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Spring–neap tidal cycles modulate the strength of the carbon source at the estuary–coast interface

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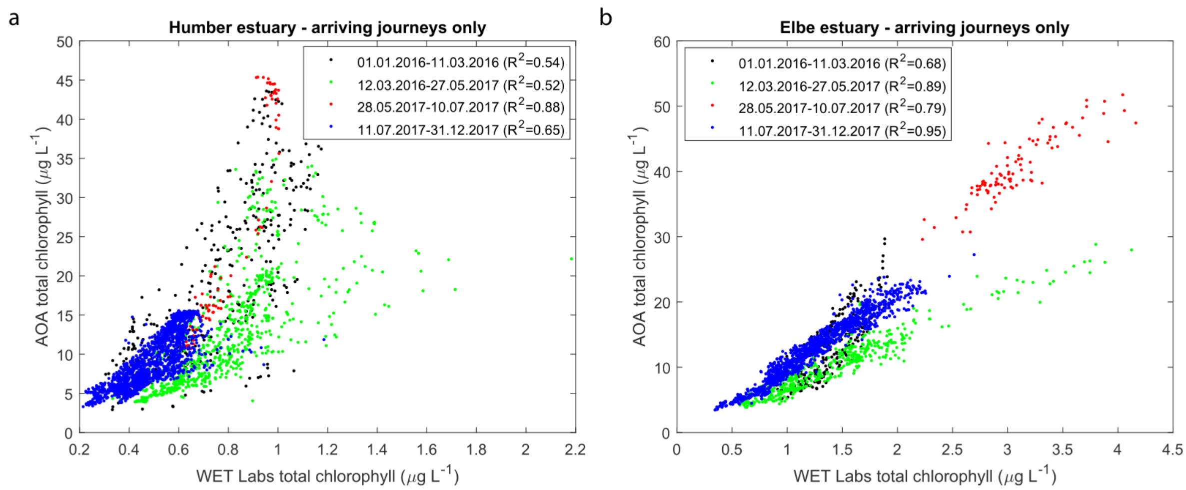

Fig. S1 The linear relationships between the total chlorophyll-a measurements provided by the AOA and WET Labs sensors in the Humber and Elbe Outer Estuaries, respectively, used as one of the steps in the final data correction.

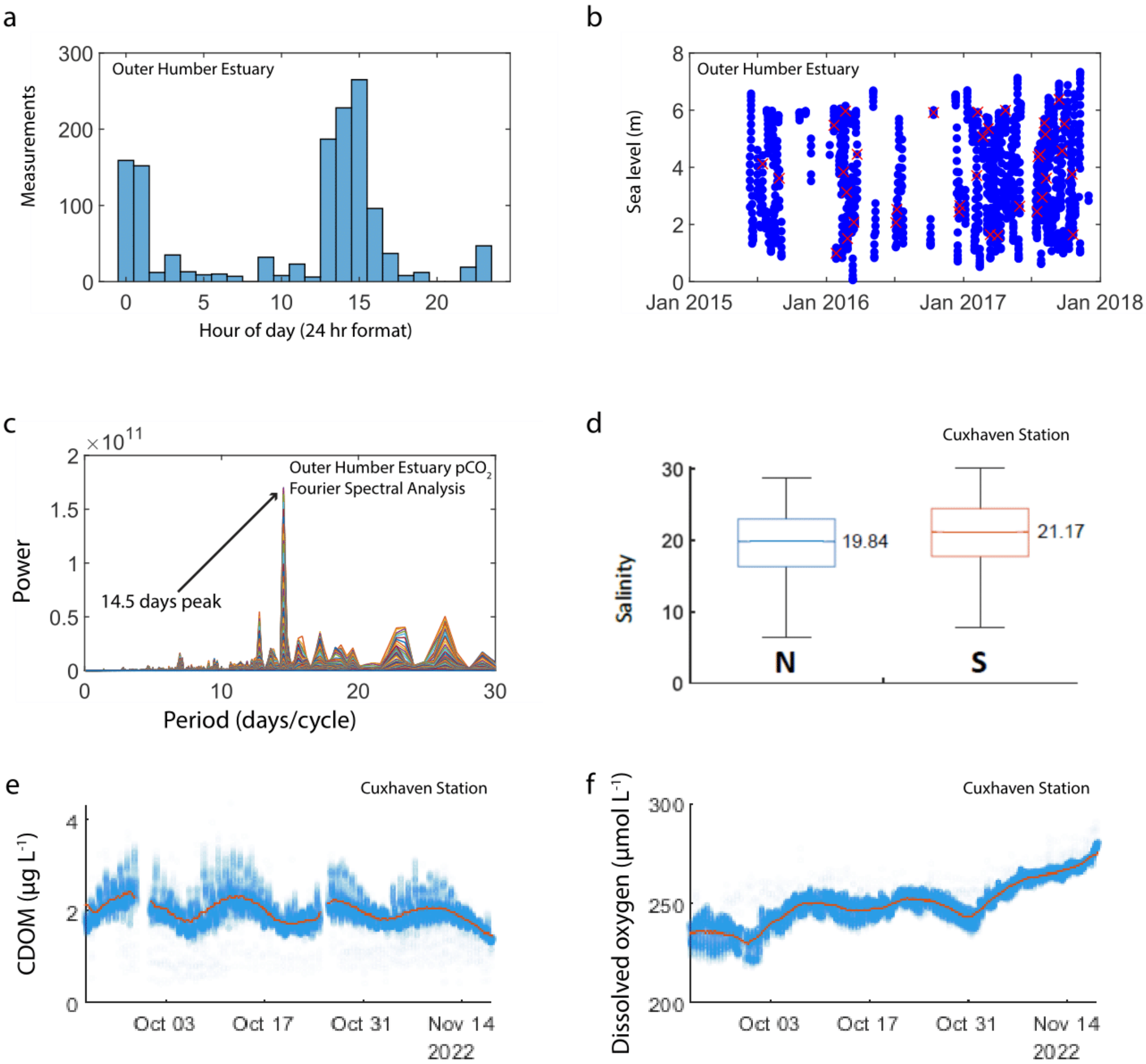

Fig. S2 (**a**) Histogram showing the ship arrival time in Immingham port in the Humber Outer Estuary. (**b**) The sea level at the arrival time (red crosses) compared to the usual sea level range (blue dots) in the Humber Outer Estuary. (**c**) The power versus period (inverse of frequency) plots resulting from a fast Fourier transform analysis on pCO_2 data in the Humber Outer Estuary. (**d**) Box plot of seawater salinity observations at the Cuxhaven fixed-point observing station in the outer Elbe Estuary, comparing the neap (blue) and spring (orange) tide measurements in 2020 and 2021. Outliers more than 1.5 times the interquartile range away from the top and bottom of the box were visually removed and the values of the medians are indicated. We are also showing the cyclical biweekly biogeochemical variability at Cuxhaven by selecting observations from a two month period in fall 2022 for CDOM (**e**) and dissolved oxygen concentration (**f**) observations shown in blue markers and a 3.5 day moving average shown in orange.

The histograms in Fig. S2 and Fig. 2 in the manuscript were obtained by selecting the measurements recorded between 0 ° and 0.02 °W – close to the arrival port in the Humber Estuary, and between 8.50 °E and 8.52 °E – close to the arrival port in the Elbe Estuary. The ship usually sails through the Humber Outer Estuary at 00 UTC, or 15 UTC and through the Elbe Outer Estuary at 01 UTC, 09 UTC, or 20 UTC. The sea level during the scheduled arrival time does not influence the ship sailing through the estuaries. There are fewer red crosses in Fig. S2b than Fig. 2b because the Humber sea level dataset we used reports data every 15 minutes, so there were fewer opportunities for an exact association between the sea level data and the ship measuring exactly in our chosen location.

Fourier analysis for time series spectral analysis in environmental science is usually applied for fixed-point observation stations with continuous data. In our case, the ship was moving through the estuaries and there were data gaps when the ship was not sailing through. We therefore created interpolated products similar to those used to create the Hovmöller diagrams in the main manuscript Figures 4 and 6. The data were interpolated every 1 hour and 0.01 degrees of longitude. We then used these pseudo-fixed and pseudo-continuous time series to investigate the dominant driver period in the pCO_2 variability. The maximum peak was found at a period of 14.5 days in the Humber (Fig. S2c) and 14.1 days in the Elbe (Fig. 2c), similar to the usual periodicity of the spring-neap tidal cycles.

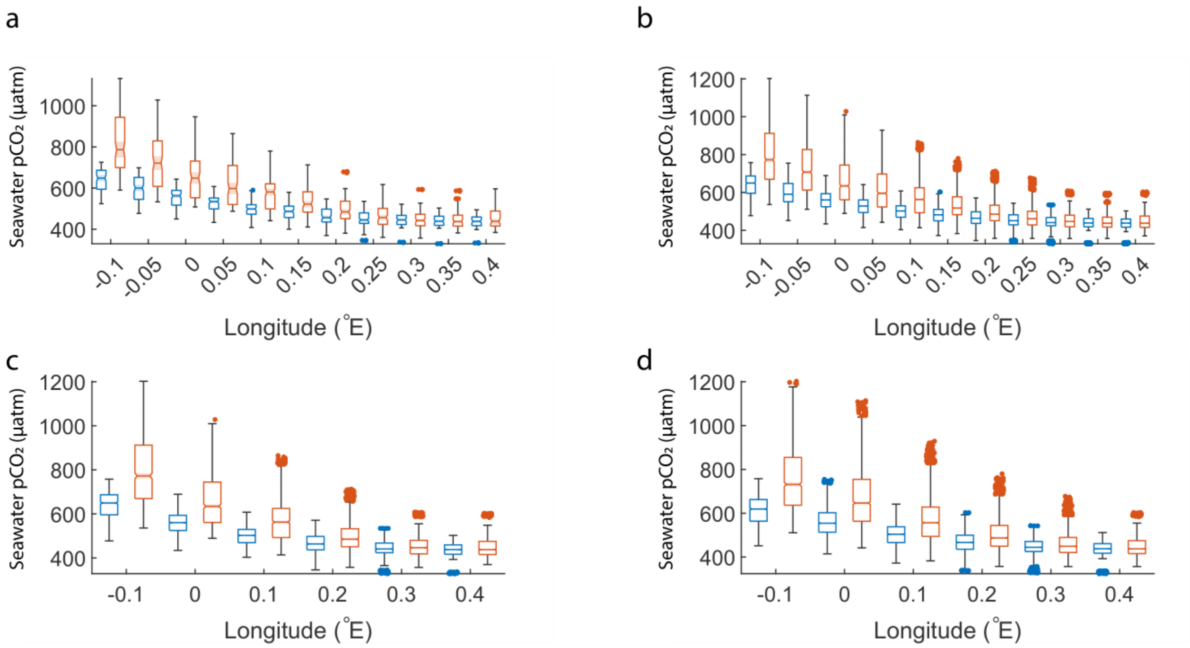

Fig. S3 Box plots of seawater pCO$_2$ observations in the outer Humber Estuary, comparing the neap (blue) and spring (red) tide measurements. The box plots display the median, interquartile range and outliers. When the notches of two box plots do not overlap, they have different medians at the 5% significance level. Compared to the plots in the main manuscript, which were produced selecting data every 0.1° with a ± 0.005° tolerance, here we use different selection criteria: every 0.05° ± 0.005° (**a**), every 0.05° ± 0.05° (**b**), every 0.1° ± 0.005° (**c**), and every 0.1° ± 0.1° (**d**).

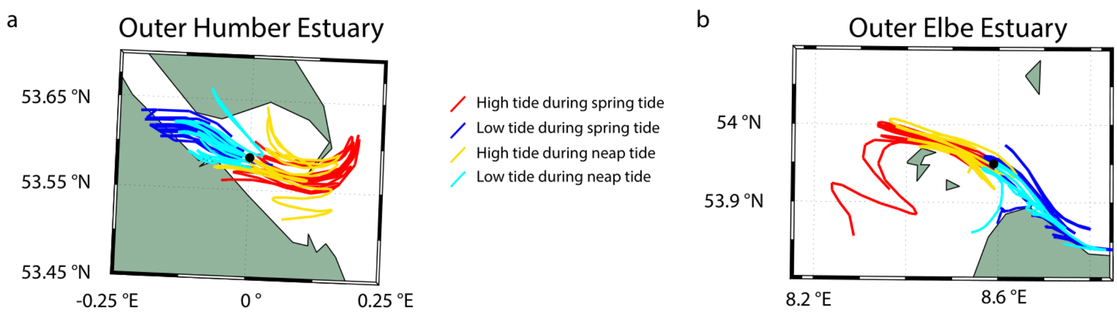

Fig. S4 The trajectories of 24-hour backward simulations of the water mass movement starting at a selected location on the ship route at the high and low tide of the four spring tide and four neap tide events during the two-month period in the Outer Humber Estuary (**a**) and Outer Elbe Estuary (**b**).

The simulations of the water mass movement show that the surface water parcel that reached our chosen location in the outer Humber Estuary at peak high tide came from offshore and had travelled the route twice in the previous 24 hours, according to the typical diurnal tides encountered in this region. When the simulation was initiated at peak low tide, the water movement is in the opposite direction, with the origin of the water parcel being upstream of the chosen location. The spring tide simulations show that the water traveled a greater distance both inshore and offshore compared to the neap tide conditions. The simulations of the water mass movement for the outer Elbe Estuary show a similar behavior as found for the outer Humber Estuary in terms of the direction of movement at high versus low tide. Although having a smaller tidal range than the Humber, the surface water in the outer Elbe Estuary travels a greater distance within the semi-diurnal tidal variation compared to the Humber. However, unlike the Humber, there is no clear difference between the extent of the distance travelled by the surface water between spring and neap tide conditions. All trajectories roughly overlap with the exception of two high spring tide and one low neap tide.