Response letter

We thank the editor and reviewers for their constructive and helpful comments and suggestions. In the following sections, we reply to each comment individually, and explain the changes we have made to the revised manuscript. Note that we also slightly corrected the revised manuscript for stylistic issues and minor mistakes (grammar mistakes, recalculation of N_2O flux densities, etc.). These changes do not affect the conclusion of the manuscript and are shown in the marked-up manuscript version. We address all comments in detail below, but would like to highlight some major changes:

(1) In accordance with comments from the editor and reviewers, we adapted the manuscript to put our research in a wider scientific context, see response below. Furthermore, we changed the title to "Seasonal variability of nitrous oxide concentrations and emissions in a temperate estuary" to address a broader audience.

(2) We recalculated N_2O flux densities and emissions using four different parametrizations for the gas transfer coefficient and different wind speeds.

(3) We adapted most of our figures according to the reviewers suggestions.

Reviewer comments are written in bold italics, our answers are kept in plain font.

General remarks from the editor

Thank you for submitting your paper to Biogeosciences. Two referees have evaluated your paper and provided detailed feedback, in particular regarding the need to improve the presentation and to better put your results in a wider context (beyond a case study). In your detailed rebuttal, you indicate that you will be able to resolve most issues and I therefore believe that a revised paper might be qualified for publication in Biogeosciences. Your revised version will likely be evaluated again by one or both referees.

We understand the need to put our results into a wider context. To accomplish this, we focussed more on the relation between DIN and N_2O as suggested by reviewer 2. In line with several other researchers (Borges et al., 2015; Marzadri et al., 2017; Wells et al., 2018), we found a limited relation between both parameters and thus, we focused on understanding the drivers for this discrepancy. Since we identified organic matter availability as a main driver for N_2O production in the Elbe Estuary, we concluded that in heavily managed estuaries with high agricultural loads, N_2O emissions are clearly linked to eutrophication phenomena as already proposed by Wells et al. (2018). Therefore, we rewrote and restructured parts of our abstract and introduction towards a broader research question centered on N loads as drivers of N_2O production in estuaries, and modified the last section of the discussion and conclusion to address the interplay of DIN and N_2O in estuaries. Furthermore, we changed the title to "Seasonal variability of nitrous oxide concentrations and emissions in a temperate estuary" to address a broader audience. We hope that these changes are sufficient to meet the reviewers' suggestions.

We changed the figures in line with suggestions from both reviewers.

1. Review comment (RC1) – 08.03.2023

Line 17-18: what do you mean by "compensated the effect of decreasing dissolved inorganic nitrogen (DIN) loads"?

Also considering the comments of reviewer 2, we revised the manuscript to highlight the relevance of our research to a broader audience. Thus, we rewrote our abstract, focusing the relevance for a broader scientific community and highlighting the connection between eutrophication and N_2O emissions. We also rewrote this phrase.

Lines	**Change**
L24 - 29	Changed to: "A comparison with previous measurements in the Elbe Estuary revealed that N_2O saturation did not decrease alongside with DIN concentrations after a significant improvement of water quality in the 1990s that allowed for phytoplankton growth to reestablish in the river and estuary. This effect of phytoplankton growth and the overarching control of organic matter on N_2O production, highlights that eutrophication and agricultural nutrient input can increase N_2O emissions in estuaries."

Line 25: How does 0.24±0.06 Gg N_2O y^{-1} emission compare to global estuarine N_2O emission?

We changed the emission calculation as suggested by both reviewers. We removed the emission estimate from the abstract focusing more on the relation with DIN loads and seasonal varying drivers in the Elbe Estuary, which lead to year-round high N_2O emissions. We highlighted the relevance for a broader scientific community by focusing on the connection between N_2O emissions and DIN loads, as well as the linkage to eutrophication in estuaries with high agricultural loads. In the new section 4.5 of our discussion, we now compare N_2O emission estimates and the resulting N_2O:DIN relation across estuaries.

Lines	**Change**
	Removed 0.24 ± 0.06 Gg N_2O yr^{-1} from the abstract
L262-265	Comparison of N_2O saturation with other estuaries
L421-434	Comparison of N_2O emissions and N_2O:DIN relation with other estuaries

Lines 40-42: Denitrification could also occur in anoxic water column contributing to N_2O production (Ji et al., 2018; Tang et al., 2022).

Lines	**Change**
L44-45	Added denitrification in the water column as possible production pathway.

Line 44: specify Port Hamburg as the third largest port in Europe.

Lines	**Change**
L55	Changed "biggest" to "largest"

Line 70: how deep is the Elbe estuary? This gives an idea if sedimentary processes (e.g., N_2O production) may affect N_2O concentration in the surface water column.

Lines	**Change**
L82, L84-85	Added information about the depth of the Elbe Estuary in our study site description

Figure 1: There are too many city names on the map, which is distractive. It may be clearer to label only the key cities like Cuxhaven or island Scharhorn where the Elbe River enters the North Sea or Oortkaten.

Lines	**Change**
L86	Changed Map (Fig. 1)

Lines 85-87: Why transect sampling was performed after high tides? What's the effect of tides on N_2O concentration? Tidal cycles of N_2O concentration have been observed in other estuaries (Goncalves et al., 2015; Barnes et al., 2006).

We chose our sampling strategy (upstream against the outgoing tide) to prevent interference of tidal effects on our measurements. Our aim was to obtain comparable data for each cruise at similar tidal phase, with comparable current and mixing conditions. We started after high-tide and travelled against the outgoing tide to make sure that we did not move with the same water masses while travelling upstream.

Tidal effects will very likely affect nitrous oxide concentrations in the Elbe estuary, but this is not the focus of the present manuscript. We briefly addressed possible tidal effects in the revision.

Lines	**Change**
L94-95	Explained our chosen sampling strategy
L416-420	Addressed the possible effects of tides, diel variations and currents on N_2O emissions

Line 116 in Equation 1: is N2Ocw the partial pressure of N2O in water? Otherwise, the saturation should be calculated as the N2Ocw/N2Oeq*100 where N2Oeq is the equilibrated N2O concentration with atmosphere. Similarly in Equation 3. N2Oair should be N2Oeq.

For our calculations, we used the average atmospheric N_2O concentrations measured on each specific day of the cruise to calculate expected atmospheric equilibrium concentrations considering the solubility function of Weiss and Price (1980) and atmospheric pressure.

Lines	**Change**
L125-126	Changed: "and in the air (N_2O_{air})" to "atmospheric equilibrium concentrations (N_2O_{eq})"
L127	Changed Eq. 1: "N_2O_{air}" to "N_2O_{eq}"

Line 143: Why nitrate concentration increased at 700 km? Are there tributaries or point sources?

We regard this a result of nitrification, rather than a point source. We now refer to potential point sources in the revised version (see below). Dähnke et al. (2008) identified the Elbe estuary along its salinity gradient as a significant source of nitrate with high nitrate production in the maximum turbidity zone (MTZ). Sanders et al. (2018) measured highest nitrification in the Hamburg port region, which was not covered in the research done by Dähnke et al. (2008). Both studies highlighted the importance of nitrification along the Elbe estuary. Further, our results in section 4.2 showed ongoing nitrification fueled by marine organic matter along the mesohaline estuary and indicated that nitrate is produced by coupled remineralization with nitrification from both the riverine and marine site of the estuary.

We believe the offset between region of highest nitrification rates (Port of Hamburg) and nitrate peak in the estuary (stream kilometer 680-700) is a result of different spatiotemporal scales, as suggested by Sanders et al. (2018). They found that the position of the nitrate maximum and nitrate gain over the entire estuary depended on the processing rates and was thus coupled to discharge conditions. However, we decided not to address the offset in our manuscript. Hopefully, the added information regarding the point sources will help to clarify the text, but addressing the nitrate dynamics in more detail is beyond the scope of the paper.

Lines	**Change**
L78-79	Added information about point sources to study site description

Lines 148-149: Why ammonium and nitrite concentration increased near Hamburg Port? Is it due to internal organic matter remineralization or point sources or sedimentary flux?

We restructured section 4.3 addressing possible nitrogen turnover processes and benthic-pelagic coupling in more detail. Therefore, we added a short paragraph to clarify succession of nitrogen turnover in the Port of Hamburg.

Lines	**Change**
L344-348 L352-356	Summarized state of research regarding nitrogen turnover in the Port of Hamburg

Figure 2: It is hard to tell the difference among each cruise with so many colored lines. How about presenting data from the same season using the same color to illustrate the seasonality as a supplementary figure?

We tried to implement the suggestion of the reviewer. However, we felt that the figure did not help to illustrate seasonality and therefore we decided not to include it into the supplements (see figure below).

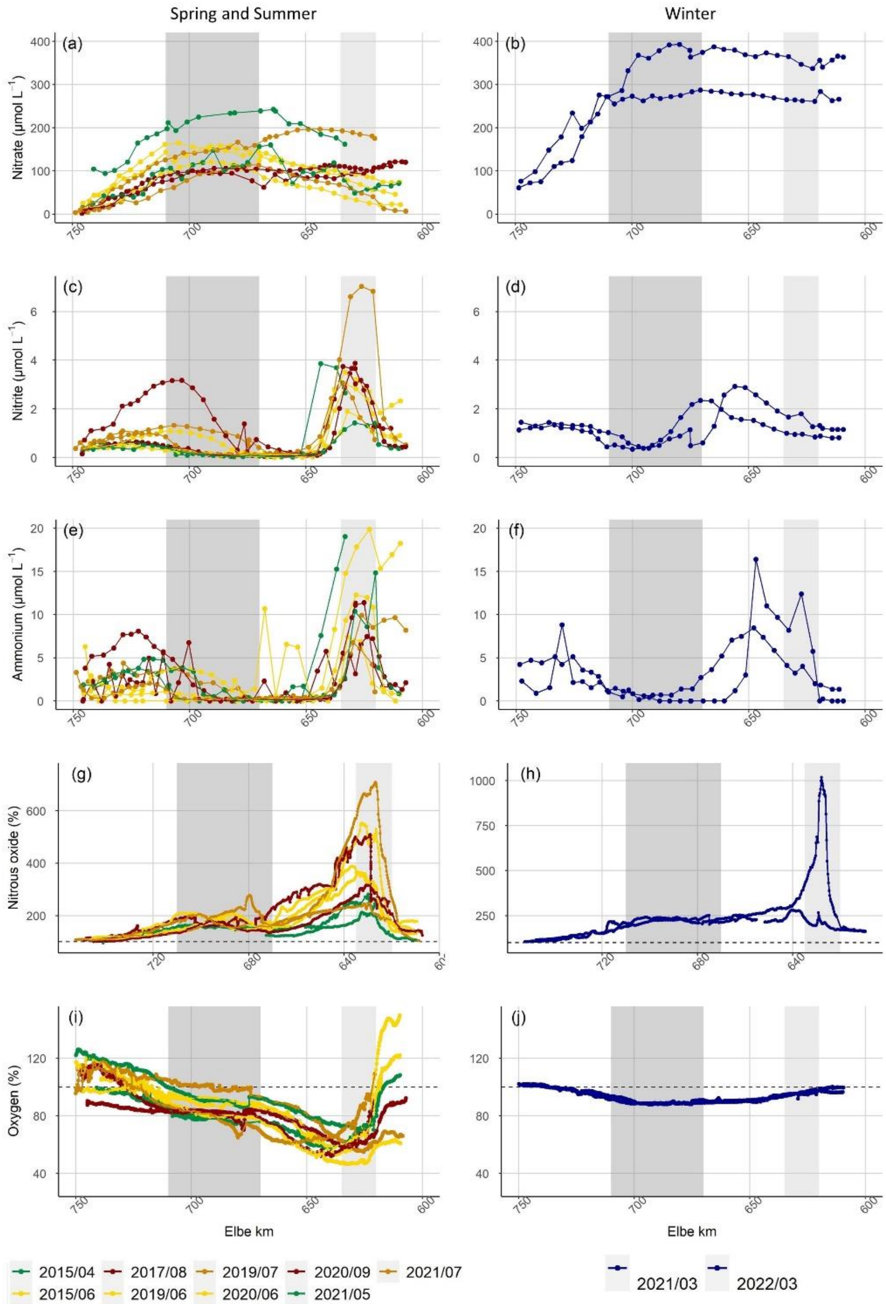

Figure 1: Salinity along the Elbe estuary (a) in spring/summer and (b) in winter. Suspended particulate matter (SPM) concentration in (mg L^{-1}) along the Elbe estuary in (c) spring/summer and (d) in winter. Particulate carbon to nitrogen ratio (C/N) along the Elbe estuary in (e) in spring/summer and (f) in winter. Particulate nitrogen (PN) content in (%) in (g) spring/summer and (h) winter. Particulate carbon (PC) content in (%) in (i) spring/summer and (j) winter. All values are potted against stream kilometers. The Hamburg port region is shown with a gray background. C/N ratios were measured with an Elemental Analyzer (Eurovector EA 3000) calibrated against a certified acetanilide standard (IVA Analysentechnik, Germany). The standard deviation was 0.05% and 0.005% for carbon and nitrogen respectively. Please note that there are no data for the suspended particulate matter composition in 2015.

Lines 211-218 and lines 232-234: Figure 4 a and b are both from June, summer. The linear positive relationship between AOU and excess N2O suggests N2O production from nitrification (e.g., Nevison et al., 2003). The increase in the slope should be interpreted as an increase in the N_2O production yield or external N_2O input (e.g., point source).

We indeed identified nitrification as responsible production processes both in the mesohaline estuary (section 4.2) and the Hamburg port region (section 4.3). In the revised manuscript, we clarified that N_2O yield varied due to changes in production, rather than point sources. As stated above, we also addressed the role of point sources in the study site description.

Lines	**Change**
L78-79	Added information about point sources to study site description
L236	Presented all plots of AOU vs N_2O_{xs} in a revised version of Fig. 3
L237-239	Changed figure caption to match new Fig. 3
L229-235	Changed to: "Plots of excess N_2O (N_2O_{xs}) and apparent oxygen utilization (AOU) revealed excess N_2O along the entire estuary (Fig. 3). During all cruises, elevated riverine N_2O_{xs} entered the estuary (stream kilometer < 620). A linear positive relationship between N_2O_{xs} and AOU suggested nitrification as main production pathway in large sections of the estuary (Nevison et al., 2003; Walter et al., 2004). However, in summer, a change of slope in the Port of Hamburg as well as in the mesohaline section of the estuary suggested either increased in-situ N_2O production or external N_2O input. In winter, we found an increasing slope in the Hamburg Port region and in the oligohaline part of the Elbe Estuary (Fig. 3h, k)."
L265-267	Rewritten: "The relation of N_2O_{xs} and AOU (Fig. 3), with changing slopes in the Port of Hamburg and mesohaline estuary, was determined by either initial riverine N_2O production, or in-situ production along the estuary"
L286-287	Rewritten: "The N_2O peak in the transition between oligohaline and mesohaline estuary was accompanied by a sudden change in the slope of the AOU vs N_2O_{xs} plots, (Fig. 3), pointing towards N_2O production in the oxic water column"

Figure 4: It would be interesting to systematically/statistically assess the relations between excess N_2O and environmental factors like salinity (non-conservative behavior of N2O) or dissolved inorganic nitrogen (infer N_2O production pathways), PN, PC, and SPM. There seems to be a good relation between N_2O and ammonium/nitrite concentration shown in Figure 2.

We understand that a systematically and statistical assessment of the relations would help the reader to follow our discussion. We did assess the statistical relations in sections the previous version of our discussions, but for clarity, we added a section regarding the statistical analysis in the results chapter in the revised manuscript.

During data interpretation, we tested diverse presentation and analysis methods and found that regressions were not necessarily well suited to visualize, describe and analyze our data. Correlations were distorted by the spatial offset between the ammonium, nitrite and N_2O peaks, which we attribute to a succession of nitrogen bearing substances during turnover processes like nitrification. Thus, we chose another way to visualize the data in Fig. 4 (L297) and Fig. S3-S13 of the supplementary material. Furthermore, we addressed the relations of N_2O and various forms of nitrogen to identify N_2O production processes and their controls in the discussion (e.g. L292-L294, L314-L315, and L356-357).

Lines	**Change**
L160-162	Added method section regarding statistical analysis
L240-259	Added result section regarding statistical analysis

Lines 242-243 and Figure 5: What about the variations of the N2O%, oxygen and total nitrogen concentration? The riverine N concentration is decreasing, what about the changes in other point sources of N input along the estuary (e.g., from wastewater treatment plants) or concentration in the estuary?

We agree with the reviewer that a more detailed analysis of a long-term trend of N_2O concentrations and reasons for changes would be very interesting. However, for our study we focus on seasonal variations rather than a long-term trend analysis. With section 4.1, we aimed to compare our results with a broader spatial and temporal scale by including a short comparison to other estuaries as well as with previous measurements from the Elbe estuary. This gives a hint towards temporal trends, but seasonal variability and data coverage make the long-term data difficult to interpret.

Briefly, the biogeochemical processes occurring in the Elbe estuary have drastically changed over the last 50 years: (1) the reunification of Germany and the collapse of East-German industry had led to significant improvements of water quality (e.g. Guhr et al., 2000). (2) The decision to combat eutrophication in the North Sea in the 1980s and (3) improved waste water management resulted in a significant reduction of riverine nutrient loads (de Jong, 2007, p.2019; Van Beusekom et al., 2019; Bergemann and Gaumert, 2010). Dähnke et al. (2008) showed that this led to a change of dominating denitrification towards significant nitrification in the Elbe estuary. Thus, a profound long-term analysis would be in need of its own paper, for which we think our data coverage is insufficient, also considering the seasonal variability. As an example, measurements from only one cruise are available for the 1990s.

Lines	Change
L78-79	Added: “Point sources along the estuary provide only small part of the total nitrogen input to the Elbe Estuary (Hofmann et al., 2005; IKSE, 2018)”
L265	Added comparison to N_2O saturation with other highly modified urban systems (Reading et al. 2020)
L279-280	Included reference to Dähnke et al. (2008) and change of dominating denitrification towards significant nitrification in the Elbe estuary
Fig. S2	Removed Fig. 4 from text and added it to supplementary material with more plot panels and adapted figure caption
L275-278	Added: “However, since the BIOGEST study in 1997 (Barnes and Upstill-Goddard, 2011), N_2O remained relatively stable at ~ 200 % saturation despite a concurrent decrease in TN concentration from ~400 µmol L^{-1} to around 200 µmol L^{-1} (Fig. S2, Hanke and Knauth, 1990; Barnes and Upstill-Goddard, 2011; Brase et al., 2017; FGG, 2021).” instead of the figure to the text.

Line 272: “this suggests”

Lines	Change
L305	Changed to “suggests”

Line 273: how is MTZ defined? What threshold of suspended particle material is used to define the MTZ?

Generally, the occurrence of an MTZ is unique to each estuary and is generated by the balance between river-induced flushing and upstream transport of marine SPM, as well as a function of estuarine geomorphology, gravitational circulation and tidal flow, trapping the particles in the MTZ (Bianchi, 2007; Sommerfield and Wong, 2011; Winterwerp and Wang, 2013). Thus, the MTZ is usually located in the onset of the salinity gradient of an estuary (Burchard et al., 2018).

The MTZ is – also in literature – often assessed based on relative changes in SPM or turbidity, and is mostly located between stream km 670 and 710 (e.g. Bergemann, 2004) in the Elbe estuary. During our cruises, SPM and turbidity were not always measured consistently, depending on instrument and personnel availability – during some cruises suspended particulate matter concentrations were measured using filtration techniques, during some cruises we obtained the data from turbidity sensors, which are not entirely intercomparable. Therefore, we did not define a threshold of suspended particulate matter to define the MTZ, but used relative changes of SPM or turbidity for MTZ identification.

We added color bars indicating the relative change of SPM concentrations to Fig. 4 and supplement material.

Lines	Change
L298	Added color bars to Fig. 4
Fig. S3-S13	Added color bars to each figure

Line 287 and 296-297: clarify the reference: Kappenberg and Fanger, 2007 (German?) and source of organic matter from the North Sea into the Elbe estuary.

We included a peer-reviewed reference (Schoer, 1990) that shows an upstream transport of suspended matter into the Elbe estuary due to tidal transports in the Elbe estuary.

Lines	**Change**
L320	Included a new reference: (Schoer, 1990)

Lines 311-313: How about showing the relations between ammonium, nitrite and N2O in figures?

We decided to show the relation between ammonium, nitrite and N_2O plotted against stream kilometers in Fig. 4 and Fig. S3-S13. We found that the spatial progression of nitrogen containing substances were more illustrative than scatter plots or correlations for each substance, cruise and production areas. These relations were distorted by the spatial offset between the occurring ammonium, nitrite and N_2O peaks, which we explain by a succession of nitrogen bearing substances during turnover processes like nitrification (e.g. section 4.2). Therefore, we find our choice of presentation better suited. To address this issue, though, we added a section about the statistical analysis and relations of individual parameters in the results section. We further rephrased the statement in L311-313).

Lines	**Change**
L160-162	Added method section regarding statistical analysis
L240-259	Added result section regarding statistical analysis
L361-364	Changed to: "Overall, our data showed the succession of ammonium, nitrite and N_2O production (Fig. 4 and supplementary material S3-S13) confirming simultaneous denitrification and nitrification responsible pathways for N_2O production in the Port of Hamburg (Brase et al. 2017)."

Line 315: What are R values? R is positive for nitrite concentration.

R is the Pearson correlation coefficient. We added a short section about our statistical analysis in the *Methods* section of our manuscript. Nitrite concentrations correlated positive with N_2O leading to a positive correlation coefficient.

Lines	**Change**
L160-162	Added method section about statistical analysis

Line 320-321: Is nitrification responsible for the remaining oxygen consumption?

Yes, nitrification is responsible for the remaining oxygen consumption. We have clarified this in the text.

Lines	**Change**
L369	Added: "whereas the remaining 25 % stem from nitrification (Schöl et al., 2014; Sanders et al., 2018)"

Line 326 and Figure S1: why C/N ratio was so high in 2021 March?

We double-checked our measurements, and the data appear correct and sound. We have no easy explanation at hand, but speculate that a calcareous algae bloom in the North Sea might be a potential cause. However, we have no further evidence for this hypothesis. We will not address this further, as the C/N ratios are not a crucial parameter for our discussion. However, we would like to keep the data in the manuscript as they might be insightful for later research and other researchers.

Line 345-347: "Ammonium and N_2O concentrations are high in the pore water of underlying sediments". Reference or example of the concentration. What about the timing of deepening and dredging works in the Hamburg Port compared to the cruise periods?

The Elbe estuary is constantly deepened and dredged along the entire transect to grant access for big container ships. However, we did not compare operation locations with the measured N_2O concentrations except for our March cruises, as we did not see big differences in the spatial variation of the N_2O profiles, which were not explainable by in-situ production, nor found strong correlations between N_2O and suspended particulate matter concentrations.

Lines	**Change**
L82	Added: "The Elbe Estuary is dredged year-round"
L340-342	Added references and rephrased: "Ammonium concentrations in the sediment pore water are high (Zander et al., 2020, 2022) and N_2O can be produced by nitrifier-denitrification in the sediments (Deek et al., 2013)"
L331-350	Moved from section 4.4 to 4.3
L389-410	Shortened discussion about possible effects of deepening and dredging in section 4.4

Lines 360-361: Has there been any N_2O measurement from this wastewater treatment plant (WWTP) Köhlbrandhöft? The ammonium concentration in 2021/03 is not exceptionally high compared to previous cruises (e.g., 2020/06). What about the direct N2O output from the wastewater treatment plant?

The operators of the WWTP measured N_2O concentrations during our cruise, but did not detect elevated N_2O concentrations. However, direct N_2O output from the WWTP was not measured and the increased ammonium loads leaving the WWTP corresponded to the measured increase of N_2O concentration. We assume that excess N_2O is not produced within WWTP itself, but stems from elevated ammonium concentrations in the Elbe that are introduced with warmer waste water.

We likely did not see an extraordinary ammonium peak due to the distance of the WWTP outflow and our measurement transect, ~ 2 km. The outflow of the WWTP is located in the Southern Elbe, which joins the sample stretch at stream kilometer 626. Ammonium is probably rapidly converted to N_2O as the warmer and biological active waste water enters the Elbe estuary before it reaches the Northern Elbe (and our sampling site).

We were admittedly surprised by the extraordinary N_2O concentrations in March 2021, and even more so when the results were not reproduced in the following year. Consequently, we concluded that an extraordinary event must have caused the N_2O

peak. Since we could not detect any relation to the deepening and dredging work in the Port area and our measurements fitted to extraordinary operation condition in the WWTP, we assumed this might be the source, especially as our hypothesis was confirmed by the WWTP operators. Additional measurements confirmed that N_2O concentration was not elevated near the WWTP outlet under normal conditions.

Lines	**Change**
L399-410	Revised: "Another possible source of N_2O is the WWTP outflow in the Southern Elbe that joins the main estuary at stream kilometer 626 (Fig. 1), matching the N_2O peak at stream kilometer 627 (Fig. 2h). As explained above (section 4.3), the effect of this WWTP on N_2O saturations under normal conditions should be negligible. This peak can be the result of an extraordinary event during our sampling. We indeed found that an extreme rain event occurred on March 11th 2021 (HAMBURG WASSER, pers. Comm., Laurich 2022) with a statistical recurrence probability of one to five years (https://sri.hamburgwasser.de/, last access: 04.04.2023). This rare event caused aggravated operation conditions in the WWTP at the time of sampling. While the operators could still meet the limits for the effluent levels of nitrate and ammonium, higher than usual ammonium loads exited the treatment plant at this time. We assume that these elevated ammonium WWTP loads, were rapidly converted to N_2O as the warmer and biologically active waste water entered the Elbe Estuary in March 2021.An important factor for aggravated conditions was a temperature drop in the WWTP caused by cold rain water, we hypothesize that a similar rain event in warmer months would not lead to comparable N_2O peaks."

Figure 7. Use month or season as the x axis instead of cruise number? Add description of the boxplot. Why not adding error bars for emissions?

As we restructured section 4.5 of our discussion, we also changed the figure. However, we considered the comment of the reviewer including description of the boxplots.

Lines	**Change**
L442	Deleted Fig. 7 included new Fig. 5
L443-447	Included description of boxplots in figure caption.

Table 3. How is annual N_2O emission calculated? Since there is a seasonal variation in the N_2O flux, monthly or seasonal N_2O emission may be more representative. Because N_2O flux was measured at a high spatial resolution, it may be useful to calculate the N_2O flux across the whole estuary by integrating the flux and area section by section (e.g., River section, Hamburg port, Oligohaline section) instead of multiplying the average N_2O flux by the whole area of Elbe estuary.

We recalculated emissions as suggested by the reviewer: We separated the Elbe estuary into five regions: limnic (stream kilometer 585 to 615), Port of Hamburg (stream kilometre 615 to 632), oligohaline (stream kilometre 632 to 704), mesohaline (stream kilometre 704 – 727) and the polyhaline section (stream kilometre 727 to 750). Respective areas are found in the supplementary material S6. For seasonality, we divided our cruises: winter (March), spring (April and May), summer (June and July) and late summer/autumn (August and September). Following this, we calculated daily emissions for each section and each season. To upscale to annual emissions, we applied our calculated emissions estimates to months without measurements (winter: January to March and November to December, spring: April to May, summer: June to July and late summer/autumn: August to October).

In line with reviewer 2, we also considered different wind speeds and parameterizations to calculate the gas transfer coefficient for flux densities calculation and emission estimates. Thus, we rewrote the results section and included our emissions estimates in section 3.3 “N_2O flux densities and emissions”.

Lines	**Change**
L142-151	We included a detailed description of the calculation in the “Method” section
L204-220	We included detailed results in the “Results” section (results section was rewritten to include new emission calculations)
Table S2	We included flux-densities calculations using other parametrizations and wind speeds in the supplementary material
L262 and L414-434	We changed flux densities and N_2O emission estimates in the revised manuscript so that they fit to the new calculations

Line 406: Why do you think there is no seasonality in N_2O emission? N_2O flux is different comparing spring, summer and winter shown in Table 3.

For the revised manuscript, we calculated emissions as suggested by the reviewer and described above. We restructured our last section of the discussion 4.5 in line with suggestions of the other reviewer focusing on the relevance of our research for a broader audience, investigating the N_2O:DIN relation discussing seasonal changing drivers for N_2O production and emissions. Thus, we also changed our abstract and conclusion.

Lines	**Change**
L413-447	Restructured and rewritten section 4.5
	Removed from abstract: “Surprisingly, estuarine N_2O emissions where equally high in winter and summer”
	Removed from conclusion: “We saw no seasonality in N_2O emissions, …”

2. Review comment (RC2) – 04.04.2023

1. Converting dissolved concentrations to emissions: Like many studies, here the authors measured the dissolved concentration of the gas (N2O), and then converted this into water-air emissions based on a gas transfer velocity (k). Gas transfer velocities can be highly variable, especially in estuaries where the importance (and magnitude) of factors like wind,

flow velocity, and water depth can all vary a lot over space and time. This complexity is reflected in the wide range of empirical k value parameterisations that have been developed for estuaries (see e.g., Rosentreter et al. (2021), also Hall and Ulseth (2019) for a good review of the topic, albeit for freshwater systems). However, here the authors convert measured concentrations to emissions using a single parameterisation (L116-125). This creates considerable uncertainty, which is not reflected in the reported estuary emissions estimates. Emissions should be recalculated using 3-5 k parameterisations, and the variability of these outputs reported in the results / figures. More information should also be supplied on the wind speed data used in the parameterisations. It is important to understand how the values measured during the campaigns compare to 'average' conditions around the estuary when considering the upscaled seasonal emissions values (e.g., are emissions estimates likely to be on the low side because cruises were only done on low-wind days?).

As suggested, we included calculations based on three other parameterizations. We calculated and discussed the effect of wind speeds in relation to average conditions along the estuary and added the information concerning average wind speed.

Lines	**Change**
L128-151	Calculated flux densities and emissions with four parametrizations and different wind speeds
L204-220	We included detailed results in the "Results" section for the new calculations of N_2O flux densities and emissions
Table S2	We included flux-densities calculations using other parametrizations and wind speeds in the supplementary material
L262 and L414-434	We changed flux densities and N_2O emission estimates in the revised manuscript so that they fit to the new calculations
L416-420	Addressed the uncertainties in the "Discussion" section

2. Relationship between N2O and N inputs: As discussed in the paper intro here, aquatic N2O emissions are generally predicted based on N loads to the system (i.e., leaching of N, inputs from WWTPs, etc). While here N2O emissions are discussed and presented, the N inputs side of the equation is not clear to me. In the site description it says that annual N load were ~80 Gg y-1 (L67) – but does this mean the estuary receives this much N, or discharges this much N? And how does this break down between sources (WWTPs v river discharge)? On L231 it says that N2O emissions were low relative to other high N input estuaries. But how do N inputs into the Elbe stack up compare to these other estuaries? I particularly wonder how the 'point source' N loads around the port might stack up with those in other urban estuaries where N2O emissions have been measured, e.g., (Wells et al., 2018). Constraining the other side of the N2O emissions v N inputs equations is critical for placing these findings into a more global context. Within the study, more information on N loads will also be important for picking apart the seasonal emissions drivers. How much N enters the estuary at the port? Is this input seasonally variable? Did it vary between the sampled years? Do these variations correspond with variations in emissions (particularly the size of the winter N2O-excess excursion)?

The N-loads of 80 Gg yr^{-1} are calculated from concentrations data at the station "Seemanshoeft", which is located at the Hamburg Port (stream kilometer 628.9). In general, point sources play a subordinate role in the nitrogen input of the Elbe estuary (Hofmann et al., 2005; IKSE, 2018) with dominating agricultural sources in the upper and middle Elbe River (Hofmann et al., 2005; Johannsen et al., 2008). Further, we calculated annual varying DIN and total nitrogen (TN) loads for our observation period and listed the results in the supplements as recent TN loads were lower varying between 43.1 kt-N yr^{-1} and 70.2 kt-N yr^{-1} from 2015 to 2021 (FGG, 2021).

We restructured our section 4.5 of the discussion: We now address the relation of N_2O emissions and N inputs based on a comparison of the amount of DIN released as N_2O (for annual loads, seasonal loads and for each cruise separately). In the revised version, we compare the relation of flux densities and N_2O emission versus N input to a wider set of literature data and across estuaries. We refer to the change of drivers of N_2O emissions in winter (high riverine input and nitrification) versus spring and summer (organic matter) more clearly. Finally, we highlight the link of N_2O emissions to eutrophication to broaden the scope of our study, which we also now address in the revised abstract, introduction and conclusion.

Lines	**Change**
L19-20	Rewritten abstract: "However, in spring and summer, N_2O saturation and emission did not decrease alongside lower riverine nitrogen loads […]"
L47-54	Adding new research aim to investigate the driving factors of N_2O emissions along the estuary as well as looking into N_2O and DIN relation.
L78-79	Added: "Point sources along the estuary provide only small part of the total nitrogen input to the Elbe Estuary (Hofmann et al., 2005; IKSE, 2018)"
L413-447	Rewritten and restructured section 4.5 focusing on N_2O:DIN relation and comparing our results with other estuaries
L449-469	Rewritten conclusion
Table S4 and S5	Included annual and seasonal nitrogen loads for station Seemanshoeft

1. Introduction: It is not entirely clear how studying N2O in the Elbe estuary will advance understanding of aquatic N2O emissions / fill a needed research gap. A stronger transition between the penultimate and last paragraphs of the discussion is needed (how does the present study relate to the broader literature). Stating a testable hypothesis, rather than just site-specific study objectives, in the last paragraph may also help make the study more clearly relevant to the broader scientific community. Is this just a case study or will the data help us understand estuary N cycling and gaseous emissions in a more fundamental way?

In the revised manuscript, we now elaborate a research question of interest for a wider audience by studying drivers for the reported discrepancies in the N_2O:DIN relation (Borges et al., 2015; Marzadri et al., 2017; Wells et al., 2018). Overall, the aim of our research is to provide insight on drivers of N_2O productions and emissions from heavily anthropogenic impacted estuaries.

Lines	Change
L47-54	Elaborated new research question from interest for broad scientific community
L58-59	Added overall goal of our research

2. Discussion: While I think overall the data interpretation makes sense, the discussion section currently reads as a bit descriptive and could go further to place these findings in a broader context (rather than just the context of how we understand the Elbe River Estuary). This could include in particular more discussion of N cycling in urban estuaries / where there are point N pollution. Where else in the world would the observed seasonal patterns be expected to be found? I also think there is missing some discussion of 'alternative hypotheses' – work through the logic of why denitrification is not thought to be the primary driver of N2O in the estuary, and why benthic production (e.g., (Chen et al., 2022)) is also ruled out. Also please carefully edit to ensure that you are not repeating results in this section.

We now discus alternative hypotheses in more detail as described below in the replies for the individual comments. We also discuss the effects of benthic fluxes and production in more detail (see specific comment below). We have removed results sections from the discussion section, and focused more on comparing our finding with research from other estuaries to address a broader audience.

3. Conclusion: This is currently very focused on untangling what exactly is happening within the Elbe River Estuary, but the implications for broader understanding of aquatic N2O production and emissions are not clear.

We modified our research question towards general controls of N_2O production and emissions from estuaries with high nitrogen loads. Consequently, we rewrote large parts of the discussion section 4.5. Thus, we also changed our conclusion and abstract to highlight the new findings.

Lines	Change
L27-29	Rewritten abstract: "This effect of phytoplankton growth and the overarching control of organic matter on N_2O production highlights that eutrophication and agricultural nutrient input can increase N_2O emissions in estuaries."
L47-54	Elaborated new research question from interest for broad scientific community
L58-59	Added overall goal of our research
L413-447	Rewritten and restructured section 4.5 focusing on N_2O:DIN relation and comparing our results with other estuaries
L449-470	Rewritten conclusion

L17-19: This sentence is not clear (how does N2O 'compensate' for decreasing N loads?), please reword.

This statement was also unclear to reviewer 1. Please see comment above for the changes in the revised version of our manuscript.

L22-24: "In winter, high riverine N2O concentrations led to high N2O emissions from the estuary, whereas in summer, estuarine biological N2O production led to equally high N2O emissions." This is I think getting at a crucial point (that although seasonal magnitude of N2O fluxes did not differ the drivers of these fluxes did), the meaning is not clear. What is the difference between winter 'high N2O concentrations' and summer 'high N2O production'? Reword to be more precise about these differences.

We revised the manuscript to highlight the relevance of our research for a broader audience. Thus, we rewrote our abstract, focusing on a comparison of our results with other research in heavily managed estuaries, highlighting that we found seasonal varying drivers of N_2O emissions that did not scale with DIN loads and were directly linked to eutrophication phenomena. Thus, we also re-wrote this phrase.

Lines	**Change**
L18-21	Changed to: "We found that the estuary was a year-round source of N_2O, with highest emissions in winter when dissolved inorganic nitrogen (DIN) loads and wind speeds are high. However, in spring and summer, N_2O saturations and emissions did not decrease alongside lower riverine nitrogen loads, suggesting that estuarine in-situ N_2O production is an important source of N_2O."

L70: How often is 'on a regular basis'? e.g., weekly, yearly, every three years?

Lines	**Change**
L82-85	Added clarification

L86: Suggest changing 'steaming upstream' to 'travelling upstream' (steaming sounds a bit antiquated)

Lines	**Change**
L95	Changed "steaming" to "travelling"

L101-104: More information on number of nutrient samples collected per survey, as well as method detection limits and precision, would be useful.

We will included the detection limits and also added a short description addressing the range of samples numbers.

Lines	**Change**
L105	Clarified numbers of samples taken
L113-114	Added detection limits

L109: How often was 'regularly'? e.g., before each cruise?.

Lines	Change
L119-120	Clarified: "Twice a day, we analyzed two standard gas mixtures of N_2O in synthetic air (500.5 ppb ± 5 % and 321.2 ppb ± 3 %) to validate our measurements."

L116: How often, and how, was dry air sampled during each cruise?

Lines	Change
L126-127	Clarified: "Atmospheric N_2O dry mole fractions were measured before and after each transect cruises using an air duct from the deck of the research vessel."

L122: The term 'flux densities' is not one I'm familiar with – more common to see something like 'water-air fluxes' or 'evasion'.

In physics, fluxes per unit area are called flux densities (Nitrous oxide mass flux | environmentdata.org, 2023), whereas the term "fluxes" only describe amount of N_2O moving between the sea-air interface and is unitless. The terms are indeed often used synonymously.

We would like to stick to the term "flux densities", which has been used previously by other researchers (e.g. Brase et al., 2017; Bange et al., 2019; Morgan et al., 2019; Forster et al., 2009).

L123-125: Please provide some clarification on the upscaling approach used to calculate whole-estuary emissions. From the description it sounds like the mean flux was multiplied by the estuary surface area? Or were these calculations area-weighted, and if so at what resolution?

We changed our way of estimate N_2O emissions, which we elaborated in detail for a comment of reviewer 1 above.

Lines	Change
L142-151	We included a detailed description of the calculation in the "Method" section
L213-220	We included detailed results in the "Results" section
Table S2	We included flux-densities calculations using other parametrizations and wind speeds in the supplementary material
L262 and L414-434	We changed flux densities and N_2O emission estimates in the revised manuscript so that they fit to the new calculations

L127-128: Citation?

Lines	Change
L154	Added a citation

L148: Low relative to what?

“low” is less than 1 µmol L^{-1} – we will specify this.

Lines	Change
L177	Added: “(< 1 µmol L^{-1})”

L163-189: Separating the N2O data into different sections for the different units (molar concentrations, % saturation, water-air fluxes) is confusing as these are all inter-related. For instances, it is hard to make sense of the meaning of the molar concentrations without also considering whether these reflect changes in percent saturation (i.e., changes due to water temperature / salinity v source / production). I suggest integrating these lines of data (and thinking) to provide a clearer picture of estuary N2O patterns.

In Figure 2, we changed N_2O concentrations to N_2O saturations. Thus, we removed our previous Fig. 3 from the text. We also changed the results sections accordingly.

Lines	Change
L182-190	Replaced Fig. 2i, j with N_2O saturations and changed figure caption
L191-203	Changed section 3.2 to “Atmospheric N_2O and N_2O saturation”
L204-220	Changed section 3.3 to “N_2O flux densities and N_2O emissions”
	Deleted the description of N_2O concentrations
	Removed previous Fig. 3 from the text

L204: High relative to what?

Lines	Change
L225	Specified: “(> 100 %)”

L209-218: The AOU v N2O-excess relationship really highlights the importance, and seasonality, of the port for estuary N2O emissions, with distinct peaks in the winter and consumption in the summer. Given that this underpins the discussion around seasonal N2O source switching, I wonder if there is a way to include more than just these 'representative' plots in the main text. For instance, a table with info on AOU v N2O-excess slopes, and min-max range for the port? I think if the port data is excluded something like an ANCOVA could be used to compare shifts in slope relationships.

In the Port region, N_2O_{xs} and AOU had no linear relation during most of our cruises (e.g. June 2015 and August 2017). Therefore, a table with slopes and min-max ranges would miss crucial information. However, we will include figure S2 from the supplement in the main text so that we do not only show representative plots but all cruises.

Lines	**Change**
L236-239	Included all AOU vs N_2O_{xs} plots in Fig. 3 and changed figure caption

L256-260: Interesting relationship between NO2- and N2O. This could be connected to previous work, e.g., (Sharma et al., 2022; Smith and Bohlke, 2019; Wertz et al., 2018)

Lines	**Change**
L291-296	Added: "This co-occurrence of nitrite accumulation and increased N_2O saturation has been interpreted as signs for N_2O production via denitrification (e.g. Wertz et al., 2018; Sharma et al., 2022). However, denitrification does not seem likely in this oxic water column. Such a succession of nitrite and ammonium peaks is also typical for remineralization and nitrification, and the slight decrease of oxygen concentrations around the higher N_2O saturation (Fig. 2g and i) suggests oxygen consumption, possibly caused by these two processes."

L314-316: This should be in the results section

Lines	**Change**
L240-259	Added section 3.4 describing results from our statistical analysis and removed this paragraph

L318-324: Interesting! I wonder if the algae themselves could also be contributing to the N2O production, e.g., (Fabisik et al., 2023)

Lines	**Change**
L372-373	Added: "Fabisik et al. (2023) showed that algae could additionally contribute to N_2O production.

L330-332: This makes sense, but is this the only possible explanation for high emissions around the port area? What about wastewater inputs, enhanced benthic production, and/or enhanced groundwater connectivity due to dredging? Some discussion of these points will make this conclusion stronger.

We restructured our discussion focusing more on elaborating potential causes for the high N_2O peak. We focused on (1) point sources – mainly the wastewater treatment plant, (2) deepening and dredging operations in the Port of Hamburg and (3) in-situ production, discussing both production in the water column and sediment. Therefore, we moved parts of section 4.4 to 4.3

Lines	**Change**
L330-356	Restructured the paragraph
L330-356 and L383-410	Moved parts from 4.4 to 4.3 and thus, adapted section 4.4

L357-358: How extreme was this rain event, i.e., was it more extreme than any rainfalls over the other five years of sampling? This will help verify the attribution, and also put the pulse into context. It would then be instructive to recalculate the seasonal budget with and without this pulse.

Considering the statistical recurrence probability, it is likely that similar events occurred during the last five years, but so far not during a comparable sampling cruise. Moreover, we assume that temperature was equally important as water mass, because cold rain water in the waste water treatment plant led to aggravated operation conditions. Thus, in warmer months the effect might be different. We discuss this in more detail in the revised manuscript.

Lines	**Change**
L213-220	Calculated N_2O emissions estimates with and without the pulse and reported the variability
L403-404	Added statistical recurrence probability
L408-410	Added: “An important factor for aggravated conditions was a temperature drop in the WWTP caused by cold rain water, we hypothesize that a similar rain event in warmer months would not lead to comparable N_2O peaks”

L392: If large riverine loads were the main driver, wouldn’t there be a continuous decrease in concentration over distance? But instead emissions peak in the port.

We restructured the section 4.5 and thus removed this statement from the text.

Lines	**Change**
L413-447	Restructured section 4.5

Table 2: Standard deviations for the air N2O concentrations would be helpful

Lines	Change
L210-212	Added standard deviations to the Tab. 2

Fig. 1: The most important pieces of info in this map (where sampling points are, where the port is, where the MTZ is) don't really stand out. Can you adjust colours, font size, etc to better highlight these key features? A scale bar for the main map would also be helpful.

We changed the style of map to highlight key features and important locations as suggested by the reviewer.

Lines	Change
L86-88	Changed Fig. 1 and figure caption

Fig. 2: I'm not sure that there is much value in showing N2O concentrations (in nM) here – the % saturation information in the subsequent figure is much more effective for showing fluctuations between seasons and over the salinity gradient, given the relatively low concentrations and the impact of both temperature and salinity on N2O solubility. It would also be helpful to have 'summer' and 'winter' headings at the top of the two columns to make the point of difference more immediately obvious.

Lines	Change
L182	Included a heading to the plot
Fig. S1	Included a heading to the plot
L182-190	Changed Fig. 2i,j from N_2O concentrations to saturations and changed figure caption
	Removed previous Fig. 3 from the text

Fig. 3: A unified y axis scale would be helpful for picking out seasonal differences

Lines	Change
	Removed previous Fig. 3 from the text

Fig. 4: As above, unified axes scales would make differences between sampling dates much clearer.

We decided against unified y-axis for all cruises. The March 2021 cruise differs so much that it is hard to see variabilities in the other cruises if we use the same y-axis. However, we used unified x-axes and y-axes scales for all other cruises.

Lines	Change
L236	Included all cruises in Fig. 3 with unified x-axes and unified y-axes except for March 2021
L237-239	Changed figure caption

Fig. 5: Different y axes are needed for the different variables (N2O, O2, TN), if not different plot panels

Lines	**Change**
Fig. S2	Moved this figure to the supplementary material
L275-278	Added instead of the figure: “However, since the BIOGEST study in 1997 (Barnes and Upstill-Goddard, 2011), N_2O remained relatively stable at ~ 200 % saturation despite a concurrent decrease in TN concentration from ~400 µmol L^{-1} to around 200 µmol L^{-1} (Fig. S2, Hanke and Knauth, 1990; Barnes and Upstill-Goddard, 2011; Brase et al., 2017; FGG, 2021)“
Fig. S2	Included a plot panel for each variable and changed figure caption

Fig. 6: I found this to be too many variables on the same plot to make much logical sense out of. I suggest separating into two panels, one for all of the N species (y axis unit is uM N), and then another with two y axes, one for PN and one for C/N.

We adapted the plot as suggested by the reviewer.

Lines	**Change**
L298-304	Changed figure and figure caption
Fig. S3-S13	Changed figure and figure caption

Fig. 7: It would be helpful to use a different pattern or colour scheme to distinguish the winter v summer cruises.

We restructured and rewrote this part of the discussion and removed Fig. 7. The new Fig. 6 shows seasonal variations in N_2O saturation, nitrous oxide emissions, DIN loads and N_2O:DIN ratios. We considered the comment of the reviewer regarding the color scheme for the new figure.

Lines	**Change**
	Removed previous Fig. 7
L442-447	Added new Figure

References

Nitrous oxide mass flux | environmentdata.org: http://www.environmentdata.org/archive/vocabpref:20656, last access: 27 April 2023.

Bange, H. W., Sim, C. H., Bastian, D., Kallert, J., Kock, A., Mujahid, A., and Müller, M.: Nitrous oxide (N_2O) and methane (CH_4) in rivers and estuaries of northwestern Borneo, Biogeosciences, 16, 4321–4335, https://doi.org/10.5194/bg-16-4321-2019, 2019.

Bergemann, M.: Die Trübungszone in der Tideelbe - Beschreibung der räumlichen und zeitlichen Entwicklung, Wassergütestelle Elbe, 2004.

Bergemann, M. and Gaumert, T.: Elbebericht 2008, Flussgebietsgemeinschaft Elbe, Hamburg, 2010.

Bianchi, T. S.: Biogeochemistry of Estuaries, Oxford University Press, New York, 706 pp., 2007.

Borges, A. V., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooh, F., Geeraert, N., Omengo, F. O., Guérin, F., Lambert, T., Morana, C., Okuku, E., and Bouillon, S.: Globally significant greenhouse-gas emissions from African inland waters, Nat. Geosci., 8, 637–642, https://doi.org/10.1038/ngeo2486, 2015.

Brase, L., Bange, H. W., Lendt, R., Sanders, T., and Dähnke, K.: High Resolution Measurements of Nitrous Oxide (N2O) in the Elbe Estuary, Front. Mar. Sci., 4, 162, https://doi.org/10.3389/fmars.2017.00162, 2017.

Burchard, H., Schuttelaars, H. M., and Ralston, D. K.: Sediment Trapping in Estuaries, Annu. Rev. Mar. Sci., 10, 371–395, https://doi.org/10.1146/annurev-marine-010816-060535, 2018.

Dähnke, K., Bahlmann, E., and Emeis, K.-C.: A nitrate sink in estuaries? An assessment by means of stable nitrate isotopes in the Elbe estuary, Limnol. Oceanogr., 53, 1504–1511, https://doi.org/10.4319/lo.2008.53.4.1504, 2008.

Deek, A., Dähnke, K., van Beusekom, J., Meyer, S., Voss, M., and Emeis, K.-C.: N2 fluxes in sediments of the Elbe Estuary and adjacent coastal zones, Mar. Ecol. Prog. Ser., 493, 9–21, https://doi.org/10.3354/meps10514, 2013.

Fabisik, F., Guieysse, B., Procter, J., and Plouviez, M.: Nitrous oxide (N2O) synthesis by the freshwater cyanobacterium Microcystis aeruginosa, Biogeosciences, 20, 687–693, https://doi.org/10.5194/bg-20-687-2023, 2023.

FGG, F. E.: FIS der FGG Elbe - Physikalisch-chemische Qualitätskomponenten: Elbe - Bunthaus (Strom-km 609,8) - Wassertemperatur - Tagesmittelwert, 2021.

Forster, G., Upstill-Goddard, R., Gist, N., Robinson, C., Uher, G., and Woodward, E.: Nitrous oxide and methane in the Atlantic Ocean between 50°N and 52°S: Latitudinal distribution and sea-to-air flux, Deep Sea Res. Part II Top. Stud. Oceanogr., 964–976, https://doi.org/10.1016/j.dsr2.2008.12.002, 2009.

Guhr, H., Karrasch, B., and Spott, D.: Shifts in the Processes of Oxygen and Nutrient Balances in the River Elbe since the Transformation of the Economic Structure, Acta Hydrochim. Hydrobiol., 28, 155–161, https://doi.org/10.1002/1521-401X(200003)28:3<155::AID-AHEH155>3.0.CO;2-R, 2000.

HAMBURG WASSER, Laurich, F.: pers. Comm.: N2O in der Elbe, 2022.

Hofmann, J., Behrendt, H., Gilbert, A., Janssen, R., Kannen, A., Kappenberg, J., Lenhart, H., Lise, W., Nunneri, C., and Windhorst, W.: Catchment–coastal zone interaction based upon scenario and model analysis: Elbe and the German Bight case study, Reg. Environ. Change, 5, 54–81, https://doi.org/10.1007/s10113-004-0082-y, 2005.

IKSE: Strategie zur Minderung der Nährstoffeinträge in Gewässer in der internationalen Flussgebietsgemeinschaft Elbe, Internationale Kommission zur Schutz der Elbe, Magdeburg, 2018.

Johannsen, A., Dähnke, K., and Emeis, K.: Isotopic composition of nitrate in five German rivers discharging into the North Sea, Org. Geochem., 39, 1678–1689, https://doi.org/10.1016/j.orggeochem.2008.03.004, 2008.

de Jong, F.: Marine Eutrophication in Perspective, Springer, Berlin, Heidelberg, 335 pp., https://doi.org/10.1007/3-540-33648-6, 2007.

Marzadri, A., Dee, M. M., Tonina, D., Bellin, A., and Tank, J. L.: Role of surface and subsurface processes in scaling N2O emissions along riverine networks, Proc. Natl. Acad. Sci., 114, 4330–4335, https://doi.org/10.1073/pnas.1617454114, 2017.

Morgan, E. J., Lavric, J. V., Arévalo-Martínez, D. L., Bange, H. W., Steinhoff, T., Seifert, T., and Heimann, M.: Air–sea fluxes of greenhouse gases and oxygen in the northern Benguela Current region during upwelling events, Biogeosciences, 16, 4065–4084, https://doi.org/10.5194/bg-16-4065-2019, 2019.

Nevison, C., Butler, J. H., and Elkins, J. W.: Global distribution of N2O and the ΔN2O-AOU yield in the subsurface ocean, Glob. Biogeochem. Cycles, 17, https://doi.org/10.1029/2003GB002068, 2003.

Reading, M. J., Tait, D. R., Maher, D. T., Jeffrey, L. C., Looman, A., Holloway, C., Shishaye, H. A., Barron, S., and Santos, I. R.: Land use drives nitrous oxide dynamics in estuaries on regional and global scales, Limnol. Oceanogr., 65, 1903–1920, https://doi.org/10.1002/lno.11426, 2020.

Sanders, T., Schöl, A., and Dähnke, K.: Hot Spots of Nitrification in the Elbe Estuary and Their Impact on Nitrate Regeneration, Estuaries Coasts, 41, 128–138, https://doi.org/10.1007/s12237-017-0264-8, 2018.

Schoer, J. H.: Determination of the origin of suspended matter and sediments in the Elbe estuary using natural tracers, Estuaries, 13, 161–172, https://doi.org/10.2307/1351585, 1990.

Schöl, A., Hein, B., Wyrwa, J., and Kirchesch, V.: Modelling Water Quality in the Elbe and its Estuary – Large Scale and Long Term Applications with Focus on the Oxygen Budget of the Estuary, Küste 81 Model., 203–232, 2014.

Schulz, K. and Umlauf, L.: Residual Transport of Suspended Material by Tidal Straining near Sloping Topography, J. Phys. Oceanogr., 46, 2083–2102, https://doi.org/10.1175/JPO-D-15-0218.1, 2016.

Sharma, N., Flynn, E. D., Catalano, J. G., and Giammar, D. E.: Copper availability governs nitrous oxide accumulation in wetland soils and stream sediments, Geochim. Cosmochim. Acta, 327, 96–115, https://doi.org/10.1016/j.gca.2022.04.019, 2022.

Sommerfield, C. K. and Wong, K.-C.: Mechanisms of sediment flux and turbidity maintenance in the Delaware Estuary, J. Geophys. Res. Oceans, 116, https://doi.org/10.1029/2010JC006462, 2011.

Van Beusekom, J. E. E., Carstensen, J., Dolch, T., Grage, A., Hofmeister, R., Lenhart, H., Kerimoglu, O., Kolbe, K., Pätsch, J., Rick, J., Rönn, L., and Ruiter, H.: Wadden Sea Eutrophication: Long-Term Trends and Regional Differences, Front. Mar. Sci., 6, https://doi.org/10.3389/fmars.2019.00370, 2019.

Walter, S., Bange, H. W., and Wallace, D. W. R.: Nitrous oxide in the surface layer of the tropical North Atlantic Ocean along a west to east transect, Geophys. Res. Lett., 31, L23S07, https://doi.org/10.1029/2004GL019937, 2004.

Weiss, R. F. and Price, B. A.: Nitrous oxide solubility in water and seawater, Mar. Chem., 8, 347–359, https://doi.org/10.1016/0304-4203(80)90024-9, 1980.

Wells, N. S., Maher, D. T., Erler, D. V., Hipsey, M., Rosentreter, J. A., and Eyre, B. D.: Estuaries as Sources and Sinks of N2O Across a Land Use Gradient in Subtropical Australia, Glob. Biogeochem. Cycles, 32, 877–894, https://doi.org/10.1029/2017GB005826, 2018.

Wertz, S., Goyer, C., Burton, D. L., Zebarth, B. J., and Chantigny, M. H.: Processes contributing to nitrite accumulation and concomitant N2O emissions in frozen soils, Soil Biol. Biochem., 126, 31–39, https://doi.org/10.1016/j.soilbio.2018.08.001, 2018.

Winterwerp, J. C. and Wang, Z. B.: Man-induced regime shifts in small estuaries—I: theory, Ocean Dyn., 63, 1279–1292, https://doi.org/10.1007/s10236-013-0662-9, 2013.

Zander, F., Heimovaara, T., and Gebert, J.: Spatial variability of organic matter degradability in tidal Elbe sediments, J. Soils Sediments, 20, 2573–2587, https://doi.org/10.1007/s11368-020-02569-4, 2020.

Zander, F., Groengroeft, A., Eschenbach, A., Heimovaara, T. J., and Gebert, J.: Organic matter pools in sediments of the tidal Elbe river, Limnologica, 96, 125997, https://doi.org/10.1016/j.limno.2022.125997, 2022.