Reduced Ocean Carbon Sink in the South and Central North Sea (2014–2018) Revealed From FerryBox Observations

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Abstract Surface seawater carbon dioxide partial pressure (pCO₂) in the south-central North Sea was measured between 2014 and 2018 using FerryBox-integrated membrane sensors on ships-of-opportunity. Average annual pCO₂ variability was biologically controlled, with thermal effects modulating its amplitude. Deseasonalized winter trends of seawater pCO₂ were positive (4.4 ± 2.0–8.4 ± 2.9 µatm yr⁻¹), biogeochemically driven, stronger than the atmospheric pCO₂ trend, and more pronounced than previous analyses. The trends calculated including all deseasonalized monthly averages were even higher (9.7 ± 2.8–12.2 ± 1.4 µatm yr⁻¹). During our investigation, the southern study area became a stronger source and the northern part became a weaker sink for atmospheric carbon. Overall, average sea-air CO₂ flux changed from −0.75 ± 0.61 mmol m⁻² day⁻¹ in 2014 to +0.20 ± 0.96 mmol m⁻² day⁻¹ in 2018.

Plain Language Summary Oceans and seas take up one fourth of the carbon dioxide (CO₂) produced by industrial and agricultural activities, and thus lower the amount left in the atmosphere that can contribute to climate change. This uptake of man-made CO₂ can only be understood by taking the natural carbon cycle into account, which is subject to distinct variability. The ability of seawater to remove carbon from the atmosphere can be limited if too much CO₂ is absorbed by the oceans and coastal seas. In this study, we show that between 2014 and 2018, the levels of carbon dioxide have increased faster in the North Sea surface waters than in the atmosphere. As a consequence, regions where atmospheric CO₂ is taken up (carbon sinks) have become less effective and regions where CO₂ is normally released back into the atmosphere (carbon sources) have become more effective. These findings help us understand how carbon cycling in the North Sea works in the context of still increasing atmospheric CO₂ concentrations. It also highlights the importance of sustained observations in dynamic coastal environments such as the North Sea.

1. Introduction

Atmospheric carbon dioxide (CO₂) concentration increased by 2.30 ± 0.01 ppm yr⁻¹ during the 2009–2018 period (Friedlingstein et al., 2019). This rate would be higher had the ocean not taken up approximately a quarter of the anthropogenic carbon emitted since the industrial revolution (Le Quéré et al., 2018). This ocean carbon uptake leads to a global increase in the partial pressure of carbon dioxide (pCO₂) in the surface ocean (Fay & McKinley, 2013). The sign of the difference between the seawater and atmospheric pCO₂ determines the direction of gas exchange and the global distribution of ocean sources and sinks of carbon (Takahashi et al., 2009). Observations in different regions and for different periods revealed seawater trends above the atmospheric trend (Landschützer et al., 2016; Macovei et al., 2020) or below it (Metzl et al., 2010; Thomas et al., 2007). This variability can only be resolved through increasing our observational coverage (Roobaert et al., 2019).

Coastal and shelf seas in low-latitude regions are generally carbon sources, while those at high and mid-latitudes are carbon sinks (Borges et al., 2005). Overall, coastal seas are carbon sinks, with an estimated global uptake of 0.20 Pg C yr⁻¹ (Roobaert et al., 2019). Similarly to the open oceans, in coastal seas, different studies found that the rate of increase in seawater pCO₂ in many shelf regions can be either lagging behind (Laruelle et al., 2018) or similar to the atmospheric rate (Wang et al., 2017). Such inconsistencies suggest regional variability and emphasize the heterogeneity of shelf seas on a global scale.
The variability of the carbonate chemistry of the North Sea, a large temperate shelf sea, has recently been investigated as part of large-scale studies of the Northwestern European Shelf (Becker et al., 2021; Hartman et al., 2019; Kitidis et al., 2019). Other studies focused on seawater pCO2 from ship-based observations in the North Sea have either been performed over short periods (Omar et al., 2010) or were restricted to the northern North Sea (Omar et al., 2019). The North Sea as a whole is exporting carbon to the North Atlantic through a process known as the “continental shelf pump”—the transfer of the carbon-enriched dense bottom shelf waters to the stratified subsurface open ocean (Thomas et al., 2004; Tsunogai et al., 1999). The North Sea is heterogeneous in its CO2 saturation state, with northern (southern) regions being undersaturated (oversaturated) (Thomas et al., 2004). Both observations (Clargo et al., 2015) and models (Lorkowski et al., 2012) have suggested an ongoing weakening in the carbon uptake capacity of the North Sea with distinct drivers of the variability in the northern and southern parts. The large spatiotemporal variability means that in order to better understand the mechanisms and improve prediction ability, sustained pCO2 observations in the North Sea are needed at a higher frequency and coverage than those already existing in Surface Ocean Carbon Atlas (SOCAT, Bakker et al., 2016, 2020).

In this study, the recent spatiotemporal variability of the surface seawater pCO2 over a large area of the North Sea is analyzed using autonomous ship-of-opportunity (SOOP) sensor observations. We identify subregions based on stratification regimes and calculate their average annual cycles and deseasonalized pCO2 trends. The relative influence of thermal and non-thermal effects on the overall variability is assessed. Finally, we investigate how the distribution and extent of carbon sink/source regions changed during the 2014–2018 study period and provide estimations on the change in average sea-air CO2 fluxes.

2. Materials and Methods

2.1. Data

FerryBoxes are automated instrument packages, usually installed on commercial ships that make use of regular shipping routes to provide surface seawater measurements (Petersen, 2014). The pCO2 measurements used in this study were taken with 4H-Jena Contros HydroC CO2-FT membrane-based instruments (manufacturer provided uncertainty of 1%) integrated with the FerryBoxes running on two cargo vessels, the Lysbris Seaways and the Hafnia Seaways. These two SOOP were regularly transiting the North Sea between 2014 and 2018, as part of Coastal Observing System for Northern and Arctic Seas (Baschek et al., 2017) monitoring efforts (Figure 1). The sensors have been regularly maintained, changed and recalibrated. The raw data were processed according to manufacturer recommendations, correcting for instrument drift (Fietzek et al., 2014). The Lysbris measurements have been evaluated and validated against a traditional showerhead equilibrator instrument in a recent intercalibration study (Macovei et al., 2021—details in the Text S1). The Lysbris data between April and June 2015 featured a strong baseline drift so they were excluded from this analysis (Macovei et al., 2021). Since Hafnia was not sailing during this time, a 2-month gap in the data exists.

The North Sea was split into regions based on the density stratification regimes defined from a 1996 to 2010 hydrobiogeochemical model simulation (van Leeuwen et al., 2015). The shapefiles are available at https://www.researchgate.net/publication/309308832_Shapefiles_Shelf-wide regimes_1996–2010. Nearly 60% of the valid FerryBox pCO2 measurements in the North Sea were taken in one of these regions of stratification.

Seawater temperature and salinity were measured with Teledyne/Falmouth Scientific Inc. sensors, also integrated within the FerryBox (uncertainties of ±0.1°C and ±0.02 respectively). Since temperature is
not measured immediately after the intake, ∼0.37°C of warming can be expected to occur in the pipes (Haller et al., 2015). The temperature, salinity, and pCO2 data are available from the European FerryBox Database (https://ferrydata.hzg.de/) and from the Pangaea Data Publisher (https://doi.org/10.1594/PANGAEA.930383). No corrections were applied to the temperature or salinity data.

We used atmospheric CO2 data from the Mace Head Observatory in Ireland (World Data Centre for Greenhouse Gases, 2020), which we assume to be a lower-bound estimate of the atmospheric value (Derwent et al., 2002). We converted the dry mole fraction to partial pressure according to Humphreys et al. (2019) using the water vapor pressure formula of Alduchov and Eskridge (1996), alongside barometric pressure and dew point temperature in our study area downloaded from the ERA5 reanalysis product (Copernicus Climate Change Service, 2020). We used 10 m wind speed from the same reanalysis product.

2.2. Processing and Calculations

Data were first sorted into the five stratification regions based on their geographical position. Investigating the pCO2 variability revealed big differences between the two main regions of freshwater influence (ROFI), off the western and eastern coasts of the North Sea. While their stratification regime is similar, our biogeochemical investigation required a further separation into ROFI-W and ROFI-E, respectively. Data were temporally averaged for every calendar month within the six resulting regions and mean annual cycles were calculated.

For each region, trends were computed after deseasonalizing by subtracting the 5-year average monthly mean from the individual monthly means, thus obtaining pCO2 anomalies. This is similar to the Tjiputra et al. (2014) method, without the need to remove regional aliasing. Our regions are small, homogeneous in pCO2 variability, and the data coverage throughout the study period did not produce spatial biases. Linear regressions against time were applied both for the entire time series as well as just for the winter months, here defined as November-February.

The effects of seawater temperature on pCO2 variability were investigated by decomposing the annual cycles into an isochemical and isothermal component, similar to Keeling et al. (2004). The change in seawater pCO2 due to the monthly change in sea surface temperature, that is the isochemical term, can be calculated according to the experimentally derived pCO2 temperature sensitivity factor of Takahashi et al. (1993) as follows:

\[
\text{Isochemical term}_{i-1:i} = \left(pCO_2\right)_{i-1:i} \times \exp\left(0.0423 \times (SST_i - SST_{i-1})\right) - \left(pCO_2\right)_{i-1:i},
\]

where SST and pCO2 are the monthly averages, and \(i\) and \(i-1\) denote the current and previous months, respectively. The isothermal term is the difference between the absolute monthly change and the isochemical change term, and mainly represents changes in dissolved inorganic carbon (DIC) concentrations.

The sea to air CO2 flux was calculated using code available online (https://github.com/mvdh7/co2flux)—see Humphreys et al. (2019)—following the parameterization according to Wanninkhof (2014):

\[
F = k\alpha \left(pCO_2^{sw} - pCO_2^{atm}\right),
\]

where \(k\) is the gas transfer velocity, calculated using the Schmidt number and the quadratic wind speed, while \(\alpha\) is a function of sea surface temperature and salinity.

3. Regional Variability

Seawater pCO2 consistently dropped during the spring season and increased during the late spring-summer season. This cyclicity is a result of the combined effect of temperature and biological effects in mid-latitude marine environments (Jiang et al., 2013; Macovei et al., 2020; Omar et al., 2010; Takahashi et al., 2002). The phytoplankton spring bloom produces organic matter by consuming DIC in the surface seawater, which consequently lowers the pCO2 to an annual minimum, in spite of sea surface temperatures increasing at the
same time with an opposite effect on \(pCO_2\). Summer warming and remineralization of the organic matter subsequently increase the \(pCO_2\). Variations from this typical cyclicity are likely caused by advective or local effects such as river influence, coastal upwelling, or exchanges with surrounding water masses (Artioli et al., 2012; Frankignoulle & Borges, 2001; Kitidis et al., 2019).

All the long-term \(pCO_2\) monthly averages in the permanently and seasonally stratified regions are below 400 \(\mu\text{atm}\) (Figures 2a and 2b). The spring drawdown is evident in these regions as the phytoplankton bloom is favored by stratification (Wakelin et al., 2012). The annual cycle in the permanently mixed and intermittently stratified regions does not display such a clear spring decrease (Figures 2c and 2d). Furthermore, these regions are situated in the south of our study area and show higher long-term \(pCO_2\) monthly averages between around 370 and 460 \(\mu\text{atm}\), consistent with past knowledge of the southern North Sea being an overall carbon source (Bozec et al., 2005; Prowe et al., 2009).

The intra-annual variability of seawater \(pCO_2\) in the regions of freshwater influence (Figures 2e and 2f) is higher, due to riverine water chemical composition, influence from nearby intertidal regions, and shallow sedimentary biogeochemical processes (Beck & Brumsack, 2012; Brenner et al., 2016; Voynova et al., 2017).
The lowest monthly averages were recorded off the Netherlands coast after the spring bloom of 2014 with values below 200 µatm. The ROFI-E region, influenced by the European continental runoff from rivers such as the Scheldt, Rhine, Weser or Elbe (Burt et al., 2016), is the only one where the multi-year monthly averages for April and May are below 300 µatm. Excess total alkalinity, brought in by river inputs, intertidal sediment pore water exchanges and bottom sediment biogeochemical interactions (Voynova et al., 2019), is known to increase the buffer capacity and strengthen the spring pCO2 drawdown in this area (Omar et al., 2010). On the other hand, the ROFI-W region had consistently higher pCO2 values and a less regular annual cycle. This is likely a result of the inputs of very high pCO2 water from the Humber river which drains agricultural and industrial areas resulting in CO2 production through estuarine microbial degradation of organic matter in the presence of high nutrient concentrations (Jarvie et al., 1997). Since the ships sailed to the estuarine port of Immingham, the measurements were influenced by the mixing of North Sea water with the very high concentration river end-member (Volta et al., 2016). This shows that while these two regions experience similar stratification, they differ in their biogeochemical characteristics.

The annual ranges of pCO2 found in this study are consistent with past North Sea observations (Hartman et al., 2019; Thomas et al., 2004). We investigated the influence of thermal and non-thermal effects on seasonality. The isochemical term is characterized by a summer maximum (July in all regions except ROFI-W), driven by the sea surface temperature maximum. The isothermal term usually features a minimum in the spring and a maximum in the fall, suggesting the main drivers of DIC changes are biological production during the spring bloom and remineralization of the organic matter later in the year. The annual isochemical amplitude is only about 60% of the isothermal annual amplitude, except in the region of intermittent stratification, where the two terms are approximately equal. Thus, the seasonal cycle of pCO2 is dominated by chemical/biological variability, with temperature effects moderating the amplitude, such as when warm late-spring temperatures counteract the pCO2 decrease caused by the phytoplankton bloom and cold winter temperatures dampen the pCO2 rise in surface waters due to remineralization. Other observations at higher latitudes have confirmed DIC variability as the main driving factor for pCO2 (Olsen et al., 2008).

4. Trends

Using all available monthly anomalies, we found statistically significant trends of increasing surface water pCO2, ranging from 9.7 ± 2.8 µatm yr⁻¹ in ROFI-W to 12.2 ± 1.4 µatm yr⁻¹ in ROFI-E (Figure 3). Winter trends were in general smaller, ranging from 4.4 ± 2.0 µatm yr⁻¹ in the region of permanent stratification to 8.4 ± 2.9 µatm yr⁻¹ in ROFI-W, all statistically significant at the 0.05 significance level. Only using winter months minimizes the effect of primary production (Fröb et al., 2019) and, in the case of our time series, lowers the trends by excluding the strong spring drawdown at the start of our study period and the high spring and summer values toward the end. The year-round and winter trends in ROFI-W were not statistically distinct, but this region's unusual annual cycle indicates that biological influence cannot be avoided in trend calculations by simply using the November-February anomalies.

The trends were calculated by grouping the data into relatively large provinces. In order to test if the strong increases are observed on smaller geographical scales, we retraced our analysis first for data around five points of interest, chosen in the middle of the regions defined by van Leeuwen et al. (2015), where pCO2 data availability was high (see Figure 1), and second by grouping all available data into 1° × 1° boxes. Similar strong positive trends were found for both of these methods (details in the Text S1). This suggests that the Central North Sea experienced a ubiquitous rise in surface seawater pCO2 during the 2014–2018 period.

An important factor influencing seawater pCO2 is seawater temperature. An increase in temperature can increase the pCO2 without any chemical composition change (Takahashi et al., 2002). We checked if the observed positive pCO2 trends are related to an increase in surface seawater temperature. We found statistically significant negative trends for FerryBox sea surface temperature in three of the six regions, the strongest decline being −0.3 ± 0.1°C yr⁻¹ in the region of permanent stratification (details in the Text S1). This is surprising, since the general trend in the North Sea until 2006 was of warming (Lorkowski et al., 2012). However, temperature data from the independent ERA5 reanalysis product over the same period also show negative, albeit not statistically significant, trends (Copernicus Climate Change Service, 2020). The
isochemical terms show no trend during the study period, suggesting that the $pCO_2$ trends are not driven by temperature changes.

The choice of start and end dates for short time series is important. Our study however took place during a period when the winter North Atlantic Oscillation (NAO) index was always in a positive phase (National Center for Atmospheric Research, 2020). The North Sea carbonate system is known to respond to NAO changes (Kuhn et al., 2010; Legge et al., 2020; Salt et al., 2013), but since there was no change in the NAO phase, we cannot determine to what extent the trends presented here are a result of a shift in large-scale climatic variability. Since it is likely that changes in biogeochemistry have strongly influenced our $pCO_2$ observations, the reduced nutrient inputs to the coastal North Sea in recent decades could be influencing the trends we identified, particularly in ROFI regions (German Environment Agency, 2020; van Beusekom et al., 2019).

The calculated seawater $pCO_2$ trends in this study are some of the highest reported in the literature for the North Sea, where long-term trends were found to be statistically insignificant or approximately parallel to the atmospheric trend (Laruelle et al., 2018; Omar et al., 2019). Similarly, in the neighboring subpolar North Atlantic, long-term trends did not exceed the atmospheric rise (Fröb et al., 2019; Lauvset & Gruber, 2014; Tjiputra et al., 2014). However, strong increasing trends were observed over shorter periods

Figure 3. Surface seawater partial pressure of carbon dioxide anomalies (difference between the individual monthly averages and the 2014–2018 monthly averages). The horizontal axis labels indicate the start of the respective year. Linear trendlines were fitted to all the data points (black) and to winter (NDJF) data points only (blue).
both in the North Sea—a rise of 26–43 µatm between 2001 and 2005 for summer temperature-normalized data (Salt et al., 2013; Thomas et al., 2007)—and in the subpolar North Atlantic—between 5.8 and 7.2 µatm yr⁻¹ for winter 2001–2008 data (Metzl et al., 2010) and as high as 14.1 µatm yr⁻¹ for summer 1993–1997 data (Leseurre et al., 2020). Since other investigations in this region suggested different pCO₂ trends, we compared our data with analogous measurements available in the most recent SOCAT release (Bakker et al., 2020). We concluded that our accelerated trends are determined by the fortuitous choice of start and end dates as well as the much higher data resolution, allowing the identification of statistically significant trends in regions where data are otherwise scarce (details in the Text S1). While the long-term observational trends in the North Sea analyzed by Becker et al. (2021) were similar to, or below the currently reported atmospheric trend of 2.3 µatm yr⁻¹ (Friedlingstein et al., 2019), their shortest length trends calculated over the most recent years were higher (2–3.5 µatm yr⁻¹), confirming the recent accelerated rise in seawater pCO₂. Since all our seawater pCO₂ trends are stronger than the atmospheric trend over the 2014–2018 study period, we expect a weakening of the carbon uptake capacity of the North Sea.

Indeed, the extensive seawater pCO₂ increase in the North Sea has led to changes in the difference between seawater and atmospheric pCO₂ (ΔpCO₂—Figure 4a) and implicitly the carbon uptake capacity of large regions in this shelf sea. The strong undersaturation in the spring observed at the start of our study period weakened, while the summer oversaturation in the southern North Sea strengthened. The divide between the summertime under- and oversaturated regions has shifted to higher latitudes during this time period. The spatio-temporal distribution of the CO₂ flux (Figure 4b) roughly matches that of ΔpCO₂. The average sea to air CO₂ flux in our study area changed from −0.75 ± 0.61 mmol m⁻² day⁻¹ in 2014 to −0.07 ± 0.71 mmol m⁻² day⁻¹ in 2017 and +0.20 ± 0.96 mmol m⁻² day⁻¹ in 2018 (details in the Text S1). These recent estimates suggest a long-term weakening of the North Sea carbon uptake capacity when compared to the start of the century: −4.08 mmol m⁻² day⁻¹ in 2001/2002 (Meyer et al., 2018) or a climatological estimate of −8.5 mmol m⁻² day⁻¹ for the year 2000 (Takahashi et al., 2009). However, our estimates do not cover the northwestern part of the North Sea, which is known to be a stronger CO₂ sink. Integrating over the ∼2.2 × 10¹¹ m² surface area of our study region, we estimate that 0.72 Tg C were taken up here through sea-air gas exchange in 2014, while 0.19 Tg C were released into the atmosphere in 2018. Were these trends to continue, the North Sea could lose its annually averaged carbon sink status. On the other hand, negative feedback effects, such as the generation of alkalinity, could buffer the carbonate system and potentially dampen the current trends (Thomas et al., 2009). For example, in the Wadden Sea and adjacent North Sea coastal regions (part of ROFI-E), total alkalinity is produced during spring and summer, perhaps through denitrification and sulfate reduction in the mostly anoxic bottom sediments, or in the intertidal regions (Beck et al., 2008; Brenner et al., 2016; Voynova et al., 2019). An efficient export of DIC to the North Atlantic
would also improve the North Sea’s carbon uptake capacity (Holt & Proctor, 2008). It is unclear however if these processes will intensify in the future.

5. Conclusions

High resolution (spatial and temporal) pCO2 measurements, such as the ones in this study, are particularly important in dynamic and heterogeneous coastal environments (Schiettecatte et al., 2007). Our observations revealed increasing North Sea seawater pCO2 anomalies since 2014, a trend of CO2 increase larger than the one in the atmosphere. This has consequences for regional air-sea gas exchange and surface seawater biogeochemistry, and here we showed a reduced efficiency in the carbon uptake efficiency. Increasing pCO2 can lead to decreasing pH (Doney et al., 2009) and the potential seawater acidification could inhibit the metabolism of some phytoplankton species (Gao et al., 2019), affect nitrogen cycling (Blackford & Gilbert, 2007), or reduce future ability of CO2 uptake (Humphreys et al., 2020).

We provided the most recent in situ pCO2 observations in the south and central North Sea, which revealed an accelerated, non-thermally-driven increase in seawater pCO2 compared to previous investigations. This data set is shorter than the 12 years timeframe suggested by Keller et al. (2014) as necessary to calculate seawater pCO2 trends from large scale models, and much shorter than the 25 years timeframe found by McKinley et al. (2011) as necessary to discern long-term trends in observations from decadal variability. Furthermore, significant interannual variability is observed in the SOCAT data from the North Sea. However, the FerryBox project is ongoing and improving and the data set will be developed in the future (Petersen & Colijn, 2017). The continuation of these time series will enable revisiting this topic to ensure the calculated trends are not an artifact of decadal variability.

Data Availability Statement

The data are available from the European FerryBox Database (https://ferrydata.hzg.de/) and the Pangaea repository (https://doi.org/10.1594/PANGAEA.930383). The Surface Ocean CO2 Atlas (SOCAT) is an international effort, endorsed by the International Ocean Carbon Coordination Project (IOCCP), the Surface Ocean Lower Atmosphere Study (SOLAS) and the Integrated Marine Biosphere Research (IMBeR) program, to deliver a uniformly quality-controlled surface ocean CO2 database.

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