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Air–sea exchanges of CO_2 in the world's coastal seas

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Abstract. The air–sea exchanges of CO_2 in the world's 165 estuaries and 87 continental shelves are evaluated. Generally and in all seasons, upper estuaries with salinities of less than two are strong sources of CO_2 (39 ± 56 mol C m^{-2} yr^{-1}, positive flux indicates that the water is losing CO_2 to the atmosphere); mid-estuaries with salinities of between 2 and 25 are moderate sources (17.5 ± 34 mol C m^{-2} yr^{-1}) and lower estuaries with salinities of more than 25 are weak sources (8.4 ± 14 mol C m^{-2} yr^{-1}). With respect to latitude, estuaries between 23.5 and 50° N have the largest flux per unit area (63 ± 101 mmol C m^{-2} d^{-1}); these are followed by lower-latitude estuaries (23.5–0° S: 44 ± 29 mmol C m^{-2} d^{-1}; 0–23.5° N: 39 ± 55 mmol C m^{-2} d^{-1}), and then regions north of 50° N (36 ± 91 mmol C m^{-2} d^{-1}). Estuaries south of 50° S have the smallest flux per unit area (9.5 ± 12 mmol C m^{-2} d^{-1}). Mixing with low-pCO$_2$ shelf waters, water temperature, residence time and the complexity of the biogeochemistry are major factors that govern the pCO$_2$ in estuaries, but wind speed, seldom discussed, is critical to controlling the air–water exchanges of CO_2. The total annual release of CO_2 from the world's estuaries is now estimated to be 0.10 Pg C yr^{-1}, which is much lower than published values mainly because of the contribution of a considerable amount of heretofore unpublished or new data from Asia and the Arctic. The Asian data, although indicating high pCO$_2$, are low in sea-to-air fluxes because of low wind speeds. Previously determined flux values rely heavily on data from Europe and North America, where pCO$_2$ is lower but wind speeds are much higher, such that the CO_2 fluxes are higher than in Asia. Newly emerged CO_2 flux data in the Arctic reveal that estuaries there mostly absorb rather than release CO_2.

Most continental shelves, and especially those at high latitude, are undersaturated in terms of CO_2 and absorb CO_2 from the atmosphere in all seasons. Shelves between 0 and 23.5° S are on average a weak source and have a small flux per unit area of CO_2 to the atmosphere. Water temperature, the spreading of river plumes, upwelling, and biological production seem to be the main factors in determining pCO$_2$ in the shelves. Wind speed, again, is critical because at high latitudes, the winds tend to be strong. Since the surface water pCO$_2$ values are low, the air-to-sea fluxes are high in regions above 50° N and below 50° S. At low latitudes, the winds tend to be weak, so the sea-to-air CO_2 flux is small. Overall, the world's continental shelves absorb 0.4 Pg C yr^{-1} from the atmosphere.

1 Introduction

Carbon is arguably one of the most important elements on earth, and understanding the global carbon cycle is fundamental to elucidating the effect of human activities in the Anthropocene era. The oceans are known to have an important role in regulating the climate on annual to millennial scales by absorbing CO_2 and exchanging carbon with various carbon-storing compartments, such as the atmosphere, the land, the biota and the fossil fuel carbon pool. Yet, despite the success of quantifying the air–sea CO_2 exchange and the uptake of anthropogenic CO_2 by the major oceans, the effect of the land on these processes is still poorly understood and little discussed (Khatiwala et al., 2013; Le Quéré et al., 2013; Schuster et al., 2013; Wanninkhof et al., 2013).

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Coastal waters link the land, the oceans, the atmosphere, biota and sediments. Although they constitute only a little over 7 % of the surface area of oceans and less than 0.5 % of the volume of the oceans, coastal oceans have a disproportionately large role in primary and new production, remineralization and sedimentation of organic matter (Walsh et al., 1981; Walsh, 1988, 1991; Kempe and Pegler, 1991; Mackenzie et al., 1991, 1998a, b; Chen, 1993; Wollast, 1993, 1998; Gattuso et al., 1998; Carrillo and Karl, 1999; Liu et al., 2000; de Haas et al., 2002; Elliott and McLusky, 2002; Muller-Karger et al., 2005; Thomas, 2010). Coastal waters receive large inputs of terrestrial material, such as suspended sediments and nutrients in solution or in particulate matter, in organic or inorganic forms and through river and groundwater discharge, as well as by exchange with the atmosphere, the sediments and the open ocean. They therefore tend to show greater temporal and spatial variability than open oceans, and are more affected by human activities (Cameron and Pritchard, 1963; Alongi, 1998; Chen and Tsunogai, 1998; Rabouille et al., 2001; Chen, 2002, 2003, 2004; Slomp and Van Cappellen, 2004; Beusen et al., 2005; Chavez et al., 2007; Doney et al., 2007; Radach and Patsch, 2007; Peng et al., 2008; Seitzinger et al., 2010; Dürr et al., 2011; Jiang et al., 2013). However, unlike the open oceans, in which millions of observations have been made and the air–sea exchanges of CO_2 have been valued using various developed models (such as by Khatiwala et al., 2013; Schuster et al., 2013; Wanninkhof et al., 2013), coastal waters have been relatively poorly examined.

Although estuaries are known to be generally sources of CO_2 (Frankignoulle et al., 1998; Cai et al., 1999, 2000; Sarma et al., 2001, 2011; Abril et al., 2002; Borges et al., 2003; Dagg et al., 2005; Gao et al., 2005; Dai et al., 2008; Leinweber et al., 2009), only in the last few years have continental shelves been firmly established to absorb CO_2 from the atmosphere. (See, for example, Liu et al., 2000; Chen et al., 2003; Chen, 2004; Abril and Borges, 2005; Borges, 2005; Borges et al., 2005; Cai et al., 2006; Chen and Borges, 2009; Laruelle et al., 2010, and references therein.) Indeed, whether coastal seas are sources or sinks of CO_2 has remained an open question until only recently. The first report of the project on the Land Ocean Interaction in the Coastal Zone (LOICZ) under the International Geosphere Biosphere Programme (IGBP) is entitled, "Coastal seas: a net source or sink of atmosphere carbon dioxide" (Kempe, 1995). The first report of LOICZ did not provide any data concerning the air–sea exchanges of carbon in the continental margins, although it concluded that net carbon oxidation in the coastal zone is around 7×10^{12} mol yr^{-1} (Crossland et al., 2005), implying that the coastal zone is a source of CO_2 to the atmosphere.

Unfortunately, Fasham et al. (2001), summarizing the work of the Joint Global Ocean Flux Study (JGOFS, another IGBP project), concluded that there is a net sea-to-air CO_2 flux from continental margins of 0.5 Pg C yr^{-1}. They drew this conclusion despite the fact that, at the time, the joint JGOFS/LOICZ Continental Margins Task Team (Chen et al., 1994) had already gathered sufficient data to demonstrate that the margins, rather than being a source of CO_2, are in fact a sink of CO_2. Indeed, in the same year, Fasham published another paper that claimed that the continental shelves are actually a sink of CO_2 of the order of 0.6 Pg C yr^{-1} (Yool and Fasham, 2001). In 2003, the JGOFS also concluded that the shelves take up 0.3 Pg C yr^{-1} of atmospheric CO_2 (Chen et al., 2003). This view, however, was not universally accepted (Cai et al., 2003; Cai and Dai, 2004) until more data, especially data obtained in the winter, became available. Many shelves that had been thought to be sources of CO_2 are now known to be sinks of CO_2 when winter data reveal severe undersaturation of CO_2 (Thomas et al., 2004; Cai et al., 2006; Schiettecatte et al., 2007; Jiang et al., 2008b).

Strangely, despite the fact that coastal waters play a major role in the livelihood of humans, and are strongly affected by human activities, our understanding of these waters is mostly semi-quantitative. For example, such basic information as the area of the continental shelf is uncertain. The most recent work of Kang et al. (2013) yielded an area of 26.15×10^6 km^2 for waters shallower than 200 m. This value compares with 26.39×10^6 km^2 obtained by Laruelle et al. (2013), 24.72×10^6 km^2 presented by Laruelle et al. (2010), 30.16×10^6 km^2 obtained by Jahnke (2010), 26×10^6 km^2 presented by Chen and Borges (2009), 25.83×10^6 km^2 presented by Cai et al. (2006) and 36×10^6 km^2 presented by Liu et al. (2000), which may seem to be an outlier. Merely comparing the total flux across various studies may not be very useful, whereas comparing flux per unit area eliminates the problem of an uncertain global shelf area, which varies by as much as 50 % among studies. Even more strangely, despite the fact that rivers export approximately 1 Pg C yr^{-1} (Meybeck, 1982), or roughly half of the carbon that is absorbed by the open oceans each year, this value needs to be confirmed as it was based only on a few studies, and the well-regarded study of Meybeck was based on a database of only 27 rivers.

The export of carbon by rivers comprises 40 % organic carbon (0.22 Pg C yr^{-1} of dissolved organic carbon (DOC) and 0.18 Pg C yr^{-1} of particulate organic carbon (POC)) and 60 % inorganic carbon (0.43 Pg C yr^{-1} of dissolved inorganic carbon (DIC) and 0.17 Pg C yr^{-1} of particulate inorganic carbon (PIC)) (Meybeck, 1982; Richey, 2004; IPCC, 2007; Schlunz and Schneider, 2000; Dai et al., 2012; Huang et al., 2012). However, estuarine filtering prevents some of the carbon that reaches the estuaries from also entering the oceans (Keil et al., 1997; Kemp et al., 1997; Middelburg and Herman, 2007; Chen et al., 2012; Dai et al., 2012). Further, the exact extent of speciation changes between the organic and inorganic or dissolved and particulate carbon in the estuaries, and how much of each of these forms of carbon actually enters the oceans are still unknown (Woodwell et al., 1973; Raymond and Bauer, 2000; Wiegner and Seitzinger, 2001; Cai, 2011; Maher and Eyre, 2011).

The above may be summarized by noting that nutrients from land, which may be transported by rivers or submarine groundwater discharge, or may be atmospheric fallout, markedly affect estuaries and continental shelves (Ittekkot et al., 1991; Cole and Caraco, 2001; Neubauer and Anderson, 2003; Clark et al., 2004; Thomas et al., 2004; Gazeau et al., 2005; Hales et al., 2008; Jiang et al., 2013; Lauerwald et al., 2012). Consequently, estuaries and proximal continental shelves typically sustain high biological productivity (Walsh et al., 1981; Wollast, 1993, 1998; Cai, 2003), which may draw down CO_2. This phenomenon, however, may be more than counteracted by enhanced heterotrophic activity, supported by organic carbon input from rivers (Smith and Hollibaugh, 1993; Heip et al., 1995; Hedges and Keil, 1995; Hedges et al., 1997; Hansell and Carlson, 1998; Bouillon et al., 2006; Jiang et al., 2010). Additionally, direct inorganic carbon input from river water, submarine groundwater discharge and exchanges with tidal marshes and mangroves play an important role in increasing the $p\mathrm{CO}_2$ of estuarine and shelf waters (Moran et al., 1991; Miller and Moran, 1997; Neal et al., 1998; Raymond et al., 2000; Raymond and Bauer, 2001; Borges et al., 2003, 2006; Cai et al., 2003; Wang and Cai, 2004; Jahnke et al., 2005; Bouillon et al., 2008; Jiang et al., 2008a, 2010; Chen et al., 2012).

Since the above complex and conflicting factors influence the $p\mathrm{CO}_2$ of estuarine and shelf waters, the air–sea exchanges of CO_2 in these waters globally cannot yet be estimated by models although regional models have been attempted (Hofmann et al., 2011; Maher and Eyre, 2012; Wakelin et al., 2012). As a result, field data are still required. Determinations of the air–sea flux of CO_2 in the world's estuaries and continental shelves, based on direct measurements, are presented below. Data from the literature and some unpublished data from C. T. A. Chen are tabulated. Data for upper, mid- and lower estuaries are compared. Seasonal and latitudinal variations are discussed, and the global flux is presented. Data concerning continental shelves are also considered with reference to season and latitude before the global flux is determined.

2 Sea-to-air CO_2 fluxes in estuaries

Rivers are the main sources of carbon to the estuaries. Riverine organic carbon is supplied primarily by the erosion of soil organic matter or plant detritus (allochthonous) and by phytoplankton in water (autochthonous). The inorganic carbon is derived mainly from soil and rock erosion, and by the oxidation of organic matter mostly through microbial processes (Odum and Hoskin, 1958; Odum and Wilson, 1962; Probst et al., 1994; Neal et al., 1998; Nelson et al., 1999; Pomeroy et al., 2000). These organic and inorganic forms of carbon in dissolved and particulate phases reach the estuaries, which are typically wider than river channels. Therefore, particles tend to settle down and decompose, releasing carbon back into the water. Salt marshes, mangroves, and submarine groundwater discharge also export carbon to estuaries, increasing their $p\mathrm{CO}_2$.

Rivers are the main sources of nutrients to estuaries. However, high turbidity and limited light cause nutrients rarely to be fully utilized for biological production in rivers or estuaries. Hence, the biological drawdown of CO_2 does not suffice to reduce the estuarine water $p\mathrm{CO}_2$ to below saturation. Consequently, almost all estuaries are sources of CO_2 to the atmosphere. The influence of freshwater from large rivers frequently extends hundreds of kilometers offshore. The enormous discharge of freshwater, sediments and the associated particulate and dissolved organic and inorganic carbon, nitrogen and phosphorus all greatly affect the biological and geochemical processes in the estuary, the plume and the adjacent continental shelf (Chen and Wang, 1999; Gong et al., 2000; Chen et al., 2003). Generally, net ecosystem production in estuaries tends to be net heterotrophic: respiration is larger than production (Battin et al., 2008). Various complex biogeochemical processes in estuaries are affected by the topography and river flow. As small deltas and large rivers' estuaries have short residence time (Dürr et al., 2011), physical mixing is the major factor affecting carbonate parameters. On the other hand, with longer residence time the transformation between inorganic and organic material becomes more active. This is because now suspended particles have more time to settle and aquatic organisms have more time to grow, and leach dissolved organic carbon, when light becomes more available in the nutrient-abundant estuaries. On the other hand, dissolved organic carbon decomposes more when the residence time is longer compared with physical force-dominant estuaries. A saline interface normally separates the plume water from the shelf water, with the width of the interface determined by interactions between river discharge and marine-driving forces (Shen, 2001; Shen et al., 2003; Chen et al., 2008a). Complex biophysical and geochemical processes govern the direction of CO_2 exchange between the plume-affected shelf area and the atmosphere (Kortzinger, 2003; Cooley et al., 2007), but in this investigation, river plumes outside of the estuaries are not considered. Tidal forcing on estuarine mixing affects submarine groundwater discharge, sediment burial and disturbance, the $p\mathrm{CO}_2$ in the surface water as well as the air-to-sea CO_2 exchange. These, however, have not been evaluated in a quantitative way.

Numerical data are gathered for 165 estuaries (Fig. 1, Table 1), of which 99 are from literature. Unpublished data from 50 estuaries and 16 from data banks are also included, and the Wanninkhof (1992) quadratic equation is used to determine the flux. The methods used to calculate the flux, as well as sources of the gas exchange coefficient and wind speed, are listed in Table 2. Of note is that using different $p\mathrm{CO}_2$ flux methods and gas transfer velocities causes disparity in flux estimations (Borges et al., 2004; Ferron et al., 2007; Jiang et al., 2008a; Zappa et al., 2007). However, there is still no consensus on the most suitable coefficient to use in

Table 1. Seasonal and annual sea-to-air fluxes of CO_2 in the world's estuaries.

Type	Long. (°)	Lat. (°)	Spring flux[c] (mmol C m^{-2} d^{-1})	Summer flux (mmol C m^{-2} d^{-1})	Autumn flux (mmol C m^{-2} d^{-1})	Winter flux (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References[f]
1-1 (fjord) (US)[b]	−152.5	57.7	−1.8		1.8		0.001	Takahashi et al. (2012) (LDEO database)
11-1 (fjord) (CA)	−55.8	52.3		−2.1			−0.8	Takahashi et al. (2012) (LDEO database)
14-1 (fjord) (IC)	−23.2	66.2	−0.7	−7.0	−12.9	−4.8	−2.3	Takahashi et al. (2012) (LDEO database)
14-2 (fjord) (IC)	−23.6	66.1		−7.7			−2.8	Takahashi et al. (2012) (LDEO database)
14-3 (fjord) (IC)	−23.7	65.7			5.4		2.0	Takahashi et al. (2012) (LDEO database)
14-4 (fjord) (IC)	−24.1	65.6	−0.3				−0.1	Takahashi et al. (2012) (LDEO database)
14-5 (fjord) (IC)	−18.6	66.0	−48.2	−7.8	−11.2	−9.0	−7.0	Takahashi et al. (2012) (LDEO database)
Aby lagoon (CI)	−3.3	5.4	−10.1	1.2	−11.3	−4.1	−2.7	Kone et al. (2009)
Altamaha Sound (US)	−81.3	31.3	57.8	127.0	79.7	28.5	26.8	Jiang et al. (2008a)
Ambalayaar (IN)	79.3	10.0		−0.02			−0.007	Sarma et al. (2012)
Amur River (RU)	141.1	52.9		0.1	1.5		0.3	Johnson et al. (2009) (WOD09 database)
Ason (ES)	−3.5	43.3		−3.0			−1.1	Ortega et al. (2005)
Aveiro lagoon (PT)	−8.7	40.7					12.4	Borges and Frankignoulle (unpublished)
Baitarani (IN)	86.9	20.5		20.7			7.6	Sarma et al. (2012)
Bancal (PH)	115.0	5.0	2.2				0.8	Chen (unpublished)
Bebar River (MY)	103.4	3.1			17.7		6.5	Chen (unpublished)
Bellamy (US)	−70.9	43.1	−11.0	43.0	6.0		4.6	Hunt et al. (2011)
Betsiboka (MG)	46.3	−15.7					3.3	Ralison et al. (2008)
Bharatakulza (IN)	76.0	11.2		11.7			4.3	Sarma et al. (2012)
Bothnian Bay (FI)	21.0	63.0					3.5	Algesten et al. (2004)
Brazos River (US)	−95.4	28.9					0.033	Zeng et al. (2011)
Brunei River (BN)	96.4	16.5		53.7			19.6	Chen (unpublished)
Cauvery (IN)	79.89	11.26		2.23			0.8	Sarma et al. (2012)
Chalakudi (IN)	76.18	10.69		12.86			4.70	Sarma et al. (2012)
Changjiang (Yangtze) (CN)	120.5	31.5	23.5	65.5	33.7	37.8	14.6	Zhai et al. (2007)
Chishui River (TW)	120.11	23.29		176		68.5	44.6	Chen (unpublished)
Chilka (lagoon) (IN)	85.5	19.1	9.8	141.0			27.5	Gupta et al. (2008)
Cho Shui River (TW)	120.3	23.9	651.0	13.4			121.0	Chen (unpublished)
Chung Kang River (TW)	120.8	24.7	45.8	53.4	28.8	144.0	24.8	Chen (unpublished)
Churchill River (CA)	−94.2	58.8		1.2	−3.6		−0.4	Stainton (2009)
Citanduy River (ID)	108.8	−7.7	25.7[d]				9.4	Chen (unpublished)
Ciujung-Kragilan (ID)	106.4	−6.0	36.9[d]				13.5	Chen (unpublished)
Cocheco (US)	−70.8	43.1	2.0	26.0	2.0		3.7	Hunt et al. (2011)
Cochin (IN)	76.0	9.5			267.0	65.0	60.6	Gupta et al. (2008)
Cross Sound (fjord) (US)	−134.1	56.6		−0.2	45.1		8.2	Takahashi et al. (2012) (LDEO database)
Doboy Sound (US)	−81.3	31.4	15.2	47.4	51.0	16.0	11.9	Jiang et al. (2008a)
Douro (PT)	−8.7	41.1			240.0		87.6	Frankignoulle et al. (1998)
Duplin River (US)	−81.3	31.5	53.4	83.0	73.2	23.4	21.3	Wang and Cai (2004)
Ebrié lagoon (CI)	−4.3	5.5	56.4	109.0	61.9	47.9	26.6	Kone et al. (2009)
Elbe (DE)	8.8	53.9	180.0				65.7	Frankignoulle et al. (1998)
Ems (DE)	6.9	53.4		110.0			40.2	Frankignoulle et al. (1998)
Endau River (MY)	103.6	2.7			1.0		0.4	Chen (unpublished)
Erh Jen River (TW)	120.2	22.9	68.5	11.1		26.5	12.9	Chen (unpublished)
Florida Bay (US)	−80.8	25.0					1.7	Millero et al. (2001)
Fong Kang River (TW)	120.7	22.2	6.7	−17.9		18.0	0.8	Chen (unpublished)
Gaderu creek (IN)	82.3	16.8		56.0			20.4	Borges et al. (2003)
Gironde (FR)	−1.1	45.6	110.0	110.0	65.0	50.0	30.6	Frankignoulle et al. (1998)
Godavari (IN)	82.3	16.7					8.0	Bouillon et al. (2003), Sarma et al. (2012)
Godthåbsfjord (GL)[e]	−51.9	64.1					−7.25	Rysgaard et al. (2012)
Golfo Almirante Montt (fjord) (CL)	−72.0	−52.1			−17.7[d]		−6.5	Takahashi et al. (2012) (LDEO database)

Table 1. Continued.

Type	Long. (°)	Lat. (°)	Spring flux^{c} (mmol C m^{-2} d^{-1})	Summer flux (mmol C m^{-2} d^{-1})	Autumn flux (mmol C m^{-2} d^{-1})	Winter flux (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References^{f}
Great Bay (US)	−70.9	43.1					3.6	Hunt et al. (2011)
Guadalquivir (ES)	−6.0	37.4		104.0			37.9	de la Paz et al. (2007)
Haldia (IN)	88.2	21.9		12.3			4.5	Sarma et al. (2012)
Hanjiang (CN)	116.8	23.4				0.9	0.3	Chen (unpublished)
Ho Ping River (TW)	121.8	24.3	5.3	22.0		68.5	11.7	Chen (unpublished)
Hooghly (IN)	88.0	22.0	31.8	−1.1	16.7	2.5	4.9	Mukhopadhyay et al. (2002)
Hou Lung River (TW)	120.8	24.6	72.9	9.3	7.6	21.0	10.1	Chen (unpublished)
Hsiu Ku Luan River (TW)	121.5	23.5	26.5	41.9		19.2	10.7	Chen (unpublished)
Hua Lien River (TW)	121.6	23.9	93.4	75.3		4.8	21.1	Chen (unpublished)
Hudson River estuary (US)	−74.0	40.7					5.9	Raymond et al. (1997)
Isla Gordon (fjord) (CL)	−68.9	−55.2			−1.2^{d}		−0.4	Takahashi et al. (2012) (LDEO database)
Itacuruca creek, Sepetiba (bay) (BR)	−44.0	−23.0					41.4	Ovalle et al. (1990), Borges et al. (2003)
Jiulong Jiang (Xiamen Bay) (CN)	118.1	24.5					0.5	Dai et al. (2009)
Jiulongjiang (CN)	118.0	24.5				4.3	1.6	Chen (unpublished)
Johor River (MY)	104.0	1.5			2.3		0.8	Chen (unpublished)
Kakinada Bay (IN)	82.3	16.7					3.0	Bouillon et al. (2003)
Kali (IN)	74.2	14.8		3.2			1.2	Sarma et al. (2012)
Kaneohe Bay and stream (US)	−157.8	21.5					1.5	Fagan and Mackenzie (2007)
Kao Ping River (TW)	120.4	22.5	98.1	51.8	30.5	12.4	17.6	Chen (unpublished)
Kapuas River (ID)	109.1	0.1				148.3	54.1	Chen (unpublished)
Kennebec River (US)	−69.8	43.8	22.5	22.0	−0.2	−49.6	−0.5	Takahashi et al. (2012) (LDEO database)
Khura River estuary (TH)	98.3	9.2					35.7	Miyajima et al. (2009)
Kidogoweni creek (Gazi Bay) (KE)	39.5	−4.4				154.4^{d}	21.8	Bouillon et al. (2007b)
Kien Vang creeks(VN)	105.1	8.7	32.2		154.7		34.2	Kone and Borges (2008)
Klang River (MY)	101.4	3.0			7.7		2.8	Chen (unpublished)
Kobbe fjord (GL)	−51.5	64.2	−2.7		−136.6	−2.6	−17.3	Ruiz−Halpern et al. (2010)
Kochi backwaters (IN)	76.4	10.0		8.1			2.9	Sarma et al. (2012)
Kola Bay (RU)	33.4	69.1	−2.5	−0.2	−3.5	−3.9	−0.9	Johnson et al. (2009) (WOD09 database)
Krishna (IN)	81.1	15.8		6.8			2.5	Sarma et al. (2012)
Lan Yang River (TW)	121.8	24.7	65.5	66.0		23.2	18.8	Chen (unpublished)
Liminganlahti Bay (FI)	25.4	64.9		−0.9			−0.9	Silvennoinen et al. (2008)
Lin Pien River (TW)	120.5	22.4	44.4	54.5		49.0	18.0	Chen (unpublished)
Little Bay (US)	−70.9	43.1	−5.1	33.9	3.9		4.0	Hunt et al. (2011)
Loire (FR)	−2.2	47.2			155.0		64.4	Abril et al. (2003)
Luohe (CN)	115.6	22.9				0.1	0.022	Chen (unpublished)
Mahanadi (IN)	86.6	20.0		3.1			1.1	Sarma et al. (2012)
Mahisagar (IN)	72.6	22.1		10.2			3.7	Sarma et al. (2012)
Mandovi (IN)	73.8	15.7		18.1			6.6	Sarma et al. (2012)
Mandovi-Zuari (IN)	73.5	15.3					14.2	Sarma et al. (2001)
Matolo creek (KE)	40.1	−2.1					21.2	Bouillon et al. (2007a)
Mekong (VN)	106.5	10.0					30.8	Borges (unpublished)
Mempawah River (ID)	89.0	22.0		23.2			8.5	Chen (unpublished)
Mtoni (TZ)	39.3	−6.9					2.4	Kristensen et al. (2008)
Nagada creek (Papua New Guinea) (ID)	145.8	−5.2				43.6^{d}	15.9	Borges et al. (2003)
Nagavali (IN)	84.0	18.2		0.2			0.1	Sarma et al. (2012)
Nalonghe (CN)	112.0	21.8				10.1	3.7	Chen (unpublished)
Narmada (IN)	73.0	20.2		8.8			3.2	Sarma et al. (2012)
Netravathi (IN)	75.0	12.7		70.7			25.8	Sarma et al. (2012)
Norman's Pond (BS)	−76.1	23.8				13.8	5.0	Borges et al. (2003)
Orinoco River (VE)	−62.3	8.6	31.8				11.6	Takahashi et al. (2012) (LDEO database)
Oyster (US)	−70.9	43.1	−17.2	51.5	2.5		4.5	Hunt et al. (2011)
Pa Chang River (TW)	120.1	23.3	29.9	94.2		34.8	19.3	Chen (unpublished)
Pahang River (MY)	103.5	3.5			3.5		1.3	Chen (unpublished)

Table 1. Continued.

Type	Long. (°)	Lat. (°)	Spring flux[c] (mmol C $\mathrm{m^{-2}\,d^{-1}}$)	Summer flux (mmol C $\mathrm{m^{-2}\,d^{-1}}$)	Autumn flux (mmol C $\mathrm{m^{-2}\,d^{-1}}$)	Winter flux (mmol C $\mathrm{m^{-2}\,d^{-1}}$)	Annual flux (mol C $\mathrm{m^{-2}\,yr^{-1}}$)	References[f]
Palau lagoon (PW)	134.5	7.5	0.03		−1.0		−0.2	Watanabe et al. (2006)
Parker River estuary (US)	−70.8	42.8		3.2	2.9		1.1	Raymond and Hopkinson (2003)
Pei Kang River (TW)	120.2	23.5	27.3	80.0	35.1	28.8	15.6	Chen (unpublished)
Pei Nan River (TW)	121.2	22.8	155.0	96.2		147.0	48.4	Chen (unpublished)
Penna (IN)	80.2	14.4		5.2			1.9	Sarma et al. (2012)
Piauí River estuary (BR)	−37.5	−11.5					15.0	Souza et al. (2009)
Po Tzu River (TW)	120.1	23.4		85.5		89.9	32.0	Chen (unpublished)
Ponnayaar (IN)	80.3	12.4		96.3			35.2	Sarma et al. (2012)
Potou lagoon (CI)	−3.8	5.6	40.3	186.0	45.5	82.7	36.8	Kone et al. (2009)
Qiantang River (CN)	122.0	30.1					0.1	Chen (unpublished)
Qinjiang (CN)	108.6	21.7				6.3	2.3	Chen (unpublished)
Rajang River (MY)	115.5	2.1			7.1		2.6	Chen (unpublished)
Randers Fjord (DK)	10.3	56.6	−5.0	52.9			8.7	Gazeau et al. (2005)
Ras Dege creek (TZ)	39.3	−6.9					12.0	Kristensen et al. (2008), Bouillon et al. (2007c)
Rhine (NL)	4.1	52.0		160.0	75.1		21.9	Frankignoulle et al. (1998)
Ría de Vigo (FR)	8.6	42.1	−0.1	−0.5	0.5	−0.6	−0.1	Álvarez-Salgado et al. (1999)
Río San Pedro (ES)	−6.1	36.4					39.4	Ferron et al. (2007)
Rompin River (MY)	103.5	2.8			1.5		0.6	Chen (unpublished)
Rongjiang (CN)	116.7	23.3				14.0	5.1	Chen (unpublished)
Rushikulya (IN)	85.2	19.3		−0.02			−0.01	Sarma et al. (2012)
S. Muar (MY)	102.6	2.0			3.2		1.2	Chen (unpublished)
Sabarmathi (IN)	72.8	21.6		13.8			5.1	Sarma et al. (2012)
Sado (PT)	−8.9	38.5			396.0		145.0	Frankignoulle et al. (1998)
Saja-Besaya (ES)	−4.0	43.4		446.0			163.0	Ortega et al. (2005)
São Francisco Estuary (US)	−122.3	37.7		1.8		0.5	0.4	Peterson (1979)
Sapelo Sound (US)	−81.3	31.6	19.1	41.1	47.1	16.8	10.5	Jiang et al. (2008a)
Saptamukhi creek (IN)	89.0	22.0					20.7	Ghosh et al. (1987), Borges et al. (2003)
Satilla River (US)	−81.5	31.0			116.0		42.5	Cai and Wang (1998)
Scheldt (BE/NL)	3.5	51.4	175.0	233.0	326.0	240.0	94.1	Frankignoulle et al. (1998)
Sedili Besar (MY)	104.1	1.9			12.6		4.6	Chen (unpublished)
Sentosa River (MY)	104.1	1.9			17.2		6.3	Chen (unpublished)
Sharavathi (IN)	74.5	14.4		10.2			3.7	Sarma et al. (2012)
Shark River (US)	−81.1	25.2					16.0	Kone and Borges (2008)
Skeena River (US)	−130.1	53.9			65.6		23.9	Takahashi et al. (2012) (LDEO database)
Subarnalekha (IN)	87.6	21.5		0.03			0.01	Sarma et al. (2012)
Sizhong River (TW)	120.7	22.1	12.9	50.4		−0.8	7.6	Chen (unpublished)
Ta An River (TW)	120.6	24.4	−0.4	3.4	27.3	17.0	4.3	Chen (unpublished)
Ta Chia River (TW)	120.6	24.3	−6.3	25.3	−29.2		−1.2	Chen (unpublished)
Tagba lagoon (CI)	−5.0	5.4	18.1	114.0	28.5	13.2	18.5	Kone et al. (2009)
Tam Giang creeks (VN)	105.2	8.8	141.5		128.5		49.3	Kone and Borges (2008)
Tamar (UK)	−4.2	50.4	90.1	120.0			38.3	Frankignoulle et al. (1998)
Tan Shui River (TW)	121.5	25.1	168.0	160.0	214.0	3.3	49.8	Chen (unpublished)
Tana (KE)	40.1	−2.1					21.2	Bouillon et al. (2007a)
Tapti (IN)	72.7	21.1		362.5			132.4	Sarma et al. (2012)
Tendo lagoon (CI)	−3.2	5.3	−17.7	75.6	−4.9	−3.0	7.0	Kone et al. (2009)
Thames (UK)	0.9	51.5			250.0		91.3	Frankignoulle et al. (1998)
Tou Chien River (TW)	120.9	24.8	55.9	10.5	7.2	46.6	11.0	Chen (unpublished)
Trang River estuary (TH)	99.4	7.2					30.9	Miyajima et al. (2009)
Tseng Wen River (TW)	120.1	23.1	93.2	−1.8	12.4		34.6	Chen (unpublished)
Tung Kang River (TW)	120.4	22.5	114.0	160.0	48.9	121.0	40.5	Chen (unpublished)
Urdaibai (ES)	−2.7	43.4		22.8			8.3	Ortega et al. (2005)
Vaigai (IN)	78.9	9.3		0.2			0.1	Sarma et al. (2012)
Vamsadhara (IN)	84.7	18.9		0.4			0.1	Sarma et al. (2012)
Vellar (IN)	79.9	11.7		17.0			6.2	Sarma et al. (2012)
Wadden Sea estuary (NL)	4.8	53.0	−160.0				−58.4	Zemmelink et al. (2009)
Wailoa River estuary (US)[e]	−159.5	22.2	1032		422	607	251	Paquay et al. (2007)
Wailuku River (US)	−155.08	19.72	5.73				5.73	Paquay et al. (2007)
Wu River (TW)	120.5	24.2	44.4	92.1			24.9	Chen (unpublished)
Yangon (MM)	121.8	31.3				5.4	2.0	Chen (unpublished)
Yen Shui River (TW)	120.2	23.0	50.1	125.0		14.4	23.1	Chen (unpublished)

Table 1. Continued.

Type	Long. (°)	Lat. (°)	Spring flux[c] (mmol C m^{-2} d^{-1})	Summer flux (mmol C m^{-2} d^{-1})	Autumn flux (mmol C m^{-2} d^{-1})	Winter flux (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References[f]
Yenisey (RU)	82.7	71.8	29.7	16.7	3.5	27.5	7.1	Johnson et al. (2009) (WOD09 database)
York River (US)	−76.4	37.2	10.0	29.0	16.7	6.5	5.6	Raymond et al. (2000)
Zhujiang (Pearl River) (CN)	113.5	22.5	60.2	70.7	47.0	22.2	6.9	Guo et al. (2009)
Zuari (IN)	74.0	15.3		6.4			2.3	Sarma et al. (2012)

[a] Positive fluxes indicate an emission of CO_2 from water to the atmosphere.

[b] BE: Belgium; BN: Brunei; BR: Brazil; BS: Bahamas; CI: Côte d'Ivoire; CL: Chile; CN: China; DE: Germany; DK: Denmark; ES: Spain; FI: Finland; FR: France; GL: Greenland; IC: Iceland; ID: Indonesia; IN: India; KE: Kenya; MG: Madagascar; MM: Myanmar; MY: Malaysia; NL: Netherlands; PH: Philippines; PT: Portugal; PW: Palau; RU: Russia; TH: Thailand; TW: Taiwan; TZ: Tunisia; UK: United Kingdom; US: United States; VE: Venezuela; VN: Vietnam.

[c] Spring: March–May; summer: June–August; autumn: September–November; winter: December–February.

[d] Austral seasons.

[e] Not used in the calculation.

[f] LDEO: Lamont-Doherty Earth Observatory; WOD09: World Ocean Database 2009.

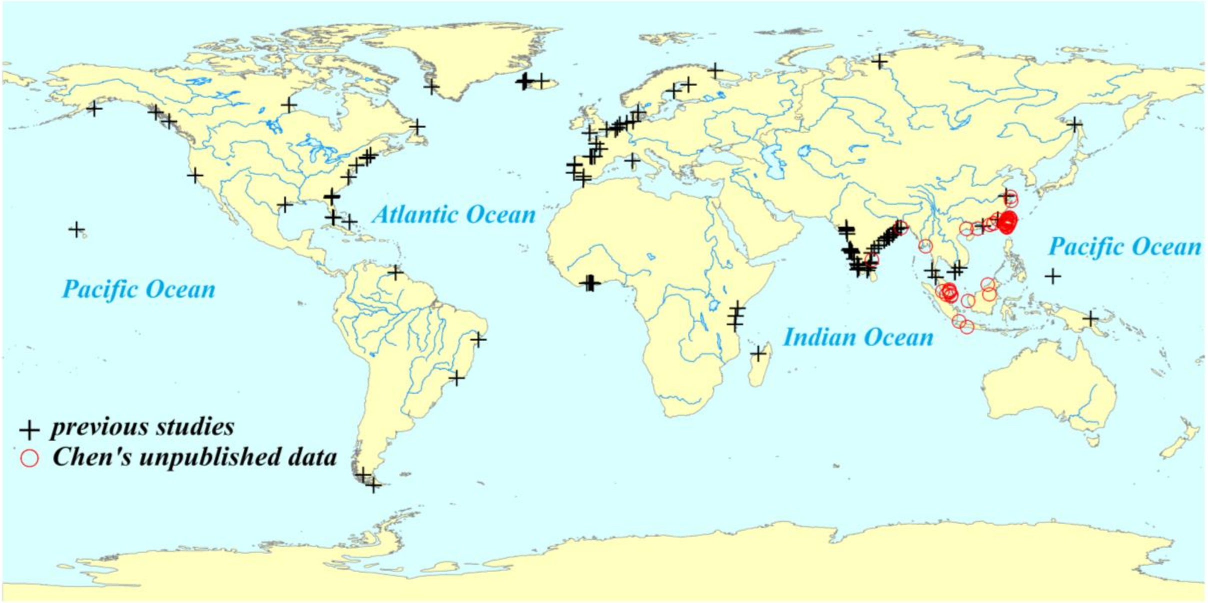

Fig. 1. Distribution of estuaries studied.

estuaries. Factors affecting gas exchange coefficients include wind speed, tidal current and bottom stress, whereas the wind speed is the most considered. It is important to point out that this paper deals mostly with published results. It is not possible to re-do the flux calculations, say, based on the same gas exchange coefficient, as the original data were not provided in the papers cited. Further, there is a lack of temporal coverage as previous studies (Bozec et al., 2011; Dai et al., 2009; Kitidis et al., 2012) have demonstrated short-term changes in pCO_2 at scales of days or less. Yet, typically data on such a scale are limited to only a few cruises. The lack of seasonality in the numerically averaged fluxes is almost certainly an artifact influenced by averaging all available data.

Figure 2 presents the pCO_2 and CO_2 fluxes per unit area in the upper, mid- and lower estuaries worldwide. Upper, mid-, and lower estuaries are defined as those areas of estuaries with salinities below 2, between 2 and 25, and above 25, respectively, as salinity data are the most readily available. Otherwise, divisions are made based approximately on one-third of the distance from the point where the river starts to widen to the river mouth. Almost all estuaries outside of the Arctic region except for only a few release CO_2 to the atmosphere. Unsurprisingly, upper estuaries, where the riverine effect is the strongest (Kempe, 1979, 1982; Chen et al., 2012), have the highest pCO_2 (numerical average = 5026 ± 6190 µatm) and the highest sea-to-air CO_2 flux (numerical average = 39.0 ± 55.7 mol C m^{-2} yr^{-1}, where the positive sign indicates that the seawater is losing CO_2); these are followed by the mid-estuaries (numerically averaged pCO_2 = 2230 ± 2725 µatm; numerically averaged

Table 2. The $p\mathrm{CO}_2$ and flux method, the gas exchange coefficient and the wind speed in the world's estuaries.

Type[a]	$p\mathrm{CO}_2$ method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
1-1(fjord) (US)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
11-1(fjord) (CA)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
14-1(fjord) (IC)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
14-2(fjord) (IC)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
14-3(fjord) (IC)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
14-4(fjord) (IC)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
14-5(fjord) (IC)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Aby lagoon (CI)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Koné et al. (2009)
Altamaha Sound (US)	equilibrator	TBL	Wannikhof (1992)	QuikSCAT	Jiang et al. (2008a)
Ambalayaar (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Amur River (RU)	calculated from TA & pH	TBL	Wannikhof (1992)	NCEP/NCAR Reanalysis	NODC database
Ason (ES)	calculated from TA & pH	TBL	Raymond and Cole (2001)	weather station	Ortega et al. (2005)
Aveiro lagoon (PT)	–	–	–	–	Borges and Frankignoulle (unpublished)
Baitarani (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Bancal (PH)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Bebar River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Bellamy (US)	equilibrator	TBL	Raymond and Cole (2001)	on site & weather station	Hunt et al. (2011)
Betsiboka (MG)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Ralison et al. (2008)
Bharatakulza (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Bothnian Bay (FI)	headspace	TBL	Wannikhof (1992)	on site	Algesten et al. (2004)
Brazos River (US)	headspace	TBL	Raymond et al.(1997); Richey et al.(2002); Zeng and Masiello (2010)	NOAA, National Weather Service	Zeng et al. (2011)
Brunei River (BN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Cauvery (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Chalakudi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Changjiang (Yangtze) (CN)	equilibrator	TBL	Wanninkhof (1992); Raymond and Cole (2001); Borges et al. (2004)	on site	Zhai et al. (2007)
Chi Shui River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Chilka (lagoon) (IN)	calculated from DIC & pH	TBL	Borges et al.(2004)	weather station	Gupta et al. (2008)
Cho Shui River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Chung Kang River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Churchill River (CA)	equilibrator	TBL	Wannikhof (1992)	on site	Stainton (2009)
Citanduy River (ID)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Ciujung-Kragilan (ID)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)

Table 2. Continued.

Type[a]	$p\mathrm{CO}_2$ method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
Cocheco (US)	equilibrator	TBL	Raymond and Cole (2001)	on site & weather station	Hunt et al. (2011)
Cochin (IN)	calculated from DIC & pH	TBL	Borges et al. (2004)	on site	Gupta et al. (2009)
Cross Sound (fjord) (US)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Doboy Sound (US)	equilibrator	TBL	Wannikhof (1992)	QuikSCAT	Jiang et al. (2008a)
Douro (PT)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Duplin River(US)	equilibrator	TBL	Raymond et al. (2000)	on site	Wang and Cai (2004)
Ebrié lagoon (CI)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Koné et al. (2009)
Elbe (DE)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Ems (DE)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Endau River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Erh Jen River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Florida Bay (US)	equilibrator	TBL	constant ($4\,\mathrm{cm\,h^{-1}}$)	–	Millero et al. (2001)
Fong Kang River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Gaderu creek(IN)	equilibrator	FCM	–	on site	Borges et al. (2003)
Gironde (FR)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Godavari (IN)	equilibrator/ calculated from DIC & pH	TBL	Raymond and Cole (2001); Wannikhof (1992)	on site; weather station	Bouillon et al. (2003); Sarma et al. (2012)
Golfo Almirante Montt (fjord) (CL)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Great Bay (US)	equilibrator	TBL	Raymond and Cole (2001)	on site & weather station	Hunt et al. (2011)
Guadalquivir (ES)	equilibrator	TBL	O'Connor and Dobbins (1958); Borges et al. (2004); Cariniet al. (1996); Clark et al. (1995); Wannikhof (1992)	on site	de La Paz et al. (2007)
Haldia (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Hanjiang (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Ho Ping River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Hooghly (IN)	headspace	TBL	Wannikhof (1992)	on site	Mukhopadhyay et al. (2002)
Hou Lung River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Hsiu Ku Luan River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Hua Lien River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Hudson River estuary (US)	headspace	TBL	Clark et al.(1994)	weather station	Raymond et al. (1997)
Isla Gordon (fjord) (CL)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Itacuraca creek Sepetiba Bay (BR)	equilibrator	FCM	–	on site	Ovalle et al. (1990), Borges et al. (2003)
Jiulong Jiang (Xiamen Bay) (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Dai et al. (2009)
Jiulongjiang (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Johor River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)

Table 2. Continued.

Type[a]	$p\text{CO}_2$ method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
Kakinada Bay (IN)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Bouillon et al. (2003)
Kali (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Kaneohe Bay and stream (US)	calculated from DIC & TA	TBL	Wannikhof (1992)	on site	Fagan et al. (2007)
Kao Ping River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Kapuas River (ID)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Kennebec River (US)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Khura River estuary (TH)	–	–	–	–	Miyajima et al. (2009);
Kidogoweni creek (Gazi Bay) (KE)	calculated from TA & pH	TBL	Carini et al. (1996); Raymond and Cole (2001)	on site	Bouillon et al. (2007a)
Kien Vang creeks (VN)	calculated from TA & pH	TBL	Carini et al.(1996)	on site	Koné and Borges (2008)
Klang River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Kobbe fjord (GL)	equilibrator	TBL	Wannikhof (1992); Nightingale et al. (2000)	weather station	Ruiz-Halpern et al. (2010)
Kochi backwaters (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Kola Bay (RU)	calculated from TA & pH	TBL	Wannikhof (1992)	NCEP/NCAR Reanalysis	NODC database
Krishna (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Lan Yang River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Liminganlahti Bay (Temmesjoki River) (FI)	equilibrator	TBL/FCM	Borges et al.(2004)	weather station	Silvennoinen et al. (2008)
Lin Pien River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Little Bay (US)	equilibrator	TBL	Raymond and Cole (2001)	on site & weather station	Hunt et al. (2011)
Loire (FR)	calculated from TA & pH	TBL	constant ($13\,\text{cm h}^{-1}$)	–	Abril et al. (2003)
Luohe (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Mahanadi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Mahisagar (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Mandovi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Mandovi-Zuari (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	–	Sarma et al. (2001)
Matolo creek (KE)	calculated from TA & pH	TBL	constant ($4\,\text{cm h}^{-1}$)	–	Bouillon et al (2007b)
Mekong (VN)	–	–	–	–	Borges (unpublished)
Mempawah River (ID)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Mtoni (TZ)	equilibrator	TBL	Raymond and Cole (2001)	on site	Kristensen et al. (2008)
Nagada creek (Papua New Guinea) (ID)	equilibrator	FCM	–	on site	Borges et al. (2003)
Nagavali (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Nalonghe (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Narmada (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Netravathi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)

Table 2. Continued.

Type[a]	$p\mathrm{CO}_2$ method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
Norman's Pond (BS)	equilibrator	FCM	–	on site	Borges et al. (2003)
Orinoco River (VE)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Oyster (US)	equilibrator	TBL	Raymond and Cole (2001)	on site & weather station	Hunt et al. (2011)
Pa Chang River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Pahang River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Palau lagoon (PW)	calculated from DIC & TA	TBL	McGillis et al. (2001)	NOAA station	Watanabe et al. (2006)
Parker River estuary (US)	equilibrator	TBL	constant ($4\,\mathrm{cm\,h^{-1}}$)	–	Raymond and Hopkinson
Pei Kang River (TW)	(2003) equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Pei Nan River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Penna (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Piauí River estuary (BR)	calculated from DIC & pH	TBL	range ($1–3\,\mathrm{cm\,h^{-1}}$)	on site	Souza et al. (2009)
Po Tzu River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Ponnayaar (IN)	equilibrator	TBL	Wannikhof (1992)	on site	Sarma et al. (2012)
Potou lagoon (CI)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Koné et al. (2009)
Qiantang River (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Qinjiang (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Rajang River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Randers Fjord (DK)	equilibrator	TBL	Borges et al. (2004)	on site	Gazeau et al. (2005)
Ras Dege creek (TZ)	equilibrator/ calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Kristensen et al. (2008); Bouillon et al (2007c)
Rhine (NL)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Ría de Vigo (FR)	calculated from TA & pH	TBL	Liss and Mervilat (1986); Woolf and Thorpe (1991)	estimated	Álvarez-Salgado et al. (1999)
Río San Pedro (ES)	headspace	TBL	Clark et al. (1995); Carini et al. (1996); Kremer et al. (2003); Borges et al. (2004)	weather station	Ferrón et al. (2007)
Rompin River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Rongjiang (CN)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Rushikulya (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
S. Muar (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Sabarmathi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Sado (PT)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Saja-Besaya (ES)	calculated from TA & pH	TBL	Raymond and Cole (2001)	weather station	Ortega et al. (2005)
São Francisco Estuary (US)	calculated from TA & pH	TBL	range ($4–8\,\mathrm{cm\,h^{-1}}$)	–	Peterson (1979)
Sapelo Sound (US)	equilibrator	TBL	Jiang et al. (2008a)	QuikSCAT	Jiang et al. (2008a)
Saptamukhi creek (IN)	calculated from TA & pH/ equilibrator	FCM	–	on site	Ghosh et al. (1987); Borges et al. (2003)
Satilla River (US)	equilibrator	TBL	range ($8–17\,\mathrm{cm\,h^{-1}}$)	–	Cai and Wang (1998)

Table 2. Continued.

Type[a]	$p\mathrm{CO}_2$ method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
Scheldt (BE/NL)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Sedili Besar (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Sentosa River (MY)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Sharavathi (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Shark River (US)	calculated from TA & pH	TBL	Carini et al. (1996)	on site	Koné and Borges (2008)
Skeena River (US)	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Subarnalekha (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Sizhong River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Ta An River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Ta Chia River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Tagba lagoon (CI)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Koné et al. (2009)
Tam Giang creeks (VN)	calculated from TA & pH	TBL	Carini et al. (1996)	on site	Koné and Borges (2008)
Tamar (UK)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Tan Shui River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Tana (KE)	calculated from TA & pH	TBL	constant ($4\,\mathrm{cm\,h^{-1}}$)	–	Bouillon et al (2007b)
Tapti (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Tendo lagoon (CI)	calculated from TA & pH	TBL	Raymond and Cole (2001)	on site	Koné et al. (2009)
Thames (UK)	calculated from TA & pH/ equilibrator	TBL/FCM	constant ($8\,\mathrm{cm\,h^{-1}}$)/–	on site	Frankignoulle et al. (1998)
Tou Chien River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Trang River estuary (TH)	–	–	–	–	Miyajima et al. (2009);
Tseng Wen River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Tung Kang River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Urdaibai (ES)	calculated from TA & pH	TBL	Raymond and Cole (2001)	weather station	Ortega et al. (2005)
Vaigai (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Vamsadhara (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Vellar (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)
Wadden Sea estuary (NL)	calculated from DIC & TA	TBL	Wannikhof (1992)	–	Zemmelink et al. (2009)
Wu River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Yangon (MM)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Yen Shui River (TW)	equilibrator	TBL	Wannikhof (1992)	on site	Chen (unpublished)
Yenisey (RU)	calculated from TA & pH	TBL	Wannikhof (1992)	NCEP/NCAR Reanalysis	NODC database
York River (US)	equilibrator	TBL	Clark et al. (1994); Carini et al. (1996)	–	Raymond et al. (2000)

Table 2. Continued.

Type[a]	pCO_2 method	Flux method[b]	Gas exchange coefficient	Wind speed	References[c]
Zhujiang (Pearl River) (CN)	equilibrator	TBL	Wannikhof (1992); Borges et al. (2004)	–	Guo et al. (2009)
Zuari (IN)	calculated from DIC & pH	TBL	Wannikhof (1992)	weather station	Sarma et al. (2012)

[a] BE: Belgium; BN: Brunei; BR: Brazil; BS: Bahamas; CI: Côte d'Ivoire, CL: Chile; CN: China; DE: Germany; DK: Denmark; ES: Spain; FI: Finland; FR: France; GL: Greenland; IC: Iceland; ID: Indonesia; IN: India; KE: Kenya; MG: Madagascar; MM: Myanmar; MY: Malaysia; NL: Netherlands; PH: Philippines; PT: Portugal; PW: Palau; RU: Russia; TH: Thailand; TW: Taiwan; TZ: Tunisia; UK: United Kingdom; US: United States; VE: Venezuela; VN: Vietnam.

[b] TBL: thin boundary layer method; FCM: floating chamber method.

[c] LDEO: Lamont-Doherty Earth Observatory; WOD09: World Ocean Database 2009.

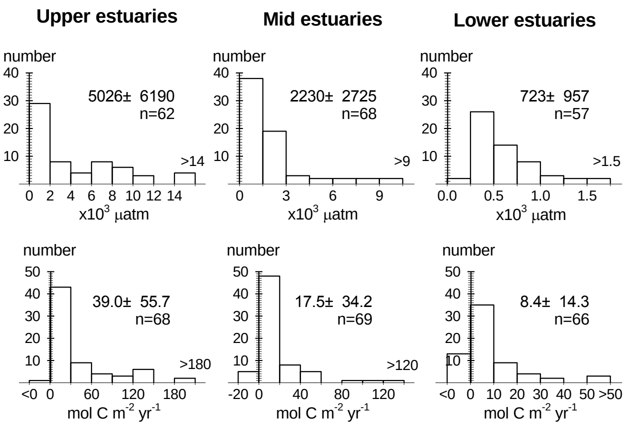

Fig. 2. CO_2 flux in **(a)** upper, **(b)** mid- and **(c)** lower estuaries.

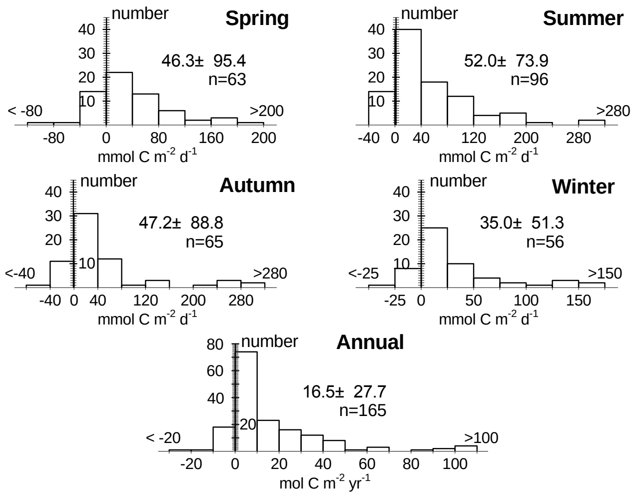

Fig. 3. Histogram of reported daily CO_2 fluxes per unit area in different seasons and the annual flux of the world's estuaries.

flux = 17.5 ± 34.2 mol C m^{-2} yr^{-1}). Lower estuaries have the lowest pCO_2 (numerical average = 723 ± 957 µatm) and CO_2 flux (numerical average = 8.4 ± 14.3 mol C m^{-2} yr^{-1}). Except for those of the upper estuaries, these pCO_2 values compare favorably with those found by Chen et al. (2012), which were 3033, 2277, and 692 µatm for the upper, mid- and lower estuaries, respectively. This study yields much higher pCO_2 values for upper estuaries mainly because new data from Asia are associated with high pCO_2 values. The fluxes obtained by Chen et al. (2012), however, are higher. Their values are 68.5, 37.4 and 9.92 mol C m^{-2} yr^{-1} for the upper, mid- and lower estuaries, respectively. The seeming inconsistency among results is discussed below.

Figure 3 displays histograms of reported daily CO_2 fluxes per unit area in different seasons and the annual flux per unit area in the world's estuaries. Little seasonality is observed, except that the flux is lower in the winter when the pCO_2 is usually lower, perhaps because the temperature is lower than other seasons. The flux is only marginally higher in summer than in spring or autumn. The numerical average annual flux per unit area is 16.5 ± 27.7 mol C m^{-2} yr^{-1}, which is significantly lower than that, 23.9 ± 33.1 mmol C m^{-2} d^{-1}, obtained by Chen et al. (2012). The numerical average annual flux per unit area, however, is not used to calculate the global release of CO_2 because small estuaries dominate the numerical average, but they contribute relatively little to the total flux. Important to note is that there is a lack of temporal coverage in most of the data sets although previous studies (Bozec et al., 2011; Dai et al., 2009; Kitidis et al., 2012) have demonstrated short-term changes in pCO_2 at scales of days or less. Yet, typically data on such a scale are limited to only a few cruises. The lack of seasonality in the numerically averaged fluxes is almost certainly an artifact influenced by averaging all available data.

With respect to latitude, the numerically averaged flux per unit area is the highest, at 63.3 ± 100.7 mmol C m^{-2} d^{-1} between 23.5 and 50° N, followed by 44.1 ± 29.3 mmol C m^{-2} d^{-1} between 23.5° and 0° S, followed by 38.8 ± 55.4 mmol C m^{-2} d^{-1} between 0° and 23.5° N, and 35.9 ± 91.2 mmol C m^{-2} d^{-1} north of 50° N. The numerically averaged flux south of 50° S (9.5 ± 11.7 mmol C m^{-2} d^{-1}) is greatly lower, but data are available for only two estuaries. By way of comparison,

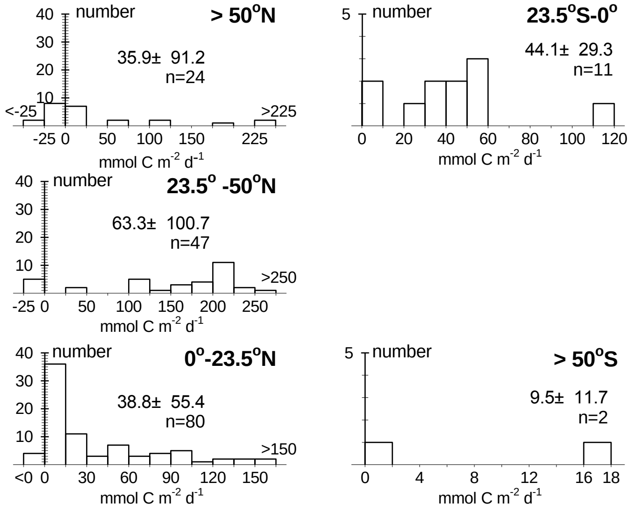

Fig. 4. Histogram of reported annual CO_2 fluxes of the world's estuaries in various latitude bands.

Chen et al. (2012) obtained $65.5 \pm 78.1\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ – a slightly higher value than obtained in this study – between 23.5° N and 23.5° S. The values of Chen et al. (2012) are $67.4 \pm 108\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ between 23.5 and 50° N and $59.2 \pm 80\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ north of 50° N, however, significantly higher than those obtained herein. Notably, most other investigations have presented fluxes higher than those that were presented by Chen et al. (2012).

The fact that the annual average flux herein is lower than those reported previously, despite the fact the average $p\mathrm{CO_2}$ is higher, warrants discussion. It follows mainly from the fact that many data from the low-latitude bands in Asia have been added, and these areas are mostly areas of low wind energy. Figure 5 plots the wind energy potential, which is, like the air–sea gas exchange rate, a quadratic function of wind speed. The areas of high wind energy at low latitudes are concentrated in the dry Middle East and northeastern, northern and northwestern Africa with few rivers, and therefore few estuaries. For example, the total area of the estuaries in the Red Sea region is almost zero (Table 3; Laruelle et al., 2013). Accordingly, the global average CO_2 flux herein is substantially affected by estuaries in areas of low wind energy, and therefore of low CO_2 flux.

The 50 newly considered estuaries in Taiwan, southern China and Southeast Asia, all at low latitudes, have lower fluxes than determined from previously obtained results (Table 1), which include many data for European rivers. For instance, only 2 of the 19 estuaries that were considered by Abril and Borges (2005), who published perhaps the first global study of CO_2 emissions from estuaries, are outside Europe and the eastern seaboard of the USA. Those authors found a global CO_2 flux per unit area of $35.7\,\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$, which is more than triple the value obtained in this study. This finding does not imply that European rivers have higher $p\mathrm{CO_2}$: they do not. Rather, Europe has more windy coasts than elsewhere in the world, and especially Asia. Parts of these higher fluxes may have resulted from higher wind speed. As mentioned above, the wind potential is a quadratic function of wind speed, as is the 1992 Wanninkhof air–sea CO_2 exchange equation. It is important to point out, however, that the water turbulence is an importance factor for gas transfer velocity in low wind speed regions, but little data is available. We have compared the Wanninkhof (1992) quadratic equation ($k660 = 0.31 \times U10^2$) with other equations such as those of Raymond and Cole (2001), Borges et al. (2004), Ho et al. (2011), and Jiang et al. (2008a). Using Wanninkhof's (1992) quadratic equation may underestimate flux, although the value is similar to that of Ho et al. (2011) at low wind speed ($< 5\,\mathrm{m\,s^{-1}}$). Note that there is no theoretical basis for the above equations as most are based on curve fitting techniques. Since we do not have data to show which equation is the best, we have chosen the Wanninkhof quadratic equation, which most references we cited used. Due to the fact that using different air–sea exchange equations results in large uncertainties, and that there is no universally accepted equation, the above conclusion can only be deemed preliminary. The mean $p\mathrm{CO_2}$ of European estuaries is roughly 1600 µatm, whereas that of Asian estuaries is much higher, around 4000 µatm. Yet, the mean wind speed on European coasts is approximately $4\,\mathrm{m\,s^{-1}}$, compared with about $1.6\,\mathrm{m\,s^{-1}}$ on Asian coasts. The resulting CO_2 fluxes for European estuaries average about $16.9\,\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$ vs. a much lower $8.1\,\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$ for Asian estuaries (Table 3; Fig. 6) despite their higher $p\mathrm{CO_2}$.

In the above calculation, the areas of groups of estuaries are taken from the most recent and comprehensive work of Laruelle et al. (2013), which divided the world into 45 regions and calculated a total estuarine area of $1.012 \times 10^6\,\mathrm{km^2}$, slightly smaller than the value of $1.067 \times 10^6\,\mathrm{km^2}$ given in Laruelle et al. (2010). Table 3 lists the total surface area in each of the 45 regions and the numerically averaged CO_2 flux per unit area for each region. Our global flux calculation is based on the sum of regional fluxes for these 45 zones (area multiplied by zonal average CO_2 flux ($\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$)). These 165 estuaries are compartmentalized into 35 regions, and the numerically averaged CO_2 flux per unit area is calculated. For 10 regions without data, the mean flux for the same classification region is used (Table 3). The outgassing of CO_2 in global estuaries is $0.094\,\mathrm{Pg\,C\,yr^{-1}}$, and is about 31 % of the global riverine organic carbon flux (Seitzinger et al., 2010). This compares with the 48 % of organic carbon released as CO_2 from estuaries and inland waters (Tranvik et al., 2009).

Estuaries in North America have the largest total area, but the lowest average flux per unit area among all continents, and therefore a low total flux of $10.8\,\mathrm{Tg\,C\,yr^{-1}}$. That is, a continent with 41 % of the world's estuarine area accounts for only 12 % of the world's estuarine CO_2 release

Table 3. Areas and air–sea fluxes of CO_2 in estuaries and continental shelves by biogeochemical provinces (Laruelle et al., 2013).

MARCATS segment number	Continent	Ocean name	System	Class	Estuarine surface (10^3 km^2)	Average CO_2 flux (mol C m^{-2} yr^{-1})	CO_2 flux (Tg C yr^{-1})	Shelf surface (10^3 km^2)	Average CO_2 flux (mol C m^{-2} yr^{-1})	CO_2 flux (Tg C yr^{-1})
1	NA	PA	Northeastern Pacific	Subpolar	33.9	10.71 ($n=3$)	4.36	461	−3.51 ($n=3$)	−19.40
2	NA/OC	PA	Californian Current	EBC	8.9	0.93 ($n=3$)	0.10	214	−2.22 ($n=3$)	−5.69
3	NA	PA	Tropical Eastern Pacific	Tropical	6.2	**14.47**	**1.08**	198	−0.05 ($n=2$)	−0.13
4	SA	PA	Peruvian Upwelling Current	EBC	4.2	**34.71**	**1.75**	143	−0.62 ($n=4$)	−1.07
5	SA	AT	South America	Subpolar	22	−3.46 ($n=2$)	−0.91	1230	−3.25 ($n=3$)	−47.98
6	SA	AT	Brazilian Current	WBC	26.3	28.20 ($n=2$)	8.90	521	3.97 ($n=1$)	24.81
7	SA	AT	Tropical Western Atlantic	Tropical	13.4	11.60 ($n=1$)	1.87	517	−12.78 ($n=1$)	−79.26
8	NA	AT	Caribbean Sea	Tropical	26.2	5.04 ($n=1$)	1.58	344	0.66 ($n=1$)	2.74
9	NA	AT	Gulf of Mexico	Marginal Sea	31.9	8.02 ($n=2$)	3.07	544	−0.19 ($n=2$)	−1.26
10	NA	AT	Florida Upwelling	WBC	34	9.81 ($n=15$)	4.00	858	−1.10 ($n=4$)	−11.27
11	NA	AT	Sea of Labrador	Subpolar	36.1	−0.76 ($n=1$)	−0.33	395	−2.11 ($n=1$)	−10.02
12	NA	AT	Hudson Bay	Marginal Sea	39	−0.44 ($n=1$)	−0.20	1064	0.84 ($n=1$)	10.73
13	NA	AR	Canadian Archipelago	Polar	163.7	**−1.08**	**−2.11**	1177	−4.06 ($n=2$)	−57.34
14	NA	AR	Northern Greenland	Polar	24.1	−2.05 ($n=5$)	−0.59	614	6.14 ($n=1$)	45.20
15	NA	AR	Southern Greenland	Polar	8.8	**−1.08**	**−0.11**	270	−5.95 ($n=1$)	−19.29
16	EU	AR	Norwegian Basin	Polar	17	−17.30 ($n=1$)	−3.53	171	−3.63 ($n=1$)	−7.45
17	EU	AT	Northeastern Atlantic	Marginal Sea	37.6	37.73 ($n=8$)	17.02	1112	−1.04 ($n=2$)	−13.88
18	EU	AT	Baltic Sea	Marginal Sea	26.3	1.28 ($n=2$)	0.40	383	−1.95 ($n=1$)	−8.96
19	EU	AT	Iberian Upwelling	EBC	12.7	58.75 ($n=10$)	8.95	283	−1.33 ($n=5$)	−4.51
20	EU	AT	Mediterranean Sea	Marginal Sea	15.1	−0.06 ($n=1$)	−0.01	580	1.47 ($n=3$)	10.21
21	EU	AT	Black Sea	Marginal Sea	10.3	**10.00**	**1.24**	172	**−0.79**	**−1.63**
22	AF	AT	Moroccan Upwelling	EBC	5.6	**34.71**	**2.33**	225	3.02 ($n=1$)	8.15
23	AF	AT	Tropical Eastern Atlantic	Tropical	26.6	17.25 ($n=5$)	5.51	284	0.29 ($n=1$)	0.99
24	AF	AT	Southwestern Africa	EBC	1.7	**34.71**	**0.71**	308	−2.41 ($n=1$)	−8.91
25	AF	IN	Agulhas Current	WBC	28.4	**14.52**	**4.95**	254	−4.03 ($n=1$)	−12.28
26	AF	IN	Tropical Western Indian	Tropical	5.8	15.73 ($n=5$)	1.09	72	1.03 ($n=1$)	0.89
27	AF	IN	Western Arabian Sea	Indian Margins	2	3.32 ($n=1$)	0.08	102	−0.32 ($n=2$)	−0.40
28	AF	IN	Red Sea	Marginal Sea	0.04	**10.00**	**0.005**	190	0.12 ($n=2$)	0.28
29	AS	IN	Persian Gulf	Marginal Sea	2.3	**10.00**	**0.28**	233	**−0.79**	**−2.20**
30	AS	IN	Eastern Arabian Sea	Indian Margins	14.5	9.02 ($n=25$)	1.57	342	0.01 ($n=1$)	0.06
31	AS	IN	Bay of Bengal	Indian Margins	10.1	19.82 ($n=10$)	2.40	230	−0.22 ($n=1$)	−0.60
32	AS	IN	Tropical Eastern Indian	Indian Margins	16.2	13.73 ($n=6$)	2.67	809	−0.28 ($n=4$)	−2.74
33	OC	IN	Leeuwin Current	EBC	0.6	**34.71**	**0.25**	118	−0.58 ($n=1$)	−0.82
34	OC	PA	Southern Australia	Subpolar	13.1	**2.82**	**0.44**	452	−0.94 ($n=1$)	−5.12
35	OC	PA	Eastern Australian Current	WBC	7.9	**14.52**	**1.38**	139	−0.19 ($n=3$)	−0.31
36	OC	PA	New Zealand	Subpolar	7.3	**2.82**	**0.25**	283	−0.17 ($n=1$)	−0.58
37	AS	PA	Northern Australia	Tropical	40.5	15.90 ($n=1$)	7.73	2463	0.11 ($n=3$)	3.35
38	AS	PA	Southeast Asia	Tropical	45.6	17.70 ($n=49$)	9.68	2318	0.86 ($n=1$)	23.92
39	AS	PA	East China Sea and Kuroshio	WBC	27.8	7.33 ($n=2$)	2.44	1299	1.04 ($n=8$)	16.26
40	AS	PA	Sea of Japan	Marginal Sea	6.7	**10.00**	**0.80**	277	−3.89 ($n=2$)	−12.93
41	AS	PA	Sea of Okhotsk	Marginal Sea	19.7	0.30 ($n=1$)	0.07	992	−1.67 ($n=1$)	−19.82
42	AS	PA	Northwestern Pacific	Subpolar	22.3	**2.82**	**0.76**	1082	−2.12 ($n=2$)	−27.56
43	AS	AR	Siberian shelves	Polar	37.8	**−1.08**	**−0.49**	1918	0.01 ($n=1$)	0.25
44	AS	AR	Barents and Kara seas	Polar	72.2	3.07 ($n=2$)	2.66	1727	0.01 ($n=1$)	0.23
45	AN	AN	Antarctic shelves	Polar	–			2952	−1.98 ($n=2$)	−69.96
Total					1012.44	7.74	94.08	30320	−1.09	−395.71

Bold numbers are regions without data, and data from a similar region are given. EBC represents Eastern Boundary Current and WBC means Western Boundary Current.

(Fig. 6). African, European and South American estuaries have similarly high fluxes per unit area but the areas of the estuaries are only moderate so they are responsible for only 16 % (14.7 Tg C yr^{-1}), 26 % (24.1 Tg C yr^{-1}) and 12 % (11.6 Tg C yr^{-1}), respectively, of the global release. The largest contributor is Asia, which has 31.5 % of the world's estuary area and releases almost the same percentage of the world's estuarine-released CO_2 (32 %, or 30.6 Tg C yr^{-1}; Fig. 6).

Largely on account of the distribution of data, which include data from high wind regions on both sides of the North Atlantic and around the Arabian Sea in the Indian Ocean, as well as those generally in the low wind regions around the Pacific Ocean, the mean CO_2 flux per unit area is the lowest for estuaries that flow into the Pacific Ocean, with a value of 10.5 mol C m^{-2} yr^{-1} (Fig. 7). This value compares with 12.4 mol C m^{-2} yr^{-1} for estuaries that flow into the Atlantic Ocean and 13.9 mol C m^{-2} yr^{-1} for estuaries that flow into the Indian Ocean. Because the total area of estuaries that enter the Atlantic Ocean exceeds the sum of areas of estuaries that enter the Pacific and Indian oceans, the total flux of CO_2 released from the estuaries around the Atlantic

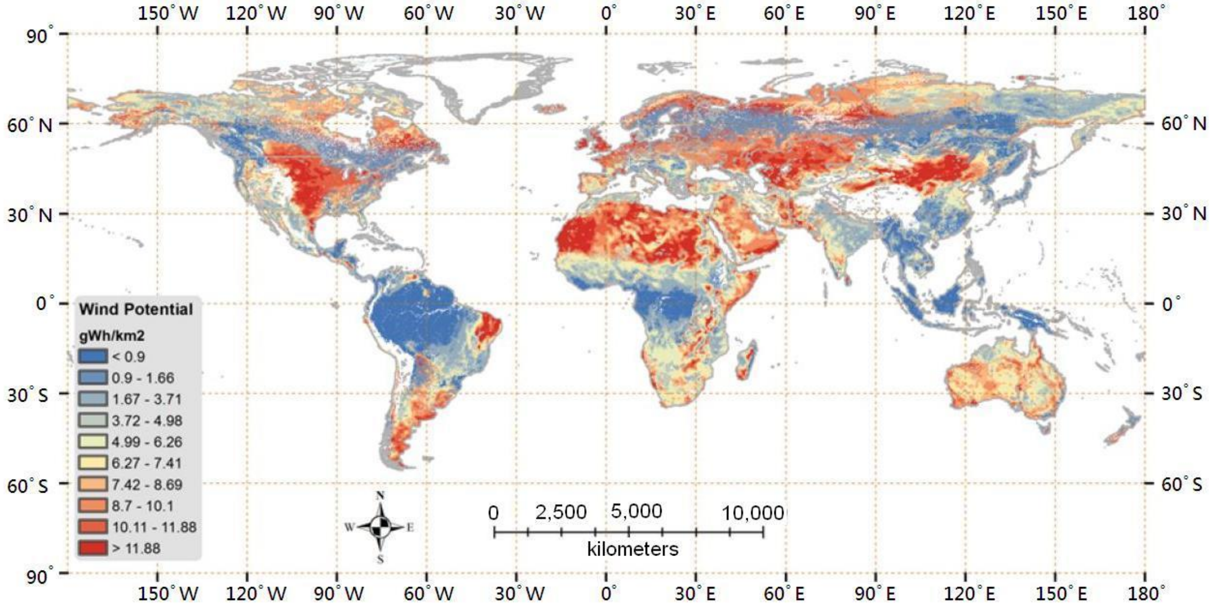

Fig. 5. Global wind potential (courtesy of Y. Y. Zhou).

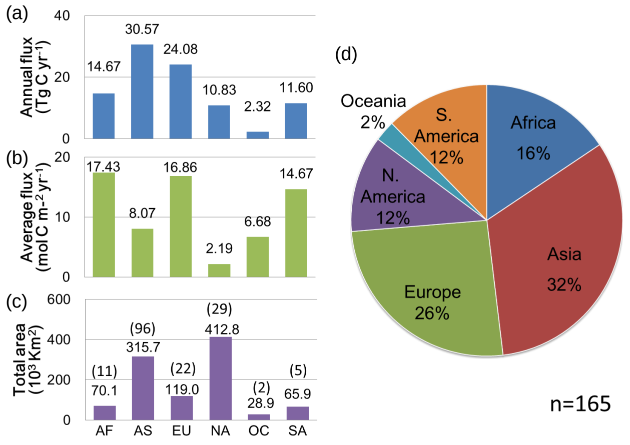

Fig. 6. Annual CO_2 flux **(a)**, average CO_2 flux per unit area **(b)**, total surface area **(c)**, and percentage of total CO_2 flux **(d)** from estuaries in each continent. Numbers in parentheses indicate the number of estuaries studied.

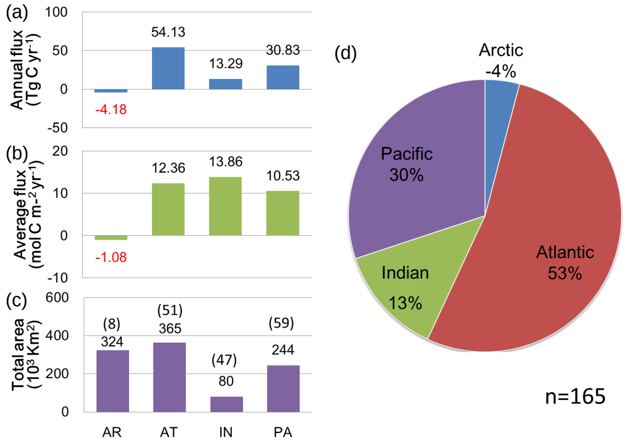

Fig. 7. Annual CO_2 flux **(a)**, average CO_2 flux per unit area **(b)**, total surface area **(c)**, and percentage of total CO_2 flux **(d)** from estuaries of each ocean. Numbers in parentheses indicate the number of estuaries studied.

(54.1 Tg C yr^{-1}) exceeds the total flux from estuaries around the Pacific (30.8 Tg C yr^{-1}) and the Indian (13.3 Tg C yr^{-1}) oceans. The total area of estuaries that enter the Arctic Ocean is substantial (324×10^3 km^2), equaling the total areas of the estuaries around the Atlantic and Indian oceans. Unfortunately, the relevant data are scarce, and the available data seem to reveal that the Arctic estuaries absorb rather than release CO_2. The numerically averaged flux per unit area and total flux are -1.1 mol C m^{-2} yr^{-1} and -4.2 Tg C yr^{-1}, respectively. The global total release of 94 Tg C yr^{-1} is less than half of any previous estimates (Table 4). New data from low wind regions and the Arctic Ocean are responsible for this difference.

3 Air-to-sea CO_2 fluxes in continental shelves

Data are available from 87 continental shelves (Table 5 and Fig. 8). The method used to calculate the flux, and sources of the gas exchange coefficient and wind speed are listed in Table 6. Similar to the case for estuaries, different pCO_2 flux methods and gas transfer velocities also cause disparity in the flux estimations in coastal regions. For instance, Jiang

Table 4. Summary of reported total sea-to-air fluxes of CO_2 in the world's estuaries.

	Unit area flux (mol C m^{-2} yr^{-1})	Area (10^6 km^2)	Total flux (Pg C yr^{-1})	References
Estuaries ($n = 19$)	35.71	1.40	0.60	Abril and Borges (2005)
Estuaries ($n = 16$)	38.12	0.94	0.43	Borges (2005)
Non-estuarine salt marshes ($n = 1$)	23.45	0.14	0.04	
Mangroves	13.66	0.20	0.04	
Average/Total	33.20	1.28	0.51	
Estuaries ($n = 16$)	28.62	0.94	0.32	Borges et al. (2005)
Non-estuarine salt marshes	21.40	0.14	0.036	
Mangroves	18.66	0.15	0.033	
Average/Total	26.42	1.23	0.39	
Estuaries ($n = 32$)	32.10	0.943	0.36	Chen and Borges (2009)
Non-estuarine salt marshes	30.40	0.384	0.09	
Mangroves	27.10	0.147	0.05	
Average/Total	28.27	1.474	0.50	
Small deltas and estuaries	25.7 ± 15.8	0.084	0.026 ± 0.016	Laruelle et al. (2010)
Tidal systems and embayments	28.5 ± 24.9	0.276	0.094 ± 0.082	
Lagoons	17.3 ± 16.6	0.252	0.052 ± 0.050	
Fjords and fjards	17.5 ± 14.0	0.456	0.096 ± 0.077	
Average/Total ($n = 60$)	21.0 ± 17.6	1.067	0.268 ± 0.225	
Estuaries (including both river-dominated and nonriverine coastal lagoons)	20.83	1.05	0.25	Cai (2011)
Estuaries ($n = 106$)	23.9 ± 33.1	1.07	0.26	Chen et al. (2012)
Estuaries ($n = 165$)	7.74	1.01	0.094	This study

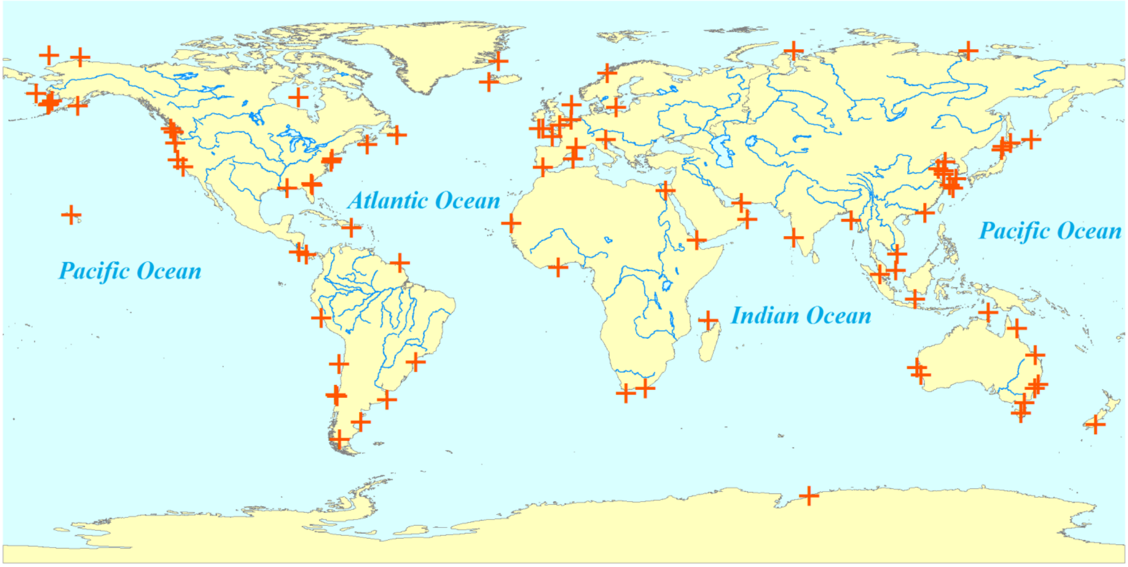

Fig. 8. Distribution of continental shelves studied.

et al. (2008b) pointed out that the average standard deviation of fluxes based on different gas transfer velocity equations reaches 14 %. The available data for 87 estuaries are compartmentalized into 43 regions based on the definition of Laruelle et al. (2013). Then the numerically averaged CO_2 flux per unit area is calculated. For two regions without data, the mean flux for the similar classification region is used (Table 3).

Table 5. Seasonal and annual air–sea fluxes of CO$_2$ in the world's continental shelves.

Type	Long. (°)	Lat. (°)	Spring fluxes[b] (mmol C m^{-2} d^{-1})	Summer fluxes (mmol C m^{-2} d^{-1})	Autumn fluxes (mmol C m^{-2} d^{-1})	Winter fluxes (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References
1 NEP	−155.9	56.4	−9.31	−12.22	−10.30		−3.87	Pfeil et al. (2013) (SOCAT database)
10T	−1.7	4.5	−0.80				0.29	Takahashi et al. (2012) (LDEO database)
11EBC	20.1	−35.7		−5.79[c]	−7.42[c]		−2.41	Takahashi et al. (2012) (LDEO database)
11LAB	−53.4	47.0	−9.77	0.46	−5.91	−7.95	−2.11	Pfeil et al. (2013) (SOCAT database)
14 NGR	−14.0	69.2	−14.98	−18.64			−6.14	Pfeil et al. (2013) (SOCAT database)
14WBC	26.2	−34.1		−11.04[c]			−4.03	Takahashi et al. (2012) (LDEO database)
15 SGR	−28.5	63.8	−16.61	−40.20	−6.07	−2.37	−5.95	Pfeil et al. (2013) (SOCAT database)
16 NOR	14.1	66.9	−11.65	−6.41	−12.77	−8.93	−3.63	Pfeil et al. (2013) (SOCAT database)
17EBC	114.8	−29.9	−3.23[c]		−3.94[c]		−1.31	Pfeil et al. (2013) (SOCAT database)
20 MED	3.1	39.5	−0.31	0.06	0.33	−2.28	−0.20	Pfeil et al. (2013) (SOCAT database)
22 MOR	−16.7	18.8	20.22	4.00	0.59		3.02	Pfeil et al. (2013) (SOCAT database)
26 TWI	46.4	−12.4			2.83[c]		1.03	Pfeil et al. (2013) (SOCAT database)
27WAS	57.1	25.3	0.71	0.66			0.25	Pfeil et al. (2013) (SOCAT database)
28 RED	32.7	29.2		0.23	1.06		0.23	Pfeil et al. (2013) (SOCAT database)
3 TEP	−82.5	8.8	1.99	−1.29	−1.28	−0.39	−0.09	Pfeil et al. (2013) (SOCAT database)
31 BEN	92.4	19.7				−0.59	−0.22	Pfeil et al. (2013) (SOCAT database)
33 LEE	113.5	−27.4	−4.27[c]	−0.39[c]	−0.10[c]		−0.58	Pfeil et al. (2013) (SOCAT database)
34 SAU	146.8	−42.1	−4.21[c]	−1.39[c]	−1.42[c]	−3.34[c]	−0.94	Pfeil et al. (2013) (SOCAT database)
39 CSK	150.2	45.6				20.05	7.32	Pfeil et al. (2013) (SOCAT database)
4 HUM−1	−77.8	−11.6			−0.14[c]		−0.05	Takahashi et al. (2012) (LDEO database)
4 HUM−2	−80.0	−26.3		−0.91[c]			−0.33	Takahashi et al. (2012) (LDEO database)
4 HUM−3	−73.1	−36.1		−11.82[c]			−4.32	Takahashi et al. (2012) (LDEO database)
42 NWP	−169.1	60.4	−33.81	−13.73	−3.41	6.61	−4.05	Pfeil et al. (2013) (SOCAT database)
4HUM−4	−72.7	−36.7	−2.14[c]	9.74[c]	10.53[c]		2.20	Pfeil et al. (2013) (SOCAT database)
5 SAM	−71.8	−50.5		−18.15[c]			−6.62	Pfeil et al. (2013) (SOCAT database)
6WBC−1	−56.5	−37.8		−4.56[c]	−5.19[c]		−1.78	Takahashi et al. (2012) (LDEO database)

Table 5. Continued.

Type	Long. (°)	Lat. (°)	Spring fluxes[b] (mmol C m^{-2} d^{-1})	Summer fluxes (mmol C m^{-2} d^{-1})	Autumn fluxes (mmol C m^{-2} d^{-1})	Winter fluxes (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References
6WBC−2	−47.4	−25.7		10.87[c]			3.97	Takahashi et al. (2012) (LDEO database)
8 CAR	−68.0	17.3	0.86	3.76	2.58	0.07	0.66	Pfeil et al. (2013) (SOCAT database)
Amazon River plume	−52.5	6					−12.78	Ternon et al. (2000), Kortzinger (2003)
Arafura Sea	136.3	−9.9	−0.02[c]				−0.01	Hydes et al. (2012)
Atlantic Bight (middle)	−74.5	38.5					−1.8	DeGrandpre et al. (2002)
Atlantic Bight (southern)	−80.6	31	−0.44	−0.22	−0.24	−0.26	−0.48	Jiang et al. (2008b)
Baltic Sea	20; 13.9	57; 54.9	−92.9	−66.5	−3.6	−34.4	−1.95	Thomas and Schneider (1999), Kuss et al. (2006)
Bass Strait	148.0	−38.8		−0.11[c]	−0.73[c]		−0.15	Hydes et al. (2012)
Bay of Biscay (northern)	−7.9	49					−0.8	Borges et al. (2006)
Bay of Biscay (southern)	−3.5	46.5					−2.65	de la Paz et al. (2010)
Beaufort shelves	−155	72		−2.81			−2.79	Murata and Takizawa (2003), Cai et al. (2006)
Bering Sea shelf	−165	57	−1.2	−0.66			−6.15	Nedashkovsky et al. (1995), Codispoti et al. (1986), Walsh and Dieterle (1994)
Bering Sea shelf	−165.4	56.7					−8	Codispoti et al. (1986)
Bristol Bay	−164	58					−0.2	Borges et al. (2005), Kelley and Hood (1971), Codispoti et al. (1986), Chen (1993), Murata and Takizawa (2003)
Canterbury Bight	170.7	−45.8	−0.64[c]	−0.43[c]	−0.41[c]	−0.37[c]	−0.17	Guilderson et al. (2005)
Chukchi Sea	−165	72.5	−0.05	−2.3	−2.47	−0.04	−5.33	Bates (2006)
Coastal California (Monterey Bay)	−121.9	36.9					0.05	Friederich et al. (2002)
East China Sea (middle)	124	31	−8.8	−4.9	2.9	−10.4	−1.9	Zhai and Dai (2009)
East China Sea (northern)	126	33	−5.04	−2.52	1.9		−0.79	Shim et al. (2007)
East China Sea (southeastern)	125	30	−4.87	−3.32	−5.14	−8.57	−1.45	Wang et al. (2000)
English Channel	−1.2	50.2					−0.15	Borges and Frankignoulle (2003), Thomas et al. (2007)
Funka Bay	140.6	42.3					−7	Nakayama et al. (2000)
Gray's Reef	−80.9	31.4	0.28	−0.35	−0.01	−1.72	−0.16	Sabine et al. (2012)
Great Barrier Reef	145.5	−15					0.33	Kawahata et al. (1999)
Gulf of Biscay	−6.5	49	−6.98	−15.08	−1.43	0.94	−2.88	Frankignoulle and Borges (2001)
Gulf of Cadiz	−6.5	36.75	−0.85	1.45	−0.4	−1.75	−0.16	Ribas-Ribas et al. (2011), Huertas et al. (2006[e])
6WBC−2	−47.4	−25.7		10.87[c]			3.97	Takahashi et al. (2012)
Gulf of Lion	4	43					7.1	de Madron et al. (2010)
Gulf of Mexico shelf (northwest)	−88.6	30.0	−1.35	−0.16	−0.31		−0.22	Sabine et al. (2012)
Gulf of Nicoya	−84.9	9.6			−0.05		−0.02	Pfeil et al. (2013) (SOCAT database)
Gulf of Trieste	13.6	45.7					−2.5	Turk et al. (2010)
Hudson Bay	−85	59		5.43	0.77		0.84	Else et al. (2008)
Ishigaki Island[e]	124.3	24.4	−27		55	25	6.45	Kayanne et al. (2005)
Java Sea	112.9	−5.6	0.26[c]	−0.01[c]	0.07[c]	0.23[c]	0.05	Hydes et al. (2012)
Jiaozhou Bay	120.3	36.15	4.14	19.47	17.07	−0.15	3.7	Li et al. (2007)
Kaneohe Bay	−157.8	21.5					1.45	Fagan and Mackenzie (2007)
Kara Sea	74.0	74.0					0.01	Fransson et al. (2001)
La Push	−125.0	48.0		−1.62	0.14		−0.27	Sabine et al. (2011)
Laptev Sea	130.0	74.0					0.01	Fransson et al. (2001)
Malacca Strait	101.6	2.4	−0.10		0.63		0.10	Hydes et al. (2012)
Mo'orea[e]	−149.9	−17.5		1.5[c]		−1.2[c]	0.05	Frankignoulle et al. (1996), Gattuso et al. (1993)
New Jersey coast	−74.2	39.4					−0.68	Boehme et al. (1998)

Table 5. Continued.

Type	Long. (°)	Lat. (°)	Spring fluxes[b] (mmol C m^{-2} d^{-1})	Summer fluxes (mmol C m^{-2} d^{-1})	Autumn fluxes (mmol C m^{-2} d^{-1})	Winter fluxes (mmol C m^{-2} d^{-1})	Annual flux (mol C m^{-2} yr^{-1})	References
North coast of California	−123.8	39.0		2.52			0.92	Pfeil et al. (2013) (SOCAT database)
North Sea (northern and middle)	2.6	56.7					−1.38	Thomas et al. (2004)
North Sea (southern)	2.5	52.0	−12.47	6.8	4.35	−0.35	−0.7	Schiettecatte et al. (2007), Hoppema (1991)[e]
Northeast coast of Australia	151.5	−23.5	−0.16[c]	0.28[c]	0.04[c]		0.02	Takahashi et al. (2012) (LDEO database)
Northeast Sunda Shelf	105.7	0.7	−0.04		0.28	0.01	0.03	Hydes et al. (2012), Chen (unpublished)
Okhotsk Sea	143.5	44.5		−4.1			−1.67	Chen et al. (2003), Otsuki et al. (2003), Wakita et al. (2003)
Omani coast	59.0	20.0	0.75	−7.13	−0.95	−1.17	−0.9	Goyet et al. (1998)
Oregon coast	−124.5	44.5		−20			−7.3	Hales et al. (2005)
Otaru Bay	141.0	43.3	−8.8	−8.9	7.4	−6.9	−0.78	Sakamoto et al. (2008)
Palau Islands[e]	134.4	7.4		33	49		15.0	Kayanne et al. (2005)
Patagonian Shelf	−65.0	−45.0	−7[c]	−3.8[c]	−2.9[c]	−1[c]	−1.35	Bianchi and Allison (2009)
Prydz Bay	78.9	−68.6				−75[c]	−2.45	Gibson and Trull (1999), Borges et al. (2005), Wang et al. (1998)
Red Sea	42.8	13.4			0.04		0.01	Hydes et al. (2012)
Ross Sea	180.0	−75.0				−13[c]	−1.5	Sweeney (2003), Wang et al. (1998), Bates et al. (1998)
Scotian shelf	−63.0	44.0	1.6	−3.1	−5.9	−8.3	−1.42	Shadwick et al. (2011)
Southeast coast of Australia	152.4	−32.8	−0.74[c]	−0.57[c]			−0.24	Takahashi et al. (2012) (LDEO database)
South China Sea (northern)	116.0	22.0	2.7	7.5	1.4		0.86	Zhai et al. (2005), Zhai et al. (2007)
Sydney coast (Port Hacking time series station)	151.2	−34.1					−0.17	McNeil (2010)
Taiwan St.[e]	120.3	25.0	−17.6				−6.4	Ma et al. (1999)
Vancouver Is. coast	−126.0	49.0					−0.5	Ianson and Allen (2002)
West coast of India	74.0	14.1	0.06		0.03	0.03	0.01	Hydes et al. (2012)
Yellow Sea	122.0	35.5	−4.4	1.8	−4.4	−13	−2.2	Oh et al. (2000), Wang et al. (2001)
Yellow Sea (northern)	122.5	38.5	1.88	3.38	1.39	0.24	1.68	Xue et al. (2012)
Yellow Sea (southern)	122.0	34.5	4.47	1.56	4.85		1.99	Xue et al. (2011)

[a] Positive fluxes indicate an emission of CO_2 from water to the atmosphere.
[b] Spring: March–May; Summer: June–August; Autumn: September–November; Winter: December–February.
[c] Austral seasons.
[d] Not used in the calculation.
[e] LDEO: Lamont-Doherty Earth Observatory; SOCAT: Surface Ocean CO_2 Atlas.

Figure 9 displays a histogram of the reported daily CO_2 fluxes in different seasons and the annual flux for the world's continental shelves. Respiration rates are higher in summer and autumn than in winter and spring (Hopkinson, 1985, 1988; Griffith et al., 1990; Hopkinson and Smith, 2005; Jiang et al., 2010). However, as with estuaries, no seasonality of the numerically averaged flux per unit area on continental shelves is evident, and the values fall between −4.0 and $-5.5\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$, except in autumn, when the flux is only $-0.5\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$. A negative value indicates that the shelves absorb CO_2. The numerically averaged annual mean air-to-sea flux is $-1.09 \pm 2.9\,\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$. Multiplying this value by the total global area of the shelves yields a global flux of $-0.40\,\mathrm{Pg\,C\,yr^{-1}}$, which is slightly less than the published value (Table 7).

Figure 10 presents a histogram of the reported daily fluxes of CO_2 in different latitude bands. Most shelves absorb CO_2 from the atmosphere (negative fluxes) while shelves at low latitudes have a slight tendency to release CO_2 (positive fluxes). This finding is consistent with the work of Cai et al. (2006), who found that shelves at low latitudes between 30° N and 30° S are a source of CO_2 of the order of $0.11\,\mathrm{Pg\,C\,yr^{-1}}$, whereas those in temperate and high-latitude regions are sinks of CO_2 of the order of $0.33\,\mathrm{Pg\,C\,yr^{-1}}$.

Table 6. The pCO_2 and flux method, the gas exchange coefficient and the wind speed in the world's continental shelves.

Type	pCO_2 method	Flux method[a]	Gas exchange coefficient	Wind speed	References[b]
1 NEP	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
10T	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
11EBC	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
11LAB	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
14 NGR	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
14WBC	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
15 SGR	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
16 NOR	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
17EBC	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
20 MED	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
22 MOR	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
26 TWI	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
27WAS	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
28 RED	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
3 TEP	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
31 BEN	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
33 LEE	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
34 SAU	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
39 CSK	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
4 HUM-1	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
4 HUM-2	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
4 HUM-3	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
42 NWP	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
4HUM-4	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
5 SAM	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
6WBC-1	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
6WBC-2	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)

Table 6. Continued.

Type	pCO$_2$ method	Flux method[a]	Gas exchange coefficient	Wind speed	References[b]
8 CAR	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
Amazon River plume	equilibrator/ calculated from DIC & pH	TBL	Liss and Merlivat (1986); Wanninkhof (1992)	on site/COADS wind speed climatology	Ternon et al. (2000), Kortzinger (2003)
Arafura Sea	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
Atlantic Bight (middle)	equilibrator	TBL	Liss and Merlivat (1986); Wanninkhof (1992)	NOAA NDBC buoys	DeGrandpre et al. (2002)
Atlantic Bight (southern)	equilibrator	TBL	Wannikhof (1992); Wanninkhof and McGillis (1999); Nightingale et al. (2000); McGillis et al. (2001); McGillis et al. (2004); Ho et al. (2006)	QuikSCAT	Jiang et al. (2008)
Baltic Sea	equilibrator	TBL	Wanninkhof (1992); Kuss et al. (2004)	weather station/ MARNET data set	Thomas and Schneider (1999); Kuss et al. (2006)
Bass Strait	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
Bay of Biscay (northern)	equilibrator/ calculated from TA & pH	TBL	Liss and Merlivat (1986); Tans et al. (1990); Wanninkhof (1992)	on site	Borges et al. (2006)
Bay of Biscay (southern)	equilibrator	TBL	Wanninkhof (1992)	NCEP/NCAR Reanalysis	de la Paz et al. (2010)
Beaufort shelves	equilibrator	TBL	Liss and Merlivat (1986); Wanninkhof (1992); Wannkhof and McGillis (1999); Nightingale et al. (2000)	on site	Murata and Takizawa (2003); Cai et al. (2006)
Bering Sea shelf	equilibrator	TBL	Broecker et al. (1980); Broecker and Peng (1982)	–	Nedashkovsky et al. (1995); Codispoti et al. (1986); Walsh and Dieterle (1994)
Bering Sea shelf	equilibrator	TBL	Broecker et al. (1980)	–	Codispoti et al. (1986)
Bristol Bay	equilibrator/ calculated from TA & pH	TBL	Broecker et al. (1980); Liss and Merlivat (1986); Wanninkhof (1992); Wannkhof and McGillis (1999); Nightingale et al. (2000)	on site	Borges et al. (2005) based on Kelly and Hood (1971); Codispoti et al. (1986), Chen (1993); Murata and Takiwaza (2003)
Canterbury Bight	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Chukchi Sea	calculated from DIC & TA	TBL	Wannikhof (1992)	NCEP/NCAR Reanalysis	Bates (2006)
Coastal California (M-1; Monterey Bay)	equilibrator	TBL	Wanninkhof and McGillis (1999)	on site	Friederich et al. (2002)
East China Sea (middle)	equilibrator	TBL	Wannikhof (1992)	on site	Zhai and Dai (2009)
East China Sea (northern)	equilibrator	TBL	Liss and Merlivat (1986); Wanninkhof (1992)	on site/QuikSCAT	Shim et al. (2007)
East China Sea (southeastern)	equilibrator	TBL	Liss and Merlivat (1986); Tans et al. (1990); Wanninkhof (1992)	on site	Wang et al. (2000)
English Channel	equilibrator	TBL	Nightingale et al. (2000)	PFEL/FNMOC	Borges and Frankignoulle (2003); Thomas et al. (2008)
Funka Bay	calculated from DIC & pH	–	estimated from the δ^{13}C budget	–	Nakayama et al. (2000)
Gray's Reef	equilibrator	TBL	Wannikhof (1992)	WindSat	Sabine et al. (2012)
Great Barrier Reef	equilibrator	TBL	Liss and Merlivat (1986); Wanninkhof (1992)	on site	Kawahata et al. (2000)
Gulf of Biscay	equilibrator	TBL	Liss and Merlivat (1986); Tans et al. (1990); Wanninkhof (1992)	on site	Frankignoulle and Borges (2001)
Gulf of Cadiz	equilibrator	TBL	Wannikhof (1992)	buoy	Ribas-Ribas et al. (2010)
Gulf of Lion	–	–	–	–	de Madron et al. (2008)
Gulf of Maine	equilibrator	TBL	Wannikhof (1992)	NDBC station	Salisbury et al. (2009)
Gulf of Mexico shelf (northwest)	equilibrator	TBL	Wannikhof (1992)	WindSat	Sabine et al. (2012)
Gulf of Nicoya	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
Gulf of Trieste	equilibrator	TBL	Wannikhof (1992)	buoy	Turk et al. (2010)
Hudson Bay	equilibrator	TBL	Wannikhof (1992)	Nightingale et al. (2000); NCEP/NCAR Reanalysis	Else et al. (2008)

Table 6. Continued.

Type	$p\text{CO}_2$ method	Flux method[a]	Gas exchange coefficient	Wind speed	References[b]
Java Sea	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
Jiaozhou Bay	calculated from DIC & pH	TBL	Wanninkhof (1992)	weather station	Li et al. (2007)
Kaneohe Bay	equilibrator/ calculated from DIC & TA	TBL	Liss and Merlivat (1986); Wanninkhof (1992); Wannkhof and McGillis (1999); Nightingale et al. (2000)	weather station	Fagan and Mackenzie (2007)
Kara Sea	–	Redfield ratio	–	–	Fransson et al. (2001)
La Push	equilibrator	TBL	Wannikhof (1992)	WindSat	Sabine et al. (2011)
Laptev Sea	–	Redfield ratio	–	–	Fransson et al. (2001)
Malacca Strait	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
New Jersey coast	equilibrator	TBL	Liss and Merlivat (1986); Tans et al. (1990); Wanninkhof (1992)	buoy	Boehme et al. (1998)
Northern coast of California	equilibrator	TBL	Wannikhof (1992)	WindSat	Pfeil et al. (2012) (SOCAT database)
North Sea (northern and middle)	equilibrator	TBL	Wannkhof and McGillis (1999)	The European Centre for Medium-Range Weather Forecasts	Thomas et al. (2004)
North Sea (southern)	equilibrator	TBL	Wannikhof (1992); Wanninkhof and McGillis (1999); Nightingale et al. (2000)	weather station	Schiettecatte et al. (2007)
Northeast coast of Australia	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
Northeast Sunda Shelf	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012); Chen (unpublished)
Okhotsk Sea	calculated from DIC & TA	TBL	Wanninkhof (1992)	–	Chen et al. (2003); Otsuki et al. (2003); Wakita et al. (2003)
Omani coast	equilibrator	TBL	Wannikhof (1992)	FNMOC	Goyet et al. (1998)
Oregon coast	equilibrator	TBL	McGillis et al. (2001)	buoy	Hales et al. (2005)
Otaru Bay	calculated from DIC & TA	TBL	Wanninkhof et al. (1999)	weather station	Sakamoto et al. (2008)
Patagonian shelf	equilibrator	TBL	Ho et al. (2006)	QuikSCAT	Bianchi et al. (2009)
Prydz Bay	calculated from DIC & pH/ equilibrator	TBL	Wannikhof (1992)	weather station	Gibson and Trull (1999); Borges et al. (2005); Wang et al. (1998)
Red Sea	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
Ross Sea	equilibrator	TBL	Wannikhof (1992)	NCEP/NCAR Reanalysis	Sweeney (2003); Wang et al. (1998); Bates et al. (1998)
Scotian shelf	equilibrator	TBL	Wannikhof (1992)	weather station	Shadwick et al. (2011)
Southeast coast of Australia	equilibrator	TBL	Wannikhof (1992)	WindSat	Takahashi et al. (2012) (LDEO database)
South China Sea (northern)	equilibrator	TBL	Wannikhof (1992); Raymond and Cole (2001); Borges et al. (2004)	on site	Zhai et al. (2005, 2007)
Sydney coast (Port Hacking time series station)	calculated from DIC & TA	TBL	–	weather station	McNeil (2010)
Taiwan St.	–	–	–	–	Ma et al. (1999)
Vancouver Is. coast	calculated from DIC & TA	TBL	Wannikhof (1992)	Faucher et al. (1999)	Ianson and Allen (2002)
West coast of India	calculated from DIC & TA	TBL	Wanninkhof (1992)	WindSat	Hydes et al. (2012)
Yellow Sea	equilibrator	TBL	Wannikhof (1992)	Na et al. (1992)	Oh et al. (2000); Wang et al. (2001)
Yellow Sea (northern)	equilibrator	TBL	Wannikhof (1992)	QuikSCAT	Xue et al. (2012)
Yellow Sea (southern)	equilibrator	TBL	Wannikhof (1992)	QuikSCAT	Xue et al. (2011)

[a] TBL: thin boundary layer method; FCM: floating chamber method.
[b] LDEO: Lamont-Doherty Earth Observatory; SOCAT: Surface Ocean CO_2 Atlas.

Table 7. Summary of reported annual global air–sea CO_2 fluxes in the world's continental shelves.

CO_2 sink in the coastal ocean (Pg C yr^{-1})	References
−1.00	Tsunogai et al. (1999)
−0.10	Liu et al. (2000)
0.50	Fasham et al. (2001)
−0.60	Yool and Fasham (2001)
−0.24	Rabouille et al. (2001)
−0.30	Chen et al. (2003)
−0.36	Chen (2004)
−0.40	Thomas et al. (2004)
−0.90	Ducklow and McCallister (2004)
−0.37	Borges (2005)
−0.45	Borges et al. (2005)
−0.22	Cai et al. (2006)
−0.33 to −0.36	Chen and Borges (2009)
−0.21	Laruelle et al. (2010)
−0.25	Cai (2011)
−0.40	This study

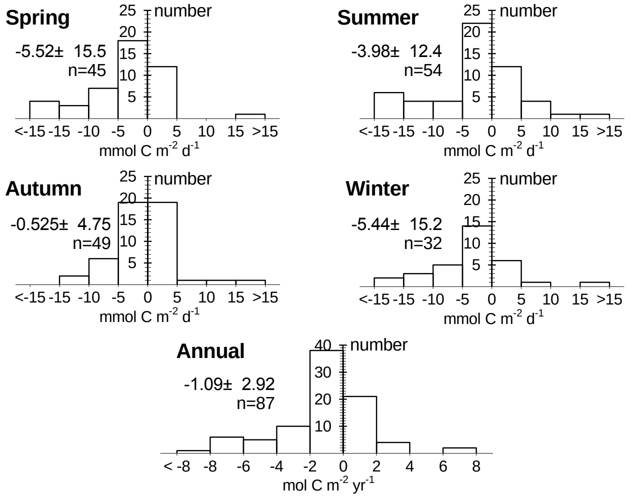

Fig. 9. Histogram of reported daily CO_2 fluxes in different seasons and annual flux on the world's continental shelves.

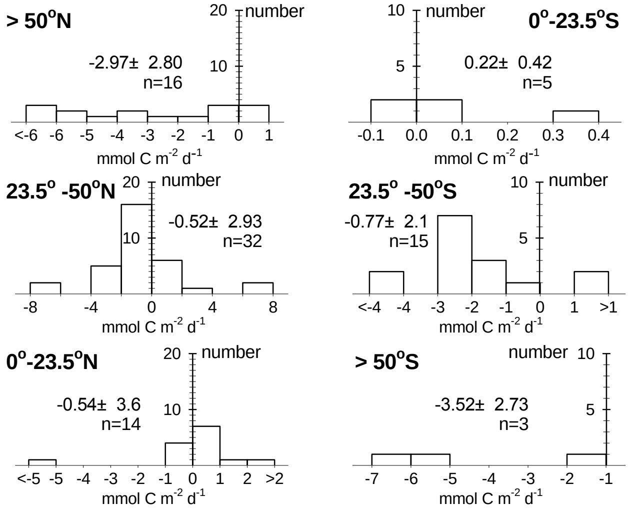

Fig. 10. Histogram of reported annual CO_2 fluxes of continental shelves in various latitude bands.

The CO_2 flux per unit area is highest on the South American shelves (−3.6 mol C m^{-2} yr^{-1}), but since their total area is moderate, the South American shelves absorb the second largest amount of CO_2 from the atmosphere annually at −103.5 Tg C yr^{-1}, or 26 % of the global shelf absorption.

Asian shelves have the highest total area, but their numerically averaged flux per unit area (−0.13 mol C m^{-2} yr^{-1}) is the lowest of all, primarily because of the generally low wind speed and because some shelves release rather than absorb CO_2. The total annual flux from Asian shelves is only −22 Tg C yr^{-1}, or 5 % of the global absorption by all shelves. North American shelves rank second in terms of both numerically averaged flux per unit area (−2.1 mol C m^{-2} yr^{-1}) and shelf area. Accordingly, North American shelves absorb the most CO_2 from the atmosphere at −156 Tg C yr^{-1}, or 39 % of the global absorption by all shelves. Shelves around Antarctica have the third highest numerically averaged flux per unit area (−2.0 mol C m^{-2} yr^{-1}) and the third largest total shelf area, resulting in the third highest total annual flux at −70 Tg C yr^{-1}, or 18 % of the global absorption (Fig. 11). Unfortunately, data are available for only two such shelves.

Figure 12 shows the total CO_2 flux per unit area and the total CO_2 flux from shelves in different oceans. Two shelves in the Southern Ocean have the highest numerically averaged flux per unit area (−2 mol C m^{-2} yr^{-1}) with a total annual flux of −70 Tg C yr^{-1}, or 18 % of the global shelf absorption. The second highest flux per unit area is that of shelves in the Arctic Ocean (−1.8 mol C m^{-2} yr^{-1}), which also have the second highest total flux at −129 Tg C yr^{-1}, or 33 % of the global absorption. Shelves in the Atlantic Ocean have the highest total absorption (−130 Tg C yr^{-1}, or 33 % of the global absorption), the third highest numerically averaged flux per unit area (−1.2 mol C m^{-2} yr^{-1}) and the second highest total shelf area. The largest shelf area is that of the shelves around the Pacific Ocean, but since the numerically averaged flux per unit area is low (−0.4 mol C m^{-2} yr^{-1}), their total absorption is only −49 Tg C yr^{-1}, or 12 % of global absorption. Shelves around the Indian Ocean have the least total area and the second lowest numerically averaged flux per unit area (−0.6 mol C m^{-2} yr^{-1}), resulting in the lowest total flux (−18 Tg C yr^{-1}, or only 4 % of the global absorption). In total, the world's shelves absorb 396 Tg C yr^{-1}, or 0.396 Pg C yr^{-1}.

The shift from the sinking of CO_2 at higher latitudes to acting as a weak source at lower latitudes is explained by four major factors. The first is that waters on continental shelves

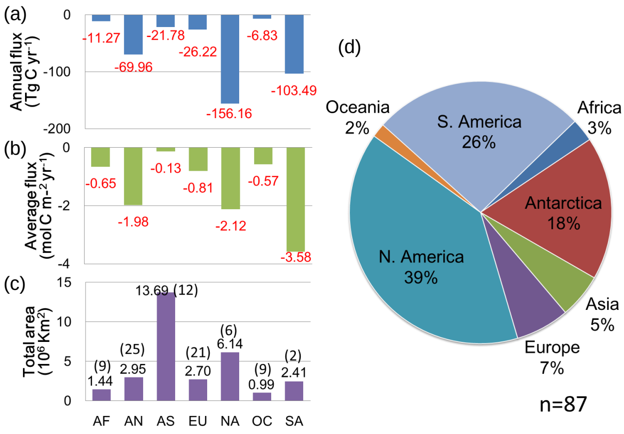

Fig. 11. Annual CO_2 flux **(a)**, average CO_2 flux per unit area **(b)**, total surface area **(c)**, and percentage of total CO_2 flux **(d)** from continental shelves in different continents. Numbers in parentheses indicate the number of estuaries studied.

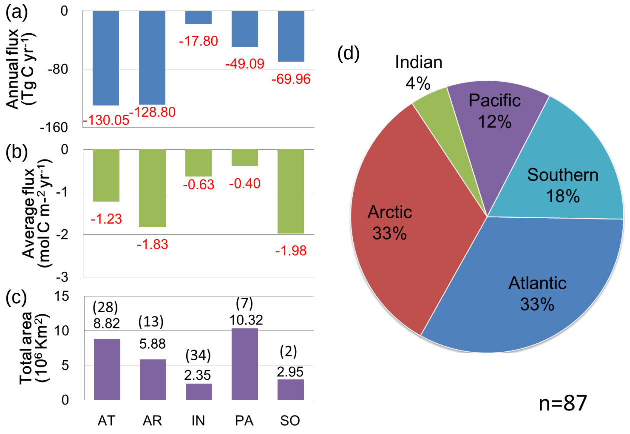

Fig. 12. Annual CO_2 flux **(a)**, average CO_2 flux per unit area **(b)**, total surface area **(c)**, and percentage of total CO_2 flux **(d)** from continental shelves in different oceans. Numbers in parentheses indicate the number of estuaries studied.

are mostly dominated by the open oceans, as revealed simply by the salinity of most shelves, which is only slightly lower than that of the open ocean waters, except close to the estuaries. For example, for a shelf with 10 % input from rivers with a salinity of 0.5 and a $p\mathrm{CO}_2$ of 1000 µatm, and 90 % input from open oceans with a salinity of 35 and a $p\mathrm{CO}_2$ of 300 µatm, the resulting salinity (S) is 31.55. For the sake of argument, the $p\mathrm{CO}_2$ of this $S = 31.55$ shelf water is approximately 370 µatm, depending on the alkalinity of the river water. Restated, mixing with open ocean waters with low $p\mathrm{CO}_2$ causes the $p\mathrm{CO}_2$ of river water with high $p\mathrm{CO}_2$ to be reduced to below saturation. Notably, open ocean waters at high latitudes are frequently undersaturated, and open ocean waters at low latitudes are frequently supersaturated (Takahashi et al., 2002; Kaltin et al., 2002; Kaltin and Anderson, 2005; Chen et al., 2006a, b, 2008a, b; Ciais et al., 2008). Therefore, mixing with open ocean waters at high latitudes helps shelf waters become undersaturated, whereas mixing with open ocean waters at low latitudes frequently yields shelf waters that are still supersaturated (Hidalgo-Gonzalez et al., 1997; Ito et al., 2005; Cai et al., 2006; Chen et al., 2008a, 2012).

The second factor that contributes to the supersaturation of shelf waters at low latitudes is temperature because $p\mathrm{CO}_2$ increases by 4.3 % for an increase of 1 °C (Bakker et al., 1999; Takahashi et al., 2002). Simply increasing by 15 °C, the temperature of the shelf water with a $p\mathrm{CO}_2$ of 370 µatm in the example given above would result in a $p\mathrm{CO}_2$ of above 600 µatm, if all other factors are held constant. Notably, the difference between the temperatures of shelves at high-latitude shelves and those at low latitude commonly exceeds 15 °C. Temperature similarly affects open ocean water, so not only do warm temperatures increase the $p\mathrm{CO}_2$ of shelf waters but also these waters also mix with open ocean waters with higher $p\mathrm{CO}_2$, mainly because they are hotter than open oceans at high latitudes. The proximal shelves in waters with a depth of, say, less than 40 m, typically exhibit a greater seasonal range of water temperatures than the distal shelves with a water depth of between 40 and 200 m. The effect of temperature on the $p\mathrm{CO}_2$ of proximal shelf waters is thus greater than that of distal shelf waters. Unfortunately, the readily available $p\mathrm{CO}_2$ data do not suffice for a meaningful synthesis. As a matter of fact, for navigational or geopolitical reasons, $p\mathrm{CO}_2$ is rarely measured along the coast, or the data are frequently not disclosed.

The third factor in affecting $p\mathrm{CO}_2$ on shelves is the fact that the discharge of organic matter by rivers is higher at lower latitudes. As much as 60 % of the riverine organic carbon discharge to the shelves occurs between 30° N and 30° S (Walsh, 1988; Ludwig et al., 1996a, b; Borges et al., 2005). The total amount is approximately 0.3 Pg C yr^{-1}, most of which is decomposed in the continental margins (McKee, 2003; Cai et al., 2006). Importantly, however, the cited studies did not identify the recipient of the riverine export. As indicated above, a significant fraction of the export is decomposed in the estuaries and does not reach the shelves (Hofmann et al., 2011; Chen et al., 2012).

The fourth factor that is responsible for the higher $p\mathrm{CO}_2$ in shelves at lower latitudes involves lower biological productivity. Shelves at mid- and high latitudes are generally highly productive, whereas those at low latitudes, especially the non-upwelling shelves, are typically oligotrophic. The more effective biological pumping in the shelves at mid- and high latitudes causes these shelves to have lower $p\mathrm{CO}_2$.

4 Temporal changes

Although efforts have been made to evaluate the parameters that affect the carbon cycle and to model past and future changes in carbon fluxes (Friederich et al., 2002; Fransson et al., 2006; Macpherson et al., 2008; Ver et al., 1999b, a; Mackenzie et al., 2000, 2004; Thomas et al., 2007; Borges, 2011), whether the size of the estuarine source and the continental shelf sink for CO_2 changes with time has not been determined because too few data are available. As stated above, the fact that the shelves are a sink rather than a source of CO_2 has only been established in the last few years. The conclusion of LOICZ that the coastal seas are a source of CO_2 (Crossland et al., 2005) was not based on data. Rather, it was based on the reasoning that since rivers transport more organic carbon to the oceans than is buried in the sediments, the oceans must be releasing the remaining CO_2 back to the atmosphere (Smith and Mackenzie, 1987; Smith and Hollibaugh, 1993). However, the amount of organic carbon that is actually transported to the oceans after it passes through the estuaries is not clear, as mentioned above.

Before industrialization, more organic carbon may well have reached the oceans than accumulated in the sediments, such that the oceans were overall a source of CO_2. However, whether the CO_2 was released in the coastal oceans or in the open oceans remains unclear. Further, the increasing CO_2 in the atmosphere must have reduced the difference between the $p\text{CO}_2$ of the atmosphere and that of the oceans, even if the oceans used to be supersaturated with CO_2 before industrialization. In any case, the present data clearly demonstrate that the coastal oceans are a sink of CO_2. Whether a threshold has been crossed or whether the metabolism of the ecosystem has been changed cannot yet be determined (Mackenzie et al., 2004).

Interestingly, heterotrophic systems are commonly treated as CO_2 sources while autotrophic systems are considered to be CO_2 sinks (Walsh et al., 1981; Smith and Hollibaugh, 1993; Ducklow and McCallister, 2004). This assumption is usually true but must be applied with caution. For instance, if a shelf is regarded as a system, then it can be heterotrophic overall. However, its surface layer may still be undersaturated owing to cooling or biological production, and so it absorbs CO_2 from the atmosphere. Alternatively, the DOC or POC that is produced in the surface layer, or imported from rivers and submarine groundwater discharge, decomposes in the deep layer. As long as more CO_2 is generated in the deep layer than is taken up by the surface layer, the shelf as a whole will remain heterotrophic.

5 Future changes in carbon fluxes

Increasing air temperature (Belkin, 2009) tends to increase precipitation and continental runoff. These processes enhanced rock weathering during the last century (Probst et al., 1994). Intuitively, this fact suggests an increased export of carbon by rivers, but whether the global river runoff has increased is uncertain (Dai et al., 2011; Syed et al., 2010). The construction of dams around the world has caused a substantial fraction of exported sediment to be impounded in recent decades (Chen, 2002; Syvitski et al., 2005). A related issue is that global warming is warming the oceans as well. The global mean sea surface temperature has reportedly risen by 0.67 °C over the last century (IPCC, 2007; Trenberth et al., 2007). The most rapid warming, two to four times the global average of 0.177 °C per decade between 1981 and 2005, has been observed in the landlocked or semi-enclosed European and East Asian seas, including the Baltic, North, Black, Japan and East China seas as well as over the Newfoundland–Labrador Shelf (Belkin, 2009). The thermodynamics of seawater dictates that for each 1 °C rise in temperature, the $p\text{CO}_2$ increases by 4 %, or approximately 14 µatm. This fact would compensate for some of the increase in CO_2 in the atmosphere, which is of the order of 18 µatm per decade. With increasing atmospheric CO_2 concentration, the $p\text{CO}_2$ difference between the air and the shelf seawater will become larger. This is to the advantage of absorbing atmospheric CO_2 in coastal seas, and even some CO_2-emitting regions may start to absorb CO_2. A related issue is that the eutrophicated coastal area is growing due to human activities such as excessive nutrient inputs and enhanced soil erosion on land (Brush, 2009; Smith and Schindler, 2009). Values of pH in the coastal seawater will drop faster than in the open ocean because decomposition of terrestrial organic material increases the total alkalinity but reduces the buffering capacity (Chen et al., 1982; Cai et al., 2011). Further, certain species of phytoplankton may grow better in a high-CO_2 environment (Riebesell and Tortell, 2011), hence deterring the increasing trend of atmospheric CO_2 in general. These effects, however, are beyond the scope of this study.

6 Conclusions

Data from 165 estuaries and 87 continental shelves around the globe have been evaluated to show that the world's estuaries release 0.094 Pg C yr^{-1} to the atmosphere. This value is substantially lower than any published values mainly because of the newly available data in Asia, which has low wind speed in general, and hence low per unit area flux. In addition, new data in the polar regions indicate that estuaries there may absorb instead of release CO_2. Overall, the world's continental shelves absorb 0.4 Pg C yr^{-1} from the atmosphere, which is in line with published data.

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