-water CO_2 fluxes were compiled (Table S2) and scaled by types based on their respective surface areas (Table 2).

[7] We excluded studies in estuaries and continental shelf seas that did not provide an adequate representation of the annual net CO_2 flux. Since it not possible to evaluate the accuracy of the individual computed air-water CO_2 fluxes given by the different studies, the standard deviation of the means for each continental shelf type and each estuarine type were propagated to provide an estimate of the uncertainty on the scaled fluxes.

3. Results

[8] A detailed description of the estuarine typology we used is given by *Dürr et al.* [2010]. In brief, fjords and fjärds (Type IV) are dominant at latitudes north of 45°N and south of 45°S (Figure 1a) and are the most extensive of the four estuarine types (~43% of the total surface area). Lagoons (Type III, ~24% of the total surface area) are dominant in the tropics and subtropics of the Northern Hemisphere (0°–45°N). Small deltas (Type I, ~8% of the total surface area) and tidal systems (Type II, ~26% of the total surface area) show no clear latitudinal pattern. The total surface area of estuaries is 1.1 10^6 km^2.

[9] The surface area of continental shelves totals 24.7 10^6 km^2 with a contribution of 6% by enclosed shelves (Type 1), 9% by coastal upwelling systems (Type 2) and 82% by the open continental shelves (Types 3a,b,c) (Figure 1b). About 75% of the surface area of continental shelf seas is located in the Northern Hemisphere, and ~45% is located north of 45°N.

[10] The emission of CO_2 to the atmosphere from estuarine environments shows two maxima, one at the equator and another at ~65°N (Figure 2a). These two maxima correspond to a small peak in surface area (associated to Types I, II and III with high air-water CO_2 fluxes) and a large peak in surface area (associated to Type IV with a lower air-water CO_2 flux), respectively (Figure 2c). The overall emission of CO_2 to the atmosphere from estuarine environments is estimated at +0.27 ± 0.23 PgC yr^{-1} (Table 1). Tidal systems (Type II) and fjords and fjärds (Type IV) contribute equally (~35%) to the global estuarine CO_2 emission, while lagoons (Type III) and small deltas (Type I) contribute 20% and 10% to the global estuarine CO_2 emission, respectively. About 79% of the total CO_2 emission to the atmosphere from estuaries occurs in the Northern Hemisphere, comparable to the areal extent (81%). The contribution to the total CO_2 emission by estuaries along climatic zones is relatively homogeneous: 32% for tropical systems, 31% for temperate systems, and 37% for high latitude systems, for 29, 31 and 40% of area, respectively.

[11] The exchange of CO_2 between continental shelf seas and the atmosphere as a function of latitude shows a clear asymmetry with regions between 30°S and 30°N (Figure 2d) acting as sources of CO_2 to atmosphere and temperate and high latitude regions (south of 30°S, north of 30°N) acting as sinks for atmospheric CO_2 (Figure 2b). The continental shelf seas of the Northern Hemisphere are a net sink of CO_2

Table 2. Air-Water CO_2 Fluxes per Surface Area and Scaled Globally for Different Types of Continental Shelves Along Three Climatic Zones[a]

	Surface Area (10^6 km^2)	Air-Water CO_2 Flux (molC m^{-2} yr^{-1})	Air-Water CO_2 Flux (PgC yr^{-1})
Polar (>60°)			
Enclosed	0.189	−0.8 ± 1.1	−0.002 ± 0.003
Open Shelf	5.477	−3.3 ± 1.7	−0.216 ± 0.111
Upwelling Pacific	0.086	3.2 ± 2.4	0.003 ± 0.002
Sub-total	5.752	−3.1 ± 1.7	−0.214 ± 0.116
Temperate (30°–60°)			
Enclosed	1.410	−0.8 ± 1.1	−0.014 ± 0.019
Open Shelf	7.170	−1.0 ± 1.0	−0.086 ± 0.087
Upwelling Pacific	0.293	3.2 ± 2.4	0.011 ± 0.008
Upwelling Atlantic	0.086	−1.6 ± 1.0	−0.002 ± 0.001
Upwelling Indian	0.123	0.9 ± 1.2[b]	0.001 ± 0.002
Sub-total	9.082	−0.8 ± 1.1	−0.090 ± 0.117
Tropical (0–30°)			
Enclosed	0.231	−0.8 ± 1.1	−0.002 ± 0.003
Open Shelf	7.909	0.9 ± 1.0	0.083 ± 0.097
Upwelling Pacific	0.515	3.2 ± 2.4	0.020 ± 0.015
Upwelling Atlantic	0.715	−1.6 ± 1.0	−0.014 ± 0.009
Upwelling Indian	0.520	0.9 ± 1.2[b]	0.006 ± 0.008
Sub-total	9.890	0.8 ± 1.1	0.093 ± 0.131
Total	24.724	−0.7 ± 1.2	−0.211 ± 0.364

[a]Air-water CO_2 fluxes per surface area in molC m^{-2} yr^{-1} based on averages of individual estimates given in Table S2 and scaled globally in PgC yr^{-1}. A positive value represents a source of CO_2 to the atmosphere.
[b]Standard deviation on the mean of seasonal fluxes at one site (Oman coast), while for the others the standard deviation is on the mean across systems of the same type.

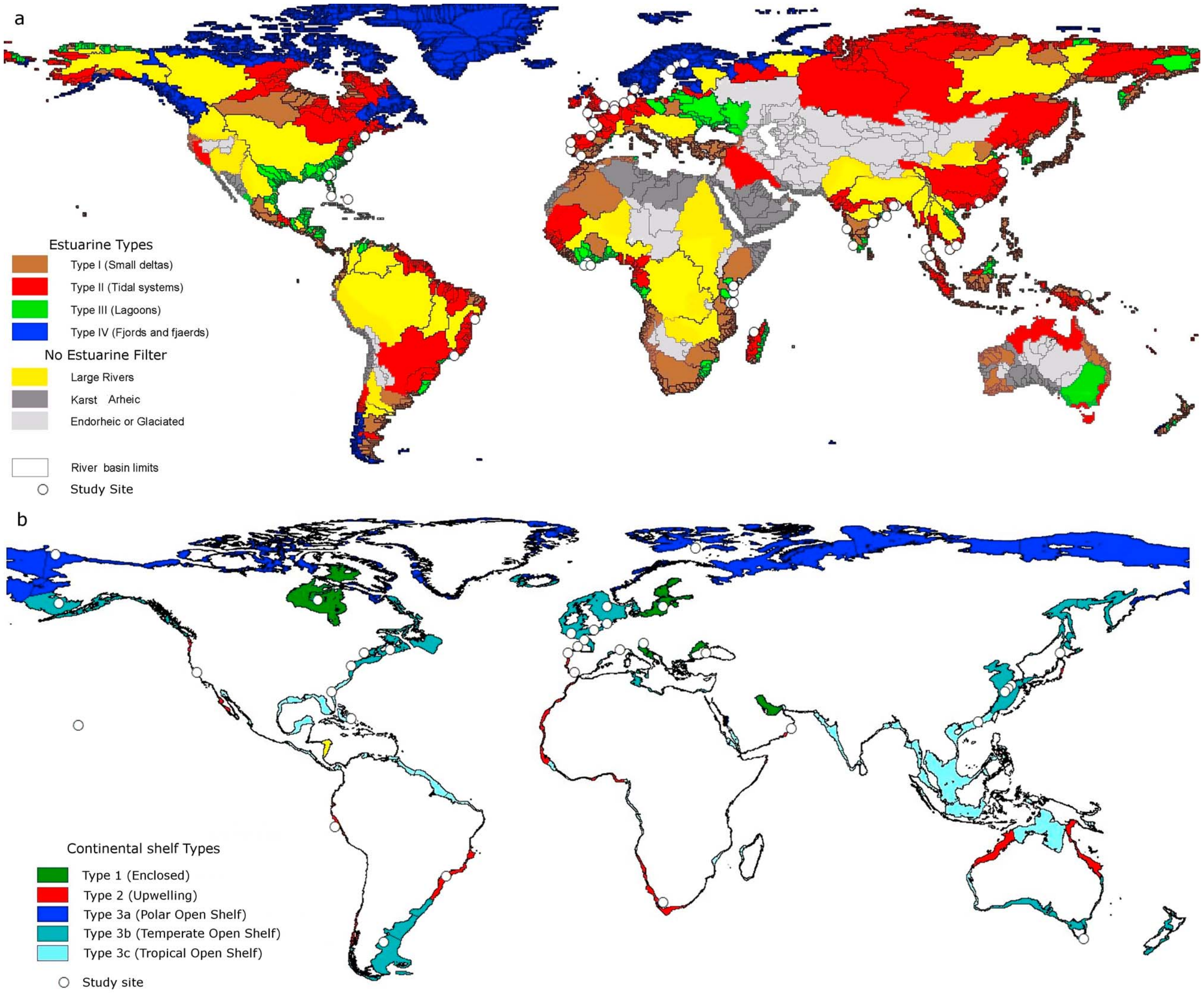

Figure 1. Typology of (a) estuarine environments (modified from *Dürr et al.* [2010]) and (b) continental shelf seas.

of −0.24 PgC yr^{-1} and the continental shelf seas of the Southern Hemisphere are a weak source of CO_2 of +0.03 PgC yr^{-1}. Globally, continental shelf seas are a net sink of atmospheric CO_2 of −0.21 ± 0.36 PgC yr^{-1}.

[12] The integrated air-water CO_2 flux in the global coastal ocean (estuaries and continental shelves) is close to neutral (+0.06 PgC yr^{-1}). The latitudinal pattern of a CO_2 source in low latitudes and sink of CO_2 at temperate and high latitudes prevails when integrating both continental shelves and estuaries (Figure 2f).

4. Discussion

[13] The general patterns of air-water CO_2 fluxes in the coastal ocean in the present study are similar to those reported by previous studies [*Borges*, 2005; *Borges et al.*, 2005; *Cai et al.*, 2006; *Chen and Borges*, 2009]. Continental shelf seas in the tropics are sources of CO_2 to the atmosphere, while temperate and high latitude continental shelf seas are sinks for atmospheric CO_2. The overall emission of CO_2 from estuarine environments is of the same order of magnitude as the sink of CO_2 of continental shelf seas. Integrated CO_2 fluxes from both continental shelf seas and estuarine environments are more intense in the Northern than in the Southern Hemisphere. An improvement in our study with respect to previous ones is that coastal upwelling systems are separated by ocean basins. Indeed, based on published data with reasonable or full annual coverage, coastal upwelling systems in the Pacific and Indian Oceans are sources of CO_2 to the atmosphere, while coastal upwelling systems in the Atlantic Ocean are sinks of atmospheric CO_2 (Table S2). This is related to the fact that oxygen minimum zones (OMZ) associated to coastal upwelling systems are shallow in the Pacific and Indian Oceans, and are deeper or absent in the Atlantic Ocean. The upwelling source waters in coastal upwelling areas associated to a shallow OMZ are sources of CO_2 to the atmosphere as denitrification leads to excess of dissolved inorganic carbon relative to nitrogen [*Friederich et al.*, 2008; *Borges*, 2010]. Due to the scarceness of data, we chose to keep the extrapolation scheme of *Borges* [2005] and *Borges et al.* [2005] by latitudinal bands of 30° irre-

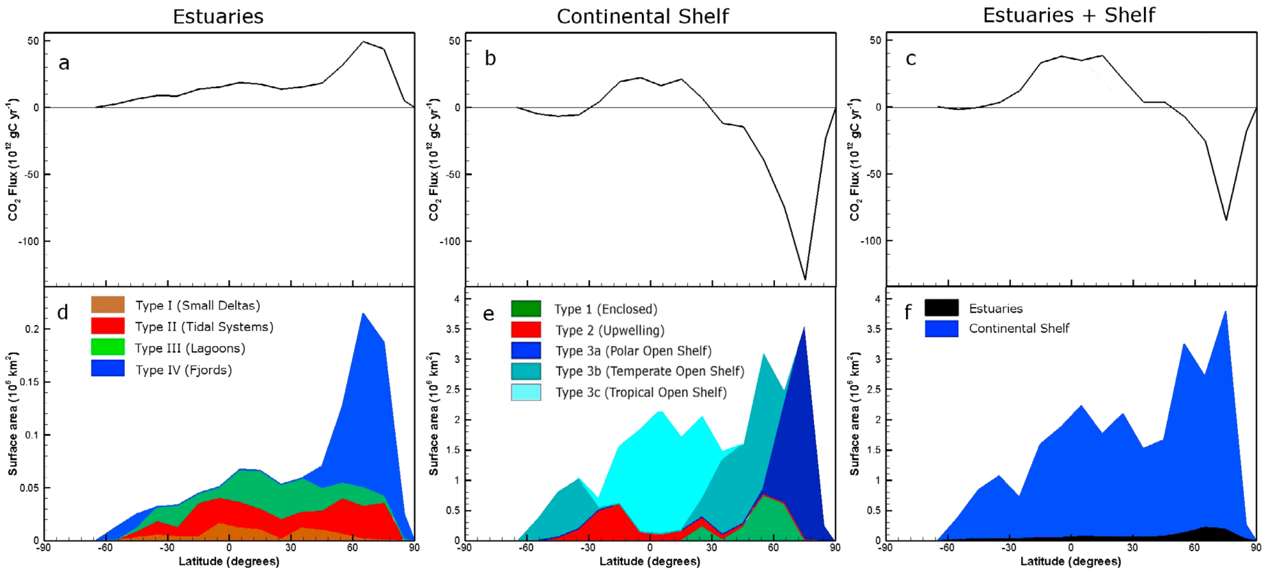

Figure 2. Latitudinal distribution of the (a–c) air-water CO_2 fluxes (in 10^{12} g C yr^{-1}) and (d–f) surface areas (in 10^6 km^2) in estuaries (Figures 2a and 2d) and continental shelf seas (Figures 2b and 2e) and the global coastal ocean (Figures 2c and 2f). A positive value represents a source of CO_2 to the atmosphere.

spective of oceanic basins or biogeochemical provinces as applied by *Cai et al.* [2006]. Moreover, the air-sea CO_2 fluxes in open continental shelf seas (Type 3) show a relatively regular pattern as a function of latitude (Figure S1).

[14] There are marked differences between the present and previous studies in the globally integrated air-water CO_2 flux values for both continental shelf seas and estuarine environments. The sink of atmospheric CO_2 over continental shelf seas (-0.21 ± 0.36 PgC yr^{-1}) is at the low end of the range of previously published estimates (-0.22 to -0.45 PgC yr^{-1}) based on compilations from different shelf systems [*Borges*, 2005; *Borges et al.*, 2005; *Cai et al.*, 2006; *Chen and Borges*, 2009], and distinctly lower than the estimate based on the global extrapolation of the air-sea CO_2 flux from the East China Sea [-1.00 PgC yr^{-1}, *Tsunogai et al.*, 1999]. Note that the value of air-water CO_2 flux in the East China Sea given by *Tsunogai et al.* [1999] of -2.9 molC m^{-2} yr^{-1} is higher than the most recent evaluations in the East China Sea (-0.9 to -2.1 molC m^{-2} yr^{-1} (Table S1)). The total surface area of continental shelf seas used in the present study (24.7 10^6 km^2) is lower than the one used by *Borges* [2005], *Borges et al.* [2005] and *Cai et al.* [2006] (25.8 10^6 km^2 based on the work by *Walsh* [1988]) and than the one used by *Chen and Borges* [2009] (30.0 10^6 km^2). Furthermore, *Borges* [2005] and *Borges et al.* [2005] used a total surface area of continental shelf seas located between 30°N and 30°S (3 10^6 km^2) that was under-estimated compared to the one of the present typology (10 10^6 km^2). The use of skewed surface areas in these studies led to an overestimation of the sink of CO_2, as the global air-water CO_2 flux per surface area was -1.17 and -1.44 molC m^{-2} yr^{-1} for tropical and temperate shelf seas, respectively. The global air-water CO_2 flux per surface area in the present study (-0.71 ± 1.23 molC m^{-2} yr^{-1}) is identical to the one computed by *Cai et al.* [2006] and close to the one by *Chen and Borges* [2009] (-0.92 molC m^{-2} yr^{-1}). The air-water CO_2 flux per surface area over continental shelf seas is the double of the value in the open ocean based on the most recent CO_2 climatology (-0.35 molC m^{-2} yr^{-1} [*Takahashi et al.* 2009]).

[15] The emission of CO_2 from estuaries given by the present study (0.27 ± 0.23 PgC yr^{-1}) is lower than previous estimates that range between $+0.36$ and $+0.60$ PgC yr^{-1} [*Abril and Borges*, 2004; *Borges*, 2005; *Borges et al.*, 2005; *Chen and Borges*, 2009]. This is due to the fact that previous global scaling attempts of the CO_2 emission from estuaries used the average of air-water CO_2 fluxes across estuarine types, and due to smaller (older) data-sets possibly biased towards tidal European (often polluted) systems. Hence, the average air-water CO_2 fluxes used for scaling ranged between $+32.1$ and $+38.2$ molC m^{-2} yr^{-1}, which is higher than the global average value of $+21.0 \pm 17.6$ molC m^{-2} yr^{-1} given in Table 1 that takes into account the relative surface area of different estuarine types. This is mainly due to the fact that a large fraction of the surface area of estuarine environments corresponds to fjords and fjärds that are characterized by lower air-water CO_2 flux rates than Types I and II. Further, the global surface area of estuarine environments based on the typology of *Dürr et al.* [2010] of ~1.1 10^6 km^2 is lower than the value of 1.4 10^6 km^2 given by *Woodwell et al.* [1973] used by *Abril and Borges* [2004]. The scaling of estuarine CO_2 emissions by *Borges* [2005], *Borges et al.* [2005] and *Chen and Borges* [2009] was based on a global estuarine surface area of 0.94 10^6 km^2, also derived from the values given by *Woodwell et al.* [1973] but excluding inter-tidal areas associated to marshes and mangroves.

[16] Our typology of continental shelf seas could be further improved by explicitly distinguishing between coastal upwelling systems with and without an OMZ. The estuarine typology could be improved by distinguishing between micro-tidal and macro-tidal systems, since the former are

usually highly stratified and are lower sources of CO_2 to the atmosphere than the latter that are usually permanently well-mixed [e.g., *Borges*, 2005; *Koné et al.*, 2009]. However, the degree of detail in a typology depends on the availability of appropriate data for each type. At present, the lack of sufficient data is the major limitation in the quantification of the spatial and temporal variability of CO_2 fluxes in coastal environments. In estuarine environments, there is a fair amount of data to characterize tidal systems (Type II) and small deltas (Type I). However, for fjords and fjärds (Type IV), that represent 43% of the total estuarine surface area, adequate air-water CO_2 flux data are only available from one location. For lagoons (Type III), most of the available data were obtained from 5 contiguous systems located in Ivory Coast (~5°N) although these estuarine ecosystems are ubiquitous at all latitudes (Figure 1).

[17] We did not attempt to explicitly scale CO_2 fluxes in river plumes (or outer estuaries). Data with adequate spatial and temporal coverage in these systems to robustly evaluate air-sea CO_2 fluxes are scarce. Some outer estuaries act as sources of CO_2 to the atmosphere such as the Scheldt (+1.9 molC m^{-2} yr^{-1} [*Borges and Frankignoulle*, 2002]), the Loire (+10.5 molC m^{-2} yr^{-1} [*de la Paz et al.*, 2010]), the Kennebec (+0.9 molC m^{-2} yr^{-1} [*Salisbury et al.*, 2009]), while others act as sinks for atmospheric CO_2 such as the Amazon (−0.5 molC m^{-2} yr^{-1} [*Körtzinger*, 2003]) and the Changjiang (−1.9 molC m^{-2} yr^{-1} [*Zhai and Dai*, 2009]). The direction of the annual net flux of CO_2 in outer estuaries is, to a large extent, related to the presence or the absence of haline stratification that promotes export of organic matter across the pycnocline and enhances light availability for primary production [*Borges*, 2005]. Haline stratification generally occurs in high freshwater discharge systems, hence, LDE systems (Amazon, Changjiang) act as sinks of CO_2, while smaller systems that are generally devoid of haline stratification (Scheldt, Loire, Kennebec) act as sources of CO_2 to the atmosphere. Hence, a typological approach taking into account physical and biogeochemical characteristics that drive a net annual sink or source of CO_2 is required to estimate the global surface of outer estuaries such as LDE and scale globally the CO_2 fluxes from these environments, in addition to more observations in different systems.

[18] The data availability in continental shelf seas is strongly biased towards the temperate regions of the Northern Hemisphere, while coastlines of the Russian Arctic, eastern South America, eastern Africa, large sections of western Africa, and most of Antarctica are dramatically under-sampled. Finally, pCO_2 temporal variability ranges from daily [*Dai et al.*, 2009] to inter-annual [*Friederich et al.*, 2002; *Borges et al.*, 2008a, 2008b] scales. The (in) adequate representation of the full range of temporal variability can impact the evaluation of the overall net annual air-sea CO_2 fluxes. For a more robust evaluation of CO_2 fluxes in continental shelf seas, an intensive, integrated, international and interdisciplinary program of observational efforts is required.

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Auxiliary Table A1: Compilation of published air-water CO_2 fluxes per surface area (molC m^{-2} yr^{-1}) evaluated from measurements of pCO_2 (excluding fluxes evaluated from models and carbon mass balances) for each estuarine type. A positive value represents a source of CO_2 to the atmosphere.

	°E	°N	Air-water CO_2 flux (mol C m^{-2} yr^{-1})	References
Small deltas and estuaries(Type I)				
Duplin River (US)	-81.3	31.5	21.4	Wang and Cai [2004]
Gaderu creek (IN)	82.3	16.8	20.4	Borges et al. [2003]
Itacuraça creek (BR)	-44.0	-23.0	41.4	Borges et al. [2003]
Khura River estuary (TH)	98.3	9.2	35.7	Miyajima et al. [2009]; T. Miyajima [pers. comm.]
Kidogoweni creek (KE)	39.5	-4.4	23.7	Bouillon et al [2007a]
Kiên Vàng creeks (wet season) (VN)	105.1	8.7	56.5	Koné and Borges [2008]
Kiên Vàng creeks (dry season) (VN)	105.1	8.7	11.8	Koné and Borges [2008]
Matolo/Ndogwe/Kalota/Mto Tana creeks (KE)	40.1	-2.1	25.8	Bouillon et al [2007b]
Mooringanga creek (IN)	89.0	22.0	8.5	Borges et al. [2003]
Mtoni (TZ)	39.3	-6.9	7.3	Kristensen et al. [2008]
Nagada creek (IN)	145.8	-5.2	15.9	Borges et al. [2003]
Norman's Pond (BS)	-76.1	23.8	5.0	Borges et al. [2003]
Ras Dege creek (TZ)	39.5	-6.9	12.4	Bouillon et al [2007c]
Rio San Pedro (ES)	-5.7	36.6	39.4	Ferrón et al. [2007]
Saptamukhi creek (IN)	89.0	22.0	20.7	Borges et al. [2003]
Shark River (US)	-81.1	25.2	18.4	Koné and Borges [2008]
Tam Giang creeks (dry season) (VN)	105.2	8.8	51.6	Koné and Borges [2008]
Tam Giang creeks (wet season) (VN)	105.2	8.8	46.9	Koné and Borges [2008]
Trang River estuary (TH)	99.4	7.2	30.9	Miyajima et al. [2009]; T. Miyajima [pers. Comm.]
Tidal systems and embayments (Type II)				
Altamaha Sound (US)	-81.3	31.3	32.4	Jiang et al. [2008]
Bellamy (US)	-70.9	43.2	3.6	Hunt et al. [2010]
Betsiboka (MG)	46.3	-15.7	3.3	Ralison et al. [2008]
Bothnian Bay (FI)	21.0	63.0	3.1	Algesten et al. [2004]
Changjiang (Yantze) (CN)	120.5	31.5	24.9	Zhai et al. [2007]
Chilka (IN)	85.5	19.1	25	Gupta et al. [2008]
Cocheco (US)	-70.9	43.2	3.1	Hunt et al. [2010]
Cochin (IN)	76	9.5	55.1	Gupta et al. [2009]
Doboy Sound (US)	-81.3	31.4	13.9	Jiang et al. [2008]
Douro (PT)	-8.7	41.1	76.0	Frankignoulle et al. [1998]
Elbe (DE)	8.8	53.9	53.0	Frankignoulle et al. [1998]

Ems (DE)	6.9	53.4	67.3	Frankignoulle et al. [1998]
Gironde (FR)	-1.1	45.6	30.8	Frankignoulle et al. [1998]
Godavari (IN)	82.3	16.7	5.5	Bouillon et al [2003]
Great Bay (US)	-70.9	43.1	3.6	Hunt et al. [2010]
Guadalquivir (ES)	-6.0	37.4	31.1	de La Paz et al. [2007]
Hooghly (IN)	88.0	22.0	5.1	Mukhopadhyay et al. [2002]
Liminganlahti Bay (FI)	25.4	64.9	7.5	Silvennoinen et al. [2008]
Little Bay (US)	-70.9	43.1	2.4	Hunt et al. [2010]
Loire (FR)	-2.2	47.2	64.4	Abril et al. [2003]
Mandovi-Zuari (IN)	73.5	15.3	14.2	Sarma et al. [2001]
Mekong (VN)	106.5	10.0	30.8	Borges [unpublished]
Oyster (US)	-70.9	43.1	4.0	Hunt et al. [2010]
Parker River estuary (US)	-70.8	42.8	1.1	Raymond and Hopkinson [2003]
Piauí River estuary (BR)	-37.5	-11.5	13.0	Souza et al. [2009]
Rhine (NL)	4.1	52.0	39.7	Frankignoulle et al. [1998]
Sado (PT)	-8.9	38.5	31.3	Frankignoulle et al. [1998]
Saja-Besaya (ES)	-2.7	43.4	52.2	Ortega et al. [2004]
Sapelo Sound (US)	-81.3	31.6	13.5	Jiang et al. [2008]
Satilla River (US)	-81.5	31.0	42.5	Cai and Wang [1998]
Scheldt (BE/NL)	3.5	51.4	63.0	Frankignoulle et al. [1998]
Tana (KE)	40.1	-2.1	47.9	Bouillon et al [2007b]
Tamar (UK)	-4.2	50.4	74.8	Frankignoulle et al. [1998]
Thames (UK)	0.9	51.5	73.6	Frankignoulle et al. [1998]
York River (US)	-76.4	37.2	6.2	Raymond et al. [2000]
Zhujiang (Pearl River) (CN)	113.5	22.5	6.9	Guo et al. [2009]
Lagoons (Type III)				
Aby lagoon (CI)	-3.3	4.4	-3.9	Koné et al. [2009]
Aveiro lagoon (PT)	-8.7	40.7	12.4	Borges and Frankignoulle [unpublished]
Ebrié lagoon (CI)	-4.3	4.5	31.1	Koné et al. [2009]
Potou lagoon (CI)	-3.8	4.6	40.9	Koné et al. [2009]
Tagba lagoon (CI)	-5.0	4.4	18.4	Koné et al. [2009]
Tendo laggon (CI)	-3.2	4.3	5.1	Koné et al. [2009]
Fjords and fjärds (Type IV)				
Randers Fjord (DK)	10.3	56.6	17.5	Gazeau et al. [2005]

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Auxiliary Table A2: Compilation of published air-water CO_2 fluxes per surface area (molC m^{-2} yr^{-1}) evaluated from measurements of pCO_2 (excluding fluxes evaluated from models and carbon mass balances) for continental shelves. A positive value represents a source of CO_2 to the atmosphere.

	°E	°N	Air-water CO_2 flux (mol C m^{-2} yr^{-1})	References
Enclosed shelves				
Baltic Sea	20.0	57.0	-0.8	Thomas and Schneider [1999]
Adriatic Sea (Gulf of Trieste)	13.6	45.5	-2.2	Turk et al. [2010]
Mediterranean Sea (Bay of Angels)	7.4	43.6	-0.6	Borges et al. [2006] based on Copin-Montégut et al. [2004]
Black Sea	32.7	42.6	-1.3	computed from data in June 2001 [Friederich, G.E., Knorr 2001 Black Sea expedition, http://www.ocean.washington.edu/cruises/Knorr2001/] and in April 2008 and October 2008 [Borges A.V., unpublished]
Hudson Bay	-85.0	59.0	0.8	Else et al. [2008]
Upwelling systems				
Atlantic Ocean				
Galician coast	-9.2	42.5	-2.2	Borges and Frankignoulle [2002]
Gulf of Cadiz	-7.0	37.0	-0.4	Huertas et al. [2006]
Benguela current (South Africa coast)	20.0	-33.0	-2.2	González-Dávila et al. [2009]
Pacific Ocean				
Southern Bering Sea slope	-192.5	54.0	3.9	Fransson et al. [2006]
Californian Coast	-122.0	36.8	0.5	Friederich et al. [2002]
Peru Coast	-80.0	-10.0	5.1	Friederich et al. [2008]
Indian Ocean				
Oman coast	59.0	20.0	0.9	Goyet et al. [1998]
Open continental shelves				
Barents Sea	30.0	75.0	-4.3	Omar et al. [2007]
Chukchi Sea	-165.0	72.5	-5.1	Bates [2006]
Bristol Bay	-164.0	58.0	-0.2	Borges et al. [2005] based on Kelly & Hood [1971], Codispoti et al. [1986], Chen [1993], Murata & Takiwaza [2002]
Northern and Central North Sea	2.6	56.7	-1.7	Thomas et al. [2004]
Southern North Sea	2.5	52.0	-0.7	Schiettecatte et al. [2007]
English Channel	-1.2	50.2	0.0	Borges & Frankignoulle [2003]
Northern Bay of Biscay	-7.9	49.0	-0.8	Borges et al. [2006]
Southern Bay of Biscay	-3.5	46.5	-2.3	de la Paz et al. [2010]
Central Bay of Biscay	-6.0	45.0	-1.9	Padin et al. [2009]
Scotian shelf	-63.0	44.0	1.5	Shadwick et al. [2010]
Otaru Bay	141.0	43.3	-0.8	Sakamato et al. [2008]

Gulf of Maine	-70.5	43.0	0.0	Salisbury et al. [2009]
US Middle Atlantic Bight	-74.5	38.5	-1.2	DeGranpre et al. [2002]
Northern East China Sea	126.0	33.0	-0.9	Shim et al. [2007]
Southern East China Sea	125.0	32.0	-2.1	Wang et al. [2000]
US South Atlantic Bight	-80.6	31.0	-0.5	Jiang et al. [2008]
Northern South China Sea	124.0	31.0	-1.9	Zhai & Dai [2009]
Caribbean Sea	-75.0	22.5	-0.5	Wanninkhof et al. [2007]
Southern South China Sea	116.0	22.0	0.9	Zhai et al. [2005, 2007]
Kaneohe Bay	-157.8	21.4	1.5	Fagan & Mackenzie [2007]
Southern Brazilian coast	-45.5	-25.0	1.8	Ito et al. [2005]
Tasmanian coast	147.5	-43.7	-2.3	Borges et al. [2008]
Patagonian shelf	-65.0	-45.0	-1.4	Bianchi et al. [2009]
Pryzd Bay	78.9	-68.6	-2.2	Gibson & Trull [1999]
Ross Sea	180.0	-75.0	-1.5	Sweeney [2003]

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Auxiliary Figure A1 : Latitudinal variations of the air-water CO_2 fluxes per surface area ($molC\ m^{-2}\ yr^{-1}$) over open continental shelves (Types 3a;b;c)