Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide

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It has been speculated that the partial pressure of carbon dioxide ($p_{CO_2}$) in shelf waters may lag the rise in atmospheric $CO_2$. Here, we show that this is the case across many shelf regions, implying a tendency for enhanced shelf uptake of atmospheric $CO_2$. This result is based on analysis of long-term trends in the air–sea $p_{CO_2}$ gradient ($\Delta p_{CO_2}$) using a global surface ocean $p_{CO_2}$ database spanning a period of up to 35 years. Using wintertime data only, we find that $\Delta p_{CO_2}$ increased in 653 of the 825 $0.5^\circ$ cells for which a trend could be calculated, with 325 of these cells showing a significant increase in excess of $+0.5 \mu atm yr^{-1}$ ($p < 0.05$). Although noisier, the deseasonalized annual data suggest similar results. If this were a global trend, it would support the idea that shelves might have switched from a source to a sink of $CO_2$ during the last century.

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The atmospheric partial pressure of CO$_2$ (pCO$_2$$_{air}$) has been increasing at a rate of about 1.8 parts per million by volume (ppmv) per year in recent decades as a result of human activities such as burning of fossil fuel, deforestation, and cement production. Although substantial regional and decadal variability has been observed, surface water pCO$_2$ levels tended to have followed more or less those of the atmosphere, particularly in the open ocean. This tracking trend is best shown by the data collected at regular intervals at a few ocean time series stations, which by now cover more than 30 years. The close atmospheric tracking of surface water pCO$_2$ is a consequence of the relatively long water residence time of the global surface ocean, with a time scale of more than a year, which is longer than an air–sea CO$_2$ exchange time scale of about 10 months. However, it is not clear whether surface water pCO$_2$ on continental shelves, defined here as shallow regions with depths between 20 and 200 m that exclude the very nearshore areas (see “Methods” section for details), also track the atmospheric pCO$_2$ increase.

Our current understanding of the long-term trend in shelf pCO$_2$ is very limited because it largely relies on observations from a few time series only with records much shorter than those in the open ocean. Furthermore, pCO$_2$ in shelf regions is characterized by high temporal and spatial variability, making trend analyses more demanding. The recent development of the community-driven global ocean pCO$_2$ data product SOCAT (for Surface Ocean CO$_2$ Atlas) now offers a complementary approach to reconstructing the evolution in the data coverage remains sparse within SOCAT, it allows discerning when combining all observational evidence. In what follows, we briefly review the current state of knowledge regarding shelf CO$_2$ dynamics and then propose novel observational evidence of rates of change in the air–sea pCO$_2$ gradient from the analysis of the SOCAT database.

Syntheses in the recent decade suggest that, globally, continental shelves currently absorb atmospheric CO$_2$ at a rate of about 0.2 Pg C annually. Despite great local variability, the data also suggest that mid- to high-latitude shelves are generally a sink of CO$_2$, while warm tropical shelves are a moderate source of CO$_2$. A broad consensus regarding the current strength of the global shelf CO$_2$ sink and its large-scale spatial variability has thus recently emerged. In particular, continuous high-resolution pCO$_2$ maps for continental shelf seas derived from the interpolation of experimental data clearly support this spatial trend in all oceanic basins. However, much less is known regarding decadal trends and associated variability in shelf CO$_2$ sources and sinks across the globe.

The limited pCO$_2$ time series obtained from coastal sites provide mixed evidence for the size of the decadal trends. Bates and co-authors reported for the coastal stations Mundia and Iceland Sea small long-term rates of increase in pCO$_2$ (+1.3 µatm yr$^{-1}$), i.e., rate that are lower than that of the atmosphere, while they show that the stations Irminger and CARIACO have rates as high as +2.4 and +2.9 µatm yr$^{-1}$, respectively (Table 1). A shorter time series at the SEATS station in the South China Sea over the 1999–2003 period reveals an even faster increase in pCO$_2$ with a rate of +4.2 µatm yr$^{-1}$. While illustrative, such trends from a handful of locations do not allow drawing any conclusion regarding the overall change in the shelf air–sea pCO$_2$ gradient over time.

Some data-driven regional analyses have also attempted to decipher the rate of pCO$_2$ increase in continental shelf settings. Data from two large semi-enclosed shelf seas (North Sea and Baltic Sea) and from the Bering Sea suggest that continental shelves may exhibit a rapid increase in pCO$_2$ toward atmospheric values, thus lowering the air–sea pCO$_2$ gradient over time (Table 2). In contrast, another study in the North Sea and reports from the warm Caribbean Sea (mostly from areas deeper than the shelf depths as defined here), the coast of Japan, West Antarctic Peninsula, and the Scotia shelf, showed that the sea surface pCO$_2$ increase lags well behind that of the atmosphere, making the areas either an increased sink (Pacific coast of Japan, Coast West Antarctic Peninsula, and Puerto Rico) or a decreased source (Scotian shelf) for atmospheric CO$_2$. However, a recent study suggests that the Japanese margin as a whole roughly tracks the atmospheric CO$_2$ increase. Overall, these regional analyses highlight that trends in CO$_2$ sources and sinks appear highly variable both within the same shelf and across different shelf systems.

Researchers have also attempted to use models to investigate the change in shelf–air–water CO$_2$ exchange. Using a box model, Mackenzie and co-workers were the first to suggest that shelves may have turned from a CO$_2$ source in the preindustrial time to a sink at present and that the CO$_2$ uptake rate would increase with time. Consistent with these predictions, Bauer et al. and Caï also provided a conceptual model and suggested an increasing global shelf CO$_2$ sink with time as a result of the atmospheric pCO$_2$ increase. Recently, an eddy-resolving global model was used to simulate the flux of anthropogenic CO$_2$ into the coastal ocean. This latter model can be viewed as an open ocean model extended to the coast that lacks a few, but important processes in the nearshore environments. In particular, the global model lacks detailed sediment interactions, the handling of river fluxes, and

### Table 1 Rates of change in pCO$_2$ and corresponding rate of change in ΔpCO$_2$ reported in the literature for coastal time series stations

| Region          | pCO$_2$ trend (µatm yr$^{-1}$) | ΔpCO$_2$ trend (µatm yr$^{-1}$) | Period   | Comment                                | Reference               |
|-----------------|--------------------------------|---------------------------------|----------|----------------------------------------|-------------------------|
| Mundia          | 1.28 ± 0.33                     | Increase                        | 1988-2011| Outside of our shelf definition        | Bates et al.            |
| Hawaii (HOT)    | 1.72 ± 0.09                     | Steady                          | 1988-2011| Outside of our shelf definition        | Bates et al.            |
| BATS            | 2.0 ± 0.5                       | Steady                          | 1983-2013| Outside of our shelf definition        | Wang et al.             |
| ESTOC           | 1.69 ± 0.11                     | Steady                          | 1983-2011| Outside of our shelf definition        | Bates et al.            |
| Irminger Sea    | 1.9 ± 0.2                       | Steady                          | 1991-2011| Outside of our shelf definition        | Wang et al.             |
| CARIACO         | 1.92 ± 0.24                     | Steady                          | 1995-2011| Outside of our shelf definition        | Bates et al.            |
| South China Sea (SEATS) | 2.37 ± 0.49               | Decrease                        | 1983-2011| Outside of our shelf definition        | Bates et al.            |
| Iceland Sea (year) | 4.2 ± 3.2               | Decrease (-2.6)               | 1999-2003| Outside of our shelf definition        | Tseng et al.            |
|                 | 1.29 ± 0.36                     | Increase                        | 1995-2008| Outside of our shelf definition        | Bates et al.            |
shallow calcification processes, which were captured in the spatially and temporally crude box model, however bolstered. Nonetheless, both approaches consistently show that the shelf water CO₂ uptake increases with increasing atmospheric CO₂ levels. However, no consensus emerges as to whether past and future decadal trends in shelf CO₂ accumulation may be reversed by air-sea exchange with the open ocean, and consequently the strongest impact on the global ocean CO₂ accumulation. This results in trends that tend to be clearer. We check on these wintertime analyses also with results from an analysis using deseasonalized data for all seasons, confirming that our choice for wintertime only does not result in artefacts. However, this does not suggest that winter contributes more than other seasons to the overall annual trend.

## Results

### Regional trends in ΔpCO₂

The results presented in our regional and global analyses are primarily derived from wintertime data when photosynthetic activity is generally the weakest, and when coastal ocean waters have the most intensive exchange with the open ocean, and consequently the strongest impact on the global ocean CO₂ accumulation. This results in trends that tend to be clearer. We check on these wintertime analyses also with results from an analysis using deseasonalized data for all seasons, confirming that our choice for wintertime only does not result in artefacts. However, this does not suggest that winter contributes more than other seasons to the overall annual trend.

### Table 2 Rates of change in pCO₂ and corresponding rate of change in ΔpCO₂ in different regions reported in the literature for continental shelf waters

| Region                          | pCO₂ trend (μatm yr⁻¹) | ΔpCO₂ trend (μatm yr⁻¹) | Period  | Comment                                                                 | Reference          |
|---------------------------------|------------------------|-------------------------|---------|------------------------------------------------------------------------|--------------------|
| North Sea                       |                        |                         |         |                                                                        |                    |
| Summer                          | 7.9                    | Fast decrease           | 2001-2005 | Both studies only compare summertime pCO₂ normalized to 16 °C for different summers | Thomas et al.²⁰, Salt et al.²² |
| Summer                          | 6.5                    | Fast decrease           | 2001-2005 |                                                                        | Salt et al.²²      |
| Summer                          | 1.33                   | Slow increase           | 2005-2008 | Interannual variations in pCO₂ minima are controlled by maximum concentration of phosphate in winter | Wesslander et al.³² |
| Baltic Sea                      |                        | Decrease                | 1994-2008 |                                                                        |                    |
| Puerto Rico                     |                        |                         |         |                                                                        |                    |
| All year                        | 1.11 ± 0.35            | Increase (+0.74)        | 2002-2009 | Increase in pCO₂ attributed to abnormally high primary production       | Park and Wanninkhof²³ |
| Summer                          | 1.57 ± 0.86            | Increase (+0.47)        | 2002-2009 |                                                                        | Park and Wanninkhof²³ |
| Winter                          | 0.17 ± 1.23            | Increase (+1.88)        | 2002-2009 |                                                                        | Park and Wanninkhof²³ |
| Bering Sea                      |                        |                         |         |                                                                        |                    |
| Basin                           | 6.5 ± 1.4              | Decrease (−6.0)         | 1995-2001 | Increase in pCO₂ attributed to abnormally high primary production       | Fransson et al.⁵¹  |
| Shelf slope                     | 11 ± 1.9               | Decrease (−10.0)        | 1995-2001 |                                                                        | Fransson et al.⁵¹  |
| Coast of Japan                  | 1.54 ± 0.33            | Increase (+0.45)        | 1994-2008 |                                                                        | Ishii et al.²⁴     |
| Tasmanian Coast                 | 2.1 ± 0.6              | Steady                  | 1992-2013 |                                                                        | Wang et al.²⁷      |
| European Margins                | 1.9 ± 0.7              | Steady                  | 1989-2014 | Increase in pCO₂ is explained by sea surface temperature increase      | Borges et al.⁴⁸    |
| Antarctic Peninsula             |                        |                         |         |                                                                        |                    |
| Summer                          | 1.45 ± 2.97            | Increase (+0.45)        | 1999-2013 |                                                                        | Hauri et al.²⁵     |
| Fall                            | 1.90 ± 0.95            | Steady                  | 1999-2013 |                                                                        | Hauri et al.²⁵     |
| Winter                          | 0.43 ± 0.77            | Increase (+1.47)        | 1999-2013 |                                                                        | Hauri et al.²⁵     |
| Spring                          | 1.22 ± 2.72            | Increase (+0.68)        | 1999-2013 |                                                                        | Shadwick et al.²⁶  |
| Scotia Shelf                    | Not reported           | Increase (+2.3)         | 1999-2008 | The increase in ΔpCO₂ is attributed to an increase of 1.3 °C in sea surface temperature |                    |
of the cells contained in our narrow and wide definitions of the shelf, respectively (see “Methods” section for details). Most regions display variable, but relatively consistent values of $\Delta CO_2/dt$. Only the Baltic Sea and the Mid-Atlantic Bight show a significant but continuous spatial gradient in the trend within their respective domains. With the exception of the Labrador Sea, regional analyses of the air–sea CO$_2$ exchange have been published for each of the areas presented here, but estimates of $\Delta CO_2/dt$ have only been reported for 9 out of the 15 regions (Table 3).

The highest positive $\Delta CO_2/dt$, with an average rate of change of $+2.9 \pm 2.4$ μatm yr$^{-1}$, occurs in the Baltic Sea (Fig. 1a). This rate of increase in ΔCO$_2$ is higher than the atmospheric pCO$_2$ increase rate and, therefore, surface water pCO$_2$ actually decreases over time, most likely as a result of increased anthropogenic nutrient inputs and resultant increases in coastal productivity in this semi-isolated inland sea, which affect the biogeochemistry of the Baltic Sea all year long$^{32}$. Our results are consistent with a recent study that the Baltic Sea is a decreasing source of CO$_2$ to the atmosphere$^{32}$. The North Sea (Fig. 1b), the Mid-Atlantic Bight (Fig. 1c), Southern Greenland, and Antarctic Peninsula (Fig. 1d) have $\Delta CO_2/dt$ values averaging close to $+2$ μatm yr$^{-1}$ with $\sigma$ of 1.2–1.5 μatm yr$^{-1}$, except for the Mid-Atlantic Bight, which has more spatial heterogeneity ($\sigma = 3.1$ μatm yr$^{-1}$). Therefore, their water pCO$_2$ values do not increase with time or increase at a rate substantially lower than that of pCO$_2_{air}$ (Table 3). The results for the North Sea contrast sharply with an earlier report based on two sets of summertime data (2005 vs. 2001), which suggested that the North Sea pCO$_2$ increased at a rate five times faster than the atmosphere$^{20}$. A more recent study, however, also comparing summertime pCO$_2$ between the years 2001, 2005, and 2008 revealed a large increase of 26 μatm between 2001 and 2005, but only a moderate increase of 4 μatm between 2005 and 2008$^{22}$. These disparate results support the idea that summertime pCO$_2$ is more affected by the short-term imbalance of biological production and respiration, whereas wintertime reflects better the long-term trend in air–sea exchange due to reduced biological activities. The increase in the CO$_2$ uptake by Greenland coastal waters reported here is in agreement with Yasunaka et al.$^{35}$. Along the East coast of the United States, the Mid-Atlantic Bight is a typical western boundary current margin with intense exchange of water between the shelf and the deep ocean at a frequency of about once every 3 months and is also influenced by anthropogenic nutrient inputs and eutrophication$^{31,34}$. A previous study suggested that the annual thermal cycle combined with high winds during wintertime dominates annual CO$_2$ uptake in this region$^{35}$. $\Delta CO_2/dt$ ranging from values >$+5$ μatm yr$^{-1}$ in the north of the region to <$-2$ μatm yr$^{-1}$ in the south could be a consequence of very different hydrodynamic characteristics along this coastal setting. The southern part of the region is under the influence of coastal currents and large estuaries (e.g., Chesapeake Bay) that effectively filter terrestrial organic carbon inputs$^{36,37}$, while the northern part is characterized by significantly colder water from the Labrador Sea all year long$^{38}$. The Antarctic margins, such as those along the Antarctic Peninsula, are dominated by an intense exchange with deep water masses and it appears that the rate of CO$_2$ uptake is driven mainly by the strength of the upwelling and low-surface temperature$^{39}$. The high $\Delta CO_2/dt$ along the West Antarctic Peninsula is consistent with another study$^{22}$, which also suggested that winter is the season for which the rate of increase in ΔCO$_2$ is the fastest. Additionally, a general strengthening of the Southern Ocean CO$_2$ sink has been recognized over the past decade$^{39}$.

A second group of regions includes the shelves of Irminger Sea and the Labrador Sea, the Coast of Japan (Fig. 1e), the Cascadian shelf (Fig. 1f), and the South Atlantic Bight. These shelf regions have $\Delta CO_2/dt$ values ranging between $+0.5$ μatm yr$^{-1}$ and $+1.0$ μatm yr$^{-1}$. This range implies that their water pCO$_2$ is increasing, but at a rate that is moderately slower than that of pCO$_2_{air}$, implying a strengthening sink, or a weakening source. The South Atlantic Bight is a moderate sink of CO$_2$ for the atmosphere$^{40}$ because of its water residence time of a few months and rapid cross-shelf exchange with the open ocean in the winter$^{41}$. Our estimate of $+0.8$ μatm yr$^{-1}$ for the Pacific coast of Japan is also consistent with a survey$^{24}$ that reports a slower increase of water pCO$_2$ ($+1.5 \pm 0.3$ μatm yr$^{-1}$, Table 2) than that of pCO$_2_{air}$ ($+2.0 \pm 1.7$ μatm yr$^{-1}$) along the Eastern Boundary current margins known for their strong upwelling off the U.S. West Coast (the California and Cascadian shelves). However, here upwelling source waters are not from the deeper Antarctic water as that in the Atlantic Ocean; rather, they are North Pacific surface water.

| Region | Narrow shelf | | | | | Wide shelf | | | |
|--------|--------------|---|---|---|---|---|---|---|---|
|        | d(ΔCO$_2$/dt) | $\sigma$ | n | d(ΔCO$_2$/dt) | $\sigma$ | n | d(ΔCO$_2$/dt) | $\sigma$ | n |
| Large regions (>50 cells according to narrow shelf definition) | | | | | | | | | |
| North Sea | 1.86 | 1.55 | 169 | 1.81 | 1.37 | 186 |
| Baltic Sea | 2.93 | 2.38 | 114 | 2.93 | 2.38 | 114 |
| Labrador Sea | 0.68 | 0.61 | 104 | 0.71 | 0.67 | 115 |
| English Channel | 0.0 | 0.43 | 86 | $-0.03$ | 0.39 | 89 |
| Mid-Atlantic Bight | 1.93 | 3.11 | 76 | 1.92 | 3.19 | 78 |
| Coast of Japan | 0.77 | 0.69 | 56 | 0.22 | 0.7 | 175 |
| Small regions (>20 cells according to narrow shelf definition) | | | | | | | | | |
| Cascadian shelf | 0.83 | 1.72 | 27 | 0.97 | 1.23 | 49 |
| Patagonia | $-0.21$ | 0.38 | 27 | $-0.11$ | 0.35 | 33 |
| Irminger Sea | 0.56 | 0.23 | 26 | 0.47 | 0.35 | 35 |
| Bering Sea | $-1.11$ | 0.74 | 24 | $-1.44$ | 0.94 | 42 |
| Antarctic Peninsula | 2.28 | 1.24 | 22 | 1.57 | 0.95 | 50 |
| South Greenland | 1.95 | 1.22 | 20 | 1.73 | 0.8 | 29 |
| South Atlantic Bight | 0.51 | 0.74 | 18 | 0.7 | 0.7 | 26 |
| Tasmania | 0.11 | 0.12 | 16 | 0.15 | 0.17 | 25 |
| Barents Sea | 0.38 | 0.52 | 10 | 0.31 | 0.41 | 42 |

The standard deviation ($\sigma$) and the number of cells available ($n$) using our narrow and wide definitions of the continental shelf are also reported.

| Region | Narrow shelf | | | | | Wide shelf | | | |
|--------|--------------|---|---|---|---|---|---|---|---|
|        | d(ΔCO$_2$/dt) | $\sigma$ | n | d(ΔCO$_2$/dt) | $\sigma$ | n | d(ΔCO$_2$/dt) | $\sigma$ | n |
| Large regions (>50 cells according to narrow shelf definition) | | | | | | | | | |
| North Sea | 1.86 | 1.55 | 169 | 1.81 | 1.37 | 186 |
| Baltic Sea | 2.93 | 2.38 | 114 | 2.93 | 2.38 | 114 |
| Labrador Sea | 0.68 | 0.61 | 104 | 0.71 | 0.67 | 115 |
| English Channel | 0.0 | 0.43 | 86 | $-0.03$ | 0.39 | 89 |
| Mid-Atlantic Bight | 1.93 | 3.11 | 76 | 1.92 | 3.19 | 78 |
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| Bering Sea | $-1.11$ | 0.74 | 24 | $-1.44$ | 0.94 | 42 |
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| South Greenland | 1.95 | 1.22 | 20 | 1.73 | 0.8 | 29 |
| South Atlantic Bight | 0.51 | 0.74 | 18 | 0.7 | 0.7 | 26 |
| Tasmania | 0.11 | 0.12 | 16 | 0.15 | 0.17 | 25 |
| Barents Sea | 0.38 | 0.52 | 10 | 0.31 | 0.41 | 42 |
Fig. 1 Rate of increase in winter air–sea pCO₂ gradient for selected best surveyed continental shelf regions. a Baltic Sea, b North Sea, c Mid-Atlantic Bight, d Antarctic Peninsula, e Coast of Japan, f Cascadian shelf, g English Channel, and h Patagonia. Each point represents a 0.5°x0.5° cell. Cells belonging to the narrow and wide definition of the shelf are displayed as squares and diamonds, respectively. The inserted histogram provides the distribution of the average ΔpCO₂/dt value, standard deviation, and the number of cells using the narrow (black lines) and wide (gray lines and numbers in brackets) definitions of the shelf.
values in $d(\Delta pCO_2)$ correspond to cells located within 100 km from the coast or depth less than 500 m. The distribution of $d(\Delta pCO_2)/dt$ for both our narrow (b) and wide (c) definitions of the continental shelf are displayed as histograms. The black bars report the distribution of all cells while the red bars report the distribution of cells for which the trend was deemed statistically significant using an $F$-test with $p < 0.05$. Here, $\Delta pCO_2 = pCO_{2,air} - pCO_2$. Thus, positive values in $d(\Delta pCO_2)/dt$ indicate slower increase in water $pCO_2$ than $pCO_{2,air}$.

The third group of regions, which includes the English Channel (Fig. 1g), the Barents Sea, and the Tasmanian shelf, show a minimal or no increase in $d\Delta pCO_2/dt$, meaning that their water $pCO_2$ more or less tracks the $pCO_{2,air}$ increase (Table 3). The interannual dynamics of $pCO_2$ in the English Channel is largely influenced by North Atlantic waters and thus partly constrained by the North Atlantic Oscillation. While no long-term $d\Delta pCO_2/dt$ has been estimated for the English Channel itself, the increase of $+1.7 \mu$atm yr$^{-1}$ for $pCO_2$ calculated for adjacent Atlantic water is consistent with an increase following that of the atmosphere. In both the Barents Sea and Tasmanian shelf, signs of a strengthening of the coastal $CO_2$ sink have been reported and were partly attributed to decreases in sea surface temperature. While marginal ($+0.1 \mu$atm yr$^{-1}$), the $d\Delta pCO_2/dt$ revealed by our calculations suggests an increase in the strength of $CO_2$ sink in the Tasmanian shelf. Finally, the Patagonian continental shelf ($-0.2 \pm 0.4 \mu$atm yr$^{-1}$; Fig. 1h) and Bering Sea ($-1.1 \pm 0.7 \mu$atm yr$^{-1}$) are the only regions displaying a negative $d\Delta pCO_2/dt$ (meaning faster increase in water $pCO_2$ than air $pCO_2$). Thus, although they are still intense $CO_2$ sinks, these shelf systems have recently experienced a weakening in their capacity to absorb atmospheric $CO_2$. While no long-term trend was reported for Patagonian shelf, it has been suggested that the $CO_2$ uptake in the Bering Sea could be decreasing at a fast pace although these observations were based on a relatively short time series (1995–2001).

Overall, 13 of the 15 regions have positive $d\Delta pCO_2/dt$ values and 10 reveal values equal or greater than $+0.5 \mu$atm yr$^{-1}$ (Table 3). Although these areas only account for a small fraction of the global coastal ocean, they show a consistent trend suggesting that winter sea surface $pCO_2$ increases significantly slower than $pCO_{2,air}$. Furthermore, in most regions, the variability around this trend is relatively limited. For instance, in 9 out of 15 regions, the standard deviation is less than 1 $\mu$atm yr$^{-1}$. However, it remains difficult to identify the mechanisms responsible for these observed patterns in $d\Delta pCO_2/dt$ considering the diversity of morphological and hydrodynamical settings of the shelf regions covered by our analysis.

Global shelf $CO_2$ sink. Globally, our analysis of the 825 temporal trends in $\Delta pCO_2$ using winter-only data covers a shelf surface area of $1.4 \times 10^6$ km$^2$, which represents ~6% of the global continental shelves. This includes data from the more isolated cells that were not considered in the previous section. While the coverage is relatively small, heterogeneous and somewhat skewed toward temperate latitudes in the northern hemisphere, it nevertheless covers most of the range of $pCO_2$ and SST encountered in continental shelf waters (Supplementary Figures 1 and 2). Exceptions are the low latitudes, which are poorly represented in our data set. While we need to recognize this limitation, the broad coverage in terms of environmental conditions permits us to assemble all estimated trends and assume that they represent a sufficiently unbiased sample of the shelf trends across the globe.
The bulk of our winter data consistently show trends that are dominantly in accordance with an increase in $\Delta p_{CO2}$ over time. Our narrow definition of the shelf yields a global average $d\Delta p_{CO2}/dt$ of $+1.3 \pm 1.9 \mu$atm yr$^{-1}$, while the wide definition for geographical extent leads to a smaller average value of $+0.8 \pm 1.8 \mu$atm yr$^{-1}$ (Fig. 2). Thus, our global-scale analysis of winter $p_{CO2}$ data reveals that trends are more likely positive than not and support the idea that air–sea $p_{CO2}$ gradients may have been increasing with time making continental shelves overall an increasing $CO2$ sink for the atmosphere. Nevertheless, as shown by the substantial standard deviations, large differences in $d\Delta p_{CO2}/dt$ can be observed across continental shelves. Within the 200 m water depth boundary, 653 cells (out of 825) display a positive $d\Delta p_{CO2}/dt$, 76% of which are greater than $+0.5 \mu$atm yr$^{-1}$ (i.e., 495 out of 653; Supplementary Table 1). For 66% of the latter cells (325 out of 495), the slope of the regression is considered statistically significant using an $F$-test with $p < 0.05$ and 71% with $p < 0.1$ (Fig. 2). On the other hand, for the 172 cells (out of 825) that display negative $d\Delta p_{CO2}/dt$ values, only 49% are more negative than $-0.5 \mu$atm yr$^{-1}$ (84 out of 172). The trend is still observed when the boundary is relaxed to 500 m or 100 km from the coast. One thousand and sixty-six cells (out of 1364) display a positive $d\Delta p_{CO2}/dt$, 64% of which is greater than $+0.5 \mu$atm yr$^{-1}$ (i.e., 682 out of 1066) and only 149 out of the 298 non-negative cells having a negative $d\Delta p_{CO2}/dt$ are then characterized by rates more negative than $-0.5 \mu$atm yr$^{-1}$ (Fig. 2). The use of the broader definition of the continental shelves not only decreases the average $d\Delta p_{CO2}/dt$, but also increases the proportion of cells with $d\Delta p_{CO2}/dt$ between $-0.5$ and $+0.5 \mu$atm yr$^{-1}$ (39% vs. 30%). Note that applying our method to all

![Fig. 3](https://www.nature.com/naturecommunications)

**Fig. 3** $\Delta p_{CO2}$ as a function of time for all cells comprised in the six regions with best data coverage. **a** Baltic Sea, **b** English Channel, **c** Coast of Japan, **d** Labrador Sea, **e** Mid-Atlantic Bight, and **f** North Sea. Red dots correspond to winter data only, black dots to data for all seasons.
open ocean waters deeper than 500 m or further than 100 km from the coast yields a much smaller average $d\Delta pCO_2/dt$ of $+0.2 \pm 1.1 \mu\text{atm yr}^{-1}$, which is close to the open ocean observation$^{1-6,32}$, further supporting the validity of our method.

The results from the analysis using data across the entire year generally confirm the results from the wintertime-only data as exemplified by the change in $\Delta pCO_2$ with time for all cells pertaining to the six largest regions used in the regional analysis (Fig. 3). For all regions, the range of $\Delta pCO_2$ values observed in winter (red) is largely less than that based on the entire year (black). Globally, calculations performed using deseasonalized data from the entire year also allow deriving trends for 3721 cells (Supplementary Table 1). Although much noisier, the overall $d\Delta pCO_2/dt$ values using all seasonal data reveal qualitatively similar trends to those observed with data from the winter months only (Supplementary Table 1). The overall proportion of cells displaying statistically significant trends is much lower when all seasonal data are used (22%) than when winter data are retained (45%). Nevertheless, nearly three times more cells display significant trends for which $d(\Delta pCO_2)/dt > +0.5 \mu\text{atm yr}^{-1}$ (574) than for which $d(\Delta pCO_2)/dt < -0.5 \mu\text{atm yr}^{-1}$ (201), a result in broad agreement with our analysis based on winter data only. Therefore, the analysis of deseasonalized data for all seasons also point toward a tendency for an enhanced shelf uptake of atmospheric $CO_2$.

The rate of change in the air–sea $CO_2$ gradient also has varied over time. Figure 4 presents the evolution from 1988 to 2007 of winter $d\Delta pCO_2/dt$ calculated for each year over a 15-year time period. Because the bulk of the data available in SOCAT are relatively recent, it is difficult to reconstruct trends earlier than the 1990s. The distribution of rates around the mean value is shown by the gray scale in Fig. 4 and the widening of the distribution can be observed as the number of data points increase but, for any given year, the bulk of the $d\Delta pCO_2/dt$ distribution remains constrained within the $-0.5$ to $+2.0 \mu\text{atm yr}^{-1}$ range. While uncertainties are high in such an analysis, in particular because the trends from the investigated regions (about 6% of the total shelf area) might not hold for all the others, our results suggest that in addition to the dominance of positive $d\Delta pCO_2/dt$, there is a good probability that the rate of change of the air–sea $CO_2$ gradient has also increased over the past 15 years. Indeed, the average $d\Delta pCO_2/dt$ appears to remain below $1 \mu\text{atm yr}^{-1}$ before 1997 but above it since then.

**Implications for the global carbon budget.** Applying the mean rate of change in the winter air–sea $CO_2$ gradient identified in Fig. 4 to a globally averaged winter $\Delta pCO_2$ of $+28 \mu\text{atm}$ for the continental shelf seas in the reference year 2000$^{17}$, leads to an increase in water $pCO_2$ that has consistently lagged behind the increase in atmospheric $CO_2$. As noted in the previous section, $d\Delta pCO_2/dt$ also has increased in recent years ($+1.2 \mu\text{atm yr}^{-1}$). The first records of shelf $pCO_2$ date back from the early 1980s and it is thus impossible to reconstruct the earlier evolution of the air–sea exchange from direct observations. Although highly speculative, it is nevertheless interesting to extend the rate of change in the 1980s and early 1990s ($+0.6 \mu\text{atm yr}^{-1}$) estimated here to the earlier decades. This approach allows comparing trends derived from observations alone with earlier modeling work and will stimulate further exploration of coastal $CO_2$ trends$^{28,30}$. Our calculations suggest that the magnitude of the average winter $\Delta pCO_2$ increased by 69% over the 1988–2007 period. By extrapolating this trend to earlier times, it can be speculated that the continental shelves might indeed have turned from a purported preindustrial source of $CO_2$ into a sink for atmospheric $CO_2$ as early as in the 1950s, at least during wintertime (Supplementary Figure 3). The occurrence of such a switch from source to sink in the mid-twentieth century would be consistent with previous model results$^{28}$, although our data-based estimate may indicate that the switchover time could have occurred earlier than previously thought. Note that our assessment excludes the high $pCO_2$ estuarine and very nearshore (proximal) zone that is believed to be a significant source of $CO_2$ for the atmosphere at present$^{12,16,53,54}$. A recent model hindcasts that the uptake rate of anthropogenic $CO_2$ by continental shelves has increased rapidly since the 1950s$^{29}$. Although this flux is much less than that modeled for the open ocean uptake$^{29}$, it would imply an increase in the total $CO_2$ uptake flux (natural plus anthropogenic) and an increase in the air–sea $pCO_2$ gradient in the coastal ocean, assuming that the natural $CO_2$ flux in their model does not change. Thus, the conjecture derived from our first global observation-based work is consistent with their model prediction. Nevertheless, this work also highlights the fact that the rate of increase of the air–sea $pCO_2$ gradient in continental shelf waters and its importance in global ocean $CO_2$ uptake is still poorly understood and deserve further study. In addition, if both observational evidence and model results support the idea that shelves are an increasing sink for the atmospheric $CO_2$, we are far from quantitatively understanding the roles of the physical pump....
and biological pumps (NEM and NEC) in explaining this enhanced CO₂ absorption and associated high variability globally. We suggest, however, that a faster exchange of shelf CO₂ with the ocean interior and increased biological production due to anthropogenic nutrient inputs may have slowed down the rate of increase of surface ocean pCO₂ in many shelf regions.

In principle, the slower pCO₂ increase in shelf waters could increase the gradient and thus the uptake of atmospheric CO₂ in the decades to come, although high spatial variability in air–sea fluxes is to be expected across shelf regions. The shift of shelf waters from releasing to absorbing CO₂ between preindustrial time and the present day, as well as the possibility of shelves becoming a more important sink in the future, is a significant temporally changing term in the global carbon cycle and pathway of exchange for atmospheric CO₂. It should thus be closely evaluated by further data collection and analysis and be considered in future global carbon cycle models and flux assessments.

Methods

Definition of the study area. For this work, we defined the continental shelf as all marine waters shallower than the 200 m isobath. This depth is commonly used in the literature as the depth at which the shelf breaks. However, we also considered marine waters shallower than the 200 m isobath. This depth is commonly used in our analysis. The

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of which 3.4 × 10⁶ and 5.2 × 10⁶ are located within our narrow and wide shelf

Data processing. Recently, numerous continental shelf pCO₂ observational data have been quality controlled and included into the SOCAT database. Version 3 released in 2015 comprises more than 14 × 10⁶ measurements for the entire ocean, of which 3.4 × 10⁶ and 5.2 × 10⁶ are located within our narrow and wide shelf definitions, respectively. This unprecedented data coverage offers the opportunity to assess whether global shelf waters show a change in the direction and magnitude of the air–sea pCO₂ gradient (ΔpCO₂ = pCO₂air−pCO₂) over time (ΔpCO₂/dt).

The coastal zone was divided into regular 0.5 × 0.5 degree cells and all the SOCAT measurements were allocated to a given cell according to their latitudes and longitudes. SOCAT fugacity data (fCO₂) were converted into CO₂ partial pressure (pCO₂) in water using the following equation:

\[
pCO₂ = \frac{fCO₂}{1.0436 - 4.6691 \times 10^{-5} \times SST},
\]

where SST is the sea surface temperature in degrees Celsius. For each month, an average ΔpCO₂ was calculated within each cell. The winter data (defined as January, February, and March in the Northern Hemisphere and July, August, and September in the Southern Hemisphere) are not modified prior to calculating the linear regressions. The data from all seasons, however, are deseasonalized using monthly pCO₂ climatological maps for continental shelves generated by artifical neuronal network interpolations. This monthly pCO₂ climatology allowed establishing an average seasonal pCO₂ cycle for each grid cell. This signal was then removed from the raw data to perform a deseasonalization prior to calculating the linear regressions.

We found no significant trend in SST in the majority of the cells (i.e., the absolute rate of change in temperature only exceeds 0.1 °C yr⁻¹ in less than 15% of the cells) and the average temperature change among all 825 cells used for the winter analysis using the narrow definition of the shelf is ~0.0021 °C yr⁻¹. In addition, warming should lead to a higher water pCO₂ and, thus, should reduce ΔpCO₂/dt.

For each data point, an atmospheric pCO₂ was also calculated using:

\[
(pCO₂)_{atm} = XCO₂/(P_{baro} - P_{baro}),
\]

where P_{baro} is the barometric pressure at sea surface and P_{baro} is the water pressure at the temperature and salinity of the water within the mixed layer. XCO₂ is the weekly mean CO₂ concentration for dry air extracted from the GLOBALVIEW-CO₂ database. P_{baro} was calculated assuming 100% humidity using sea surface temperature and salinity and P_{baro} is the monthly mean barometric pressure at

The literature as the depth at which the shelf breaks. However, we also considered marine waters shallower than the 200 m isobath. This depth is commonly used in our analysis. The

A moving spatial window of 1.5 degrees of width (i.e., three cells) was used to produce 20 subsets, each covering a period of 15 years (from 1980 to 2006) was calculated by adding or subtracting the average ΔpCO₂ over the global continental shelves in a similar fashion.

Temporal evolution of ΔpCO₂. To investigate how the rate of change in air–sea CO₂ gradient, d(ΔpCO₂)/dt, has varied globally over time, the entire SOCAT data set was used to produce 20 subsets, each covering a period of 15 years (from 1980 to 1994, then 1981 to 1995 and so on until 2001 to 2015) and used to calculate the rate of change for the central year of each period. For instance, d(ΔpCO₂)/dt for year 1988 is calculated using data ranging from 1981 to 1995. This method provides estimates for years 1988 to 2006. For each period, d(ΔpCO₂)/dt were calculated for each cell following the procedure described above. The average rate of change in ΔpCO₂ for a given period was then calculated as the average of all the rates calculated for each cell for which observations were available. A global estimate for the coastal ocean carbon sink for winter of 0.26 Pg C yr⁻¹ was used over a surface area of 30 10⁶ km² in conjunction with the gas transfer velocity of 9.0 cm h⁻¹ to estimate an average global ΔpCO₂ of 28 μatm for the continental shelf seas in the reference year 2000. Year 2000 was selected as the estimate of Laruelle et al. represents an average over the 1990–2011 period. From this reference value, the ΔpCO₂ in previous and following years (periods 1988–2006) was calculated by adding or subtracting the average d(ΔpCO₂)/dt calculated using the 20 data subsets described above. Earlier than 1988, d(ΔpCO₂)/dt was assumed to be the average over the 1988–1993 period. Using annually averaged atmospheric pCO₂ values from Mauna Loa and these d(ΔpCO₂)/dt estimates of the water pCO₂ are then calculated for each year (Supplementary Figure 3). Results show that shelf water pCO₂ could have been lower than atmospheric pCO₂ as early as 1950.

Data availability. The data that support the findings of this study are available from the corresponding author on reasonable request.

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5. Landschützer, P., Gruber, N. & Bakker, D. C. E. Decadal variations and trends

6. IPCC. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013).

7. Erez, A. R. & Pfeil, B. Global trends in surface ocean pCO2 from in situ data. Glob. Biogeochem. Cycles 27, 541–557 (2013).

8. Feely, R. A. et al. Decadal variability of the air-sea CO2 fluxes in the equatorial Pacific Ocean. J. Geophys. Res. 111, C08S90 (2006).

9. Landschützer, P., Gruber, N. & Bakker, D. C. E. Decadal variations and trends of the global ocean carbon sink. Glob. Biogeochem. Cycles 30, 1396–1417 (2016).

10. Baker, D. C. E. et al. Multiple time-series of changing ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. Oceanography 27, 126–141 (2014).

11. Craig, H. in Earth Science and Meteoritics (F.G. Houtermans volume) (eds Geiss, J. & Goldberg, E. D.) 103–114 (North-Holland Publ. Co., Amsterdam, 1963).

12. Bauer, J. E. et al. The changing carbon cycle of the coastal ocean. Nature 504, 61–70 (2013).

13. Hales, B. et al. Satellite-based prediction of pCO2 in coastal waters of the eastern North Pacific. Prog. Oceanogr. 103, 1–15 (2012).

14. Thomas, H., Bozec, Y., Elkayal, K. & de Baar, H. J. W. Enhanced open ocean storage of CO2 from shelf sea upwelling. Science 304, 1005–1008 (2004).

15. de Baar, H. J. W., Dau, M. & Wang, Y. Air-sea exchange of carbon dioxide in ocean margins: a province-based synthesis. Geophys. Res. Lett. 33, L12603 (2006).

16. Borges, A. V., Delille, B. & Frankignoulle, M. Budgeting sinks and sources of CO2 in the coastal oceans: diversity of ecosystems counts. Geophys. Res. Lett. 32, L14601 (2005).

17. Bakker, D. C. E. et al. A multi-decade record of high-quality fCO2 data in version 3 of the surface ocean CO2 atlas (SOCAT). Earth Syst. Sci. Data 8, 383–416 (2016).

18. Cai, W.-J. et al. Mapping of the air-sea CO2 exchange at the air-water interface in continental shelf seas. Glob. Biogeochem. Cycles 28, 1199–1214 (2014).

19. Wanninkhof, R. et al. Global ocean carbon uptake: magnitude, variability and trends. Biogeosciences 10, 1983–2000 (2013).

20. Laruelle, G. G. et al. Global high resolution monthly pCO2 climatology for the coastal ocean derived from neural network interpolation. Biogeosciences 14, 4539–4551 (2017).

21. Landschützer, P., Gruber, N. & Bakker, D. C. E. Global trends in surface ocean pCO2 from in situ data. Glob. Biogeochem. Cycles 27, 541–557 (2013).

22. Feely, R. A. et al. Mapping of the air-sea CO2 flux in the Arctic Ocean and its adjacent seas: Basin-wide distribution and seasonal to interannual variability. Polar Biol. 30, 323–334 (2016).

23. Signorini, S. R. et al. Surface ocean pCO2 seasonality and sea-air CO2 flux estimates for the North American east coast. J. Geophys. Res. 118, 1–22 (2013).

24. DeGrandpre, M. D., Olib, G. J., Beatty, C. M. & Hammar, T. R. Air-sea CO2 fluxes on the US Middle Atlantic Bight. Deep Sea Res. II 49, 4355–4367 (2002).

25. Landschützer, P. et al. Seasonal response of air-water CO2 exchange along the land–ocean aquatic continuum of the northeast North American coast. Biogeosciences 12, 1447–1458 (2015).

26. Laruelle, G. G., Goossens, N., Arndt, S., Cai, W.-J. & Regnier, P. Air–water CO2 evasion from US East Coast estuaries. Biogeosciences 14, 2441–2468 (2017).

27. Cai, W.-J. et al. Surface ocean alkalinity distribution in the western North Atlantic Ocean margins. Biogeosciences 15, 4007–4022 (2018).

28. Landschützer, P. et al. The reinvigoration of the Southern Ocean carbon sink. Science 349, 1221–1224 (2015).

29. Jiang, L.-Q., Cai, W.-J., Wanninkhof, R., Wang, Y. & Lüger, H. Air-sea CO2 fluxes on the US South Atlantic Bight: Spatial and seasonal variability. J. Geophys. Res. 113, C07019 (2008).

30. Lee, T. Y., Norder, J. A. & Allan, L. P. Gulf Stream Frontal Eddy Influence on Productivity of the Southeast U.S. Continental Shelf. J. Geophys. Res. 96, 22191–22205 (1991).

31. Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D. & Hales, B. Evidence for upwelling of corrosive “acidified” water onto the continental shelf. Science 290, 1490–1492 (2000).

32. Gruber, N. et al. Rapid progression of ocean acidification in the California current system. Science 337, 220–223 (2012).

33. Feely, R. A., et al. Chemical and biological impacts of ocean acidification along the west coast of North America. Estuarine Coast. Shelf Sci. 183, 260–270 (2016).

34. Wang, D., Goulier, T. C., Menge, B. A. & Ganguly, A. R. Intensification and spatial homogenization of coastal upwelling under climate change. Nature 518, 390–394 (2015).

35. Evans, W., Hales, B., Strutton, P. G. & Ianson, D. Sea-air CO2 fluxes in the western Canadian coastal ocean. Prog. Oceanogr. 101, 78–91 (2012).

36. Marre, P. et al. Dynamics of air-sea CO2 fluxes in the northwestern European shelf based on voluntary observing ship and satellite observations. Biogeosciences 12, 5371–5391 (2015).

37. Borges, A. V. et al. Inter-annual variability of the carbon dioxide oceanic sink south of Tasmania. Biogeosciences 5, 141–155 (2008).

38. Bianchi, A. A. et al. Annual balance and seasonal variability of sea-air CO2 fluxes in the Patagonia Sea: Their relationship with fronts and chlorophyll distribution. J. Geophys. Res. 114, C03018 (2009).

39. Bates, N. R., Mathis, J. T. & Jeffries, M. A. Air-sea CO2 fluxes on the Bering sea shelf. Biogeosciences 8, 1253–1257 (2011).

40. Fransson, A., Chierici, M. & Nojiri, Y. Increased net CO2 outgassing in the upwelling region of the southern Bering Sea in a period of variable marine climate. J. Geophys. Res. 112, C08014 (2007).

41. McKinley, G. A. et al. Timescales for detection of trends in the ocean carbon sink. Nature 530, 469–472 (2016).

42. Laruelle, G. et al. Global multi-scale segmentation of continental and coastal waters from the watersheds to the continental margins. Hydrol. Earth Syst. Sci. 17, 2029–2051 (2013).

43. Regnier, P. et al. Anthropogenic perturbation of the carbon fluxes from land to ocean. Nat. Geosci. 6, 597–607 (2013).

44. Takashashi, T., Sunderland, S. & Kozyr, A. Global ocean surface water partial pressure of CO2 database: measurements performed during 1957–2011 (version 2011). ORNL/CDIAC-160, NDP-088V2011 (Carbon Dioxide Information Analysis Center, Oak Ridge Natl. Lab., U.S. Dep of Energy, Oak Ridge, TN, 2012).

45. NOAA. GLOBALVIEW-CO2 (NOAA ESRL, Boulder, CO, 2012).

46. Kalnay, E. et al. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 377–417 (1996).

47. Pardo-Igúzquiza, E., Dowd, P. A. & Grimes, D. I. F. An automatic moving window approach for mapping meteorological data. Int. J. Climatol. 25, 665–678 (2005).

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Author contributions
G.G.L. performed all calculations necessary to this study, following an idea central to the conception of this paper by W.-J.C. P.R. coordinated and participated at all stages of the conception and writing of the paper. G.G.L., W.-J.C., and P.R. wrote the manuscript with input by N.G. All co-authors contributed to specific aspects of the analyses and commented on various versions of the manuscript.

Additional information
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