### Authors' Responses to Reviewers' Comments on os-2022-19

### The role of tides and sea ice on the carbonate chemistry in a coastal polynya in the south-eastern Weddell Sea\*

#### Ocean Science July 2022

Dear anonymous reviewers,

In this document, we address the comments made by anonymous reviewers #1, #2, and #3 on our paper titled, *The role of tides and sea ice on the carbonate chemistry in a coastal polynya in the south-eastern Weddell Sea*\*. Reviewer's comments are **highlighted in blue, are marked bold**, and have been numbered by the authors for easy reference. Some comments have been split up into parts a, b, and c. Responses to these comments are given in black below each comment. All references made to line numbers refer to the line numbers in the originally submitted manuscript (i.e. not the revised manuscript), unless otherwise specified.

An important note: We noticed a mistake had been made in the conversion of atmospheric  $xCO_2$  (ppm) to  $fCO_2$  ( $\mu$ atm). We had used the wrong number and units for the gas constant in the equation by Weiss (1974). The correction of this mistake impacted only the CO<sub>2</sub> flux results: the CO<sub>2</sub> flux values decreased by ~4 mmol m<sup>-2</sup> day<sup>-1</sup> for PS89 and ~1 mmol m<sup>-2</sup> day<sup>-1</sup> for PS117. This correction does not change the overall conclusions of this manuscript, as the variability in CO<sub>2</sub> flux remains the same. The only notable change is that the polynya during PS117 is not a clear net source of CO<sub>2</sub> anymore. Instead, it is almost neutral. Figures that were adapted:

- Fig. 4: dashed line showing depth of atmospheric fCO<sub>2</sub> equivalent corrected.
- Fig. 9: all CO<sub>2</sub> flux results corrected.

Numbers in the text were corrected in the abstract, section 4.2, and the conclusion. Please see overleaf for details.

On behalf of all co-authors of this work and myself, I would like to thank the reviewers for their constructive comments, which have greatly improved the quality of this manuscript.

#### Elise Droste

Mario Hoppema, Melchor González-Dávila, Juana Magdalena Santana-Casiano, Bastien Y. Queste, Giorgio Dall'Olmo, Hugh J. Venables, Gerd Rohardt, Sharyn Ossebaar, Daniel Schuller, Sunke Trace-Kleeberg, and Dorothee C. E. Bakker

\*Title has been changed to *The influence of tides on the marine carbonate chemistry of a coastal polynya in the south-eastern Weddell Sea*, according to comment 3.0.

#### Adaptations made to the text as a result of the correction of the atmospheric fCO2

Line numbers are given for the *original* manuscript.

Abstract

• Line 13-14

OG: ... that can range between a strong sink (-20 mmol  $m^{-2} day^{-1}$ ) and a small source (7 mmol  $m^{-2} day^{-1}$ ) on a semi-diurnal timescale.

Revised: ... that can range between a strong sink  $(-24 \text{ mmol m}^{-2} \text{ day}^{-1})$  and a small source  $(\underline{3} \text{ mmol m}^{-2} \text{ day}^{-1})$  on a semi-diurnal timescale.

• Line 14-16

OG: If the variability induced by tides is not taken into account, there is a potential risk of overestimating the polynya's  $CO_2$  uptake by 98% or underestimating it by 108% (mistaking it for a source instead of a variable sink), compared to the average flux determined over several days.

Revised: If the variability induced by tides is not taken into account, there is a potential risk of overestimating the polynya's CO<sub>2</sub> uptake by <u>67%</u> or underestimating it by <u>73%, compared</u> to the average flux determined over several days.

### Section 4.2

• Line 453-454

OG: The CO<sub>2</sub> sink during PS89 is as large as -19.9 mmol  $m^{-2}$  day<sup>-1</sup>, while the largest CO<sub>2</sub> source reaches 6.9 mmol  $m^{-2}$  day<sup>-1</sup> (Fig. 8).

Revised: The CO<sub>2</sub> sink during PS89 is as large as <u>-23.6</u> mmol m<sup>-2</sup> day<sup>-1</sup>, while the largest CO<sub>2</sub> source reaches <u>3.1</u> mmol m<sup>-2</sup> day<sup>-1</sup> (Fig. 8).

• Line 360-362

OG: Using the fCO<sub>2</sub> results based on the discrete water sampling, the average CO<sub>2</sub> uptake during the PS89 tidal observation period is  $-8.0 \pm 3.7$  mmol m<sup>-2</sup> day<sup>-1</sup> ( $\pm 1\sigma$ ). For PS117, the average CO<sub>2</sub> release to the atmosphere is  $1.4 \pm 0.7$  mmol m<sup>-2</sup> day<sup>-1</sup>.

Revised: Using the fCO<sub>2</sub> results based on the discrete water sampling, the average CO<sub>2</sub> uptake during the PS89 tidal observation period is <u>-11.7 ± 3.7</u> mmol m<sup>-2</sup> day<sup>-1</sup> (±1 $\sigma$ ). For PS117, the average CO<sub>2</sub> release to the atmosphere is <u>-0.1 ± 0.9</u> mmol m<sup>-2</sup> day<sup>-1</sup>.

• Line 355-360

OG: During PS117, the entire water column has a higher  $fCO_2$  than the atmospheric value, except for a patch between 50 and 20 m depth at the start and end of the tidal observation period (Fig. 4B). Even though not all PS117 CTD cast measurements started as shallow as those from PS89, the few casts that did have measurements starting <20 m showed a lack of a strong gradient in the DIC and TA content at the surface. The shallowest discrete carbonate chemistry water samples are therefore considered to be representative enough of the water properties at the surface. Accordingly, the site is likely to have been a small source of  $CO_2$  at this time in January 2019.

Revised: During PS117, <u>the seawater fCO<sub>2</sub> also dips below the atmospheric value</u> at times of rising tide. However, the fCO<sub>2</sub> gradient and the wind speed are much lower compared to PS89 (Fig. 4B), resulting in a very small CO<sub>2</sub> flux. Even though not all PS117 CTD cast measurements started as shallow as those from PS89, the few casts that did have measurements starting <20 m showed a lack of a strong gradient in the DIC and TA content at the surface. The shallowest discrete carbonate chemistry water samples are therefore considered to be representative enough of the water properties at the surface. Accordingly, the polynya is likely to have <u>had a</u> relatively neutral CO<sub>2</sub> flux at this time in January 2019.

• Line 367-375

OG: Assuming the scenario we know for the PS89 tidal observation period, if discrete water samples had unknowingly only been collected during ebbing tide (higher seawater fCO<sub>2</sub>), the calculated CO<sub>2</sub> flux (0.6 mmol m<sup>-2</sup> day<sup>-1</sup>) would have underestimated the strength of the CO<sub>2</sub> uptake by the polynya by up to 108 %, compared to the average uptake (-8.0 mmol m<sup>-2</sup> day<sup>-1</sup>), i.e. actually mistaking it for a small source rather than a sink of CO<sub>2</sub>. However, if samples had only been collected during times of rising tide (lower seawater fCO<sub>2</sub>), the capacity of the polynya to take up CO<sub>2</sub> (-15.9 mmol m<sup>-2</sup> day<sup>-1</sup>) would have been overestimated by up to 98 %, compared to the average uptake value. Since the variability of the CO<sub>2</sub> flux during PS117 was much lower (a CO<sub>2</sub> release ranging between 0.2 - 2.2 mmol m<sup>-2</sup> day<sup>-1</sup>), samples collected at any time during this 24 hour period would have been relatively representative of this tidal observation period, but not necessarily of the month or the entire summer season.

Revised: Assuming the scenario we know for the PS89 tidal observation period, if discrete water samples had unknowingly only been collected during ebbing tide (higher seawater fCO<sub>2</sub>), the calculated CO<sub>2</sub> flux (-3.1 mmol m<sup>-2</sup> day<sup>-1</sup>) would have underestimated the strength of the CO<sub>2</sub> uptake by the polynya by up to 73 %, compared to the average uptake (-11.7 mmol m<sup>-2</sup> day<sup>-1</sup>). However, if samples had only been collected during times of rising tide (lower seawater fCO<sub>2</sub>), the capacity of the polynya to take up CO<sub>2</sub> (-19.6 mmol m<sup>-2</sup> day<sup>-1</sup>) would have been overestimated by up to <u>67</u> %, compared to the average uptake value. Since the variability of the CO<sub>2</sub> flux during PS117 was much lower (a CO<sub>2</sub> release ranging between -<u>1.2 and 0.8</u> mmol m<sup>-2</sup> day<sup>-1</sup>), samples collected at any time during this 24 hour period would have been relatively representative of this tidal observation period, but not necessarily of the month or the entire summer season.

• Line 382-385

OG: Using the total area of polynyas along the south-eastern Weddell Sea coastline in the summer of  $49 \times 10^3$  km<sup>2</sup> (as estimated by Arrigo and van Dijken (2003)), the total CO<sub>2</sub> flux for all polynyas along the south-eastern coastline would be -0.78 x 10<sup>9</sup> mol day<sup>-1</sup> (net CO<sub>2</sub> uptake), if data had only been collected during rising tide. It would have been 0.03 x 10<sup>9</sup> mol day<sup>-1</sup> (net CO<sub>2</sub> release), if data had only been collected during been collected during tide.

Revised: Using the total area of polynyas along the south-eastern Weddell Sea coastline in the summer of  $49 \times 10^3 \text{ km}^2$  (as estimated by Arrigo and van Dijken (2003)), the total **<u>net CO\_2uptake</u>** for all polynyas along the south-eastern coastline

would be <u>-0.97</u> x  $10^9$  mol day<sup>-1</sup>, if data had only been collected during rising tide. It would have been <u>-0.15</u> x  $10^9$  mol day<sup>-1</sup>, if data had only been collected during ebbing tide.

• Line 383-391

OG: ... we would determine that the contribution of eastern shelf polynyas to Brown et al.'s upper summer CO<sub>2</sub> uptake estimate is 0.2 % (using the same area for the Weddell Sea:  $6.2 \times 10^{12} \text{ m}^2$  and scaling the daily flux up to the whole year). If seawater samples had only been collected during rising tide, the contribution of the eastern shelf polynyas would have been estimated at 5.9 % to the total summer CO<sub>2</sub> uptake of the Weddell Sea.

Revised: ... we would determine that the contribution of eastern shelf polynyas to Brown et al.'s upper summer CO<sub>2</sub> uptake estimate is <u>1.2</u> % (using the same area for the Weddell Sea:  $6.2 \times 10^{12} \text{ m}^2$  and scaling the daily flux up to the whole year). If seawater samples had only been collected during rising tide, the contribution of the eastern shelf polynyas would have been estimated at <u>7.3</u> % to the total summer CO<sub>2</sub> uptake of the Weddell Sea.

• Line 393-396

OG: If the average CO<sub>2</sub> flux of PS89 had been used in this simplistic upscaling exercise instead of the extreme high- and low-end scenarios, then the total CO<sub>2</sub> flux of all Weddell Sea coastal polynyas would be  $-0.4 \pm 0.18 \times 10^9$  mol day<sup>-1</sup> (3.0 % of Weddell Sea flux) for January 2015. There is an order of magnitude difference if the same upscaling exercise is done with the average flux for the PS117 experiment: 0.07  $\pm 0.034 \times 10^9$  mol day<sup>-1</sup> (0.5 % of Weddell Sea flux).

Revised: If the average CO<sub>2</sub> flux of PS89 had been used in this simplistic upscaling exercise instead of the extreme high- and low-end scenarios, then the total CO<sub>2</sub> flux of all Weddell Sea coastal polynyas would be  $-0.58 \pm 0.18 \times 10^9$  mol day<sup>-1</sup> (4.4 % of Weddell Sea flux) for January 2015. Results are two orders of magnitude lower when the same upscaling exercise is done with the average flux for the PS117 case study:  $0.003 \pm 0.034 \times 10^9$  mol day<sup>-1</sup> (0.02 % of Weddell Sea flux).

#### Conclusion

• Line 426-427

OG: Seawater CO<sub>2</sub> uptake can be underestimated by 108% and overestimated by 98%, if these tidal changes are ignored.

Revised: Seawater CO<sub>2</sub> uptake can be underestimated by  $\underline{73}$ % and overestimated by  $\underline{67}$ %, if these tidal changes are ignored.

#### Anonymous Reviewer #1

The authors have written an interesting case study that nicely demonstrates how sampling bias can influence marine observations in highly dynamic environments in Antarctic coastal waters. They illustrate this with carbonate chemistry observations from a single location over 1-2 days during two separate years. The authors attribute the observed physical and chemical oceanographic changes to tidally induced currents and mixing.

1.1 Figure 2 shows the expected tidal influence (from a model) alongside the measured currents using an ADCP. Based on this figure alone, it is a little difficult to determine to what extent the tide dominates the observed current movement during the observational period. This is mostly due to the compressed y-axis on panels A, B, G and H. I think the authors have tried to address this with Figure F1, but maybe a plot of the residual u and v component might be more helpful here, or perhaps a progressive vector diagram that shows the trajectory of a water parcel during each period? If tides really are dominant then the water parcel, of course, would pretty much end up back where it started. Although as the authors mentioned in Line 286, the net transport during the experimental period appears to be to the south/southeast. Which would imply a transport path against the prevailing coastal/Weddell Gyre current? Admittedly, this is a minor point. Even if the tidal influence was not as significant, the sampling bias problems that the paper is highlighting would remain unchanged. We thank the reviewer for the suggestions on improving the plot to show the prominence of the tidal currents. We think that Figure F1 does indeed mostly address this comment, but following the suggestion by the reviewer we have now added another figure that shows the hypothetical trajectory of a water parcel starting at the ship's sampling point. This calculation assumes a mean value of the currents for the entire water column and polynya area. disregards topographic effects, and ignores the presence of an iceshelf. It therefore serves as a simple estimate to gain a sense of the strengths/net direction of the currents and the contributions of the tidal currents to the total currents. We decided to place this figure in the appendix, just after Figure F1. We added a reference to the new figure on line 288 of the original manuscript, where we discuss transport.

**1.2** Finally, the caption in Figure D1 incorrectly labels panels C and D.

We have corrected the caption:

Original text: C) Same as B), but for temperature. D) Same as B), but for salinity. Revised text: C) Same as B), but for salinity. D) Same as B), but for temperature.

#### Anonymous Reviewer #2

This study presents physical and biogeochemical measurements in a polynya and discusses variability and controlling factors during a complete tidal cycle in 2 different years in the eastern Weddell Sea. The data and discussions include using numerical output from a tidal model and considerations of snapshot sampling that may lead to biases and are an important contribution to marine carbonate chemistry, biogeochemical cycling and air-sea CO<sub>2</sub> uptake in dynamic environments. The biogeochemical focus is DIC and TA and CO<sub>2</sub> fluxes in the context of sea ice and tides.

2.1 Calcium carbonate saturation for both aragonite and calcite are mentioned in the appendix figures but not really in the text. Some additional text in the Introduction and Methods is required to show how these variables were calculated, what they mean for these coastal polynya system and would put the results into greater context with regards the organisms found here.

To address this comment, we have made several changes in the manuscript:

We have renamed the title of section 2.2 from *CO<sub>2</sub> flux calculations* to *Marine carbonate system and CO<sub>2</sub> flux calculations*. To this section, we have added the missing information on how the aragonite and calcite saturation were determined.

Added text on line 136 of original manuscript: Alongside fCO<sub>2</sub>, the PyCO2SYS package simultaneously resolves other carbonate system parameters with DIC, TA, and auxiliary data (listed above) as input parameters (Zeebe & Wolf-Gladrow, 2001; Humphreys et al., 2022a). These include the saturation state for calcite and aragonite (polymorphous forms of calcium carbonate) and pH.

We agree with the reviewer that the relevance of the variability in the polynya system to marine organisms needs to be briefly explained. We decided that the best place in the manuscript to add these lines is between lines 324 and 325 of the original manuscript, because this follows the discussion on the drivers of the variability in the water column and the effect on primary productivity, and precedes the final paragraph(s) in which a summary is given on what we do not know and what we do know based on the results of the current study. We included the following lines in the discussion to link the relevance of the calcium/aragonite saturation variability to the bigger context:

#### Added text:

From an ecological perspective, it is relevant to consider the effect of the carbonate system variability on the diversity, structure, and production of pelagic-benthic organism communities. Calcifying organisms, such as pteropods, foraminifera, and coccolithophores, depend on the seawater calcium carbonate saturation state to form their shells and skeletons, which are made from CaCO<sub>3</sub> (Orr et al., 2005). The pH in the Ekström polynya varied between 8.02-8.12 and 8.02-8.06 for PS89 and PS117, respectively (see Fig. G1 for vertical variability). The saturation state of aragonite ( $\Omega_{ar}$ ; the less stable polymorph compared to the other common CaCO<sub>3</sub> polymorph: calcite) concurrently varied between 1.22-1.52 and 1.21-1.34, respectively. A contour in Fig. 4C and D at an arbitrary value of 1.3 for  $\Omega_{ar}$  gives a sense of the vertical variability driven by tides. Even at the lowest pH values recorded here, the  $\Omega_{ar}$  does not fall under 1, which means that the marine chemical environment does not thermodynamically promote CaCO<sub>3</sub> dissolution. The dynamic nature of the polynya might foster a

resilience among the pelagic and benthic organism communities to rapid (semi-diurnal) changes of  $\Omega_{ar}$ . However, even at a carbonate saturation level > 1, the rate of biogenic calcification rate has been shown to be affected by the CaCO<sub>3</sub> saturation state (Feely et al., 2004). The Southern Ocean is especially vulnerable to ocean acidification driven by marine anthropogenic CO<sub>2</sub> uptake (Orr et al., 2005; Negrete-García et al., 2019). Tidally induced variability may increase the sensitivity of high-latitude coastal systems to shoaling aragonite and calcite saturation state horizons. Alongside ecological impacts of tides along the Antarctic coastline, future studies can look into the tidal impacts on long-term changes of the vulnerability of pelagic-benthic organism communities.

While making these alterations in the text, we noticed that there was a mistake in the caption for Figure 4, which has now been corrected:

Original text in figure 4 caption: The red dotted line represents the depth at which the seawater pH = 8.05.

Revised text in figure 4 caption: The red dotted line represents the depth at which the  $\Omega_{ar} =$  1.3.  $\Omega_{ar}$  is lower at depths below this line. The value 1.3 is arbitrary to illustrate the vertical variability in the water column.  $\Omega_{ar}$  ranges between 1.22-1.52 and 1.21-1.34 for PS89 and PS117, respectively.

As the contour for aragonite is already shown in Figure 4, we have changed the contour in panels C and D of figure G1 from aragonite saturation state = 1.3 to calcite saturation state = 2.05. The corresponding text in the caption has been edited accordingly.

# 2.2 It would also be helpful to include more discussion of and reference to the theoretical lines drawn in Figure 5, whereby a short description of key processes that drive variability in the carbonate system in the Introduction would improve the understanding.

We thank the reviewer for this comment, which has helped us restructure and edit a paragraph in section 4.1 and has resulted in a much clearer link between our arguments and how Fig. 5 supports them. We think this is a suitable place to refer to the theoretical lines (instead of including an explanation in the introduction, as suggested), because this is where we discuss the biogeochemical processes and we can directly link it to our findings (allowing us to be concrete and avoiding repetition). This part of the text has been revised in combination to our response to comment 3.31. Please see page 15 of the <u>revised manuscript</u> to see the changes we made to the text.

#### 2.3 Figure 3 green markers in panel A are difficult to see.

We have increased the size of the markers and also the width of the markers' edges to make them clearer.

**2.4 Figure D1 panels C and D descriptions are reversed in the caption.** We have corrected this mistake. Please see our response to comment 1.2 by reviewer #1.

**2.5 Figure E1 interpretation would be assisted by marking depths of discrete samples in panels C and D to better compare to higher vertical resolution in panels A and B.** Done. We have also added this information in the caption of Fig. E1:

Added text to caption Fig. E1: Sampling depths are shown in white markers in C and D.

2.6 There is assumption that the interpretation of biogeochemical data from the discrete samples is reliable as the physical variables from the high resolution CTD data, however additional processes such as primary production/respiration, location of a deep Chl maximum... would imprint additional variability particularly in the surface layer that is not captured by changing salinity and temperature (water mass) interactions. A comment in the text to consider this and consider adding references to support the statement that would complement the discussion.

We agree to include a comment on the consideration of missing variability due to the vertical sampling resolution. We decided that a relevant spot in the manuscript to do so is on line 303, which is the end of the paragraph in which we discuss the variability in the nDIC and nTA content and which processes might have affected those values. We have not included a reference here, but instead have provided more clarification (supported by references) on the role of physical processes and the relation to TA and DIC elsewhere in the text. Please see our responses to comments 3.18 and 3.31.

Line 303: Finally, even though there is good agreement between the high vertical resolution sensor data and the discrete bottle data for salinity and temperature (exemplified with density in Fig. E1), biogeochemical processes could imprint additional variability in the DIC and TA profiles that are not reflected in salinity and temperature measurements. We must therefore consider that the discrete seawater samples might not have captured the full scale of the variability in the polynya, limiting our interpretation of relevant biogeochemical processes.

2.7 Figure G1 determining the difference between red dashed and dotted lines was difficult, perhaps a more striking difference would assist here (e.g. different colours). Aragonite saturation is mentioned here and would benefit from an introduction in the main text in terms of the definition and how it is determined, and relevance of the value depicted by the red line here, low value towards 1 relevant for calcifying organisms? To address this comment, we tried pairing a number of different colour combinations, while making sure that the choice of colours remains colour-blind friendly. Red was the colour that contrasted best with the colourmap for both colour-blind and non-colour-blind people. We have changed the colour of the dotted line to cyan to make the difference clearer with the dashed line.

We have added a section to the methods to explain how aragonite and calcite saturation states were determined and we have added text to the discussion to explain the relevance. Please also see our response to comment 2.1.

### **2.8** Figure G2 calcite saturation is shown here, check consistency with Figure G1 and include definitions and how they are determined in the text.

This comment by the reviewer helped us discover a slight mistake that we made in Figure G1, although there might have been some confusion as to what is shown in G2. Figure G1 was supposed to show the contours of calcite saturation state = 2.05 (bottom panels), but instead still had the saturation state for aragonite = 1.3. This has been corrected (see response to comment 2.1). We have also changed the caption of Figure G2 to make it clearer that it has a similar set up as for G1, but showing phosphate and silicate content instead of nDIC and nTA and does not show the pH and calcite saturation contours:

Original caption Figure G2: As for G1, for phosphate and silicate (excluding the pH and calcite saturation contours).

Revised caption Figure G2: As for Fig. G1, but instead for phosphate and silicate content and not including the pH and calcite saturation contours that are shown in Fig. G1.

#### Anonymous Reviewer #3

In this manuscript, the authors present two separate datasets (from January of two different years) documenting the evolution over a few days of physical and biogeochemical parameters measured in a coastal polynya near the Ekström Ice Shelf in the south-eastern Weddell Sea. They show that tides have a significant effect on fCO2 in the polynya surface waters, and by extension on the air-sea flux of CO2, which not only varies considerably, but can also change sign depending on the timing of sampling relative to the tidal cycle. In general, I found this a compelling study and well-written manuscript that succeeding in making its main point – that coastal polynyas near Antarctica are highly dynamic with respect to the carbonate system and that the tidal cycle has a profound influence on whether these features are strong/weak CO2 sources/sinks. I particularly liked the thought exercise that the authors go through in section 4.2 to demonstrate the different answers one might get with regards to air-sea CO2 flux if one did not appropriately account for the influence of the tidal cycle. Below, I have included a number of fairly minor comments and suggestions for the authors to consider, which I hope will help to improve the manuscript.

3.0 Title: Would it not be more correct to use "The role of tides and sea ice in the carbonate chemistry in a coastal polynya in the south-eastern Weddell Sea" or "The influence of tides and sea ice on the carbonate chemistry in a coastal polynya in the south-eastern Weddell Sea"? Additionally, the main message of this study seems to be about the tides (and not the sea ice). Of course, sea ice in inherent to the mechanisms the authors invoke to explain their observations, but I found it a little incongruous in the title.

We thank the reviewer for the correction and suggestions. The title has been changed to: The **influence** of tides **on** the **marine** carbonate chemistry **of** a coastal polynya in the southeastern Weddell Sea. Note, we have omitted "and sea ice" from the title, as we agree with the reviewer that it is a little incongruous.

### **3.1 L35-38: These two sentences are somewhat repetitive; can they be combined and made more concise?**

We have revised these two sentences as follows:

Original text: The prolonged ice-free conditions allow direct gas exchange to occur, a longer time window for equilibration of CO<sub>2</sub> with the atmosphere, as well as prolonged biological productivity (Hoppema and Anderson, 2007). Substantial biological activity is observed in coastal polynyas around the Antarctic continent (Arrigo and van Dijken, 2003).

Revised text: The prolonged ice-free conditions allow direct gas exchange to occur **over a time window that is potentially long enough for** equilibration of CO<sub>2</sub> with the **atmosphere** (Hoppema and Anderson, 2007). Additionally, substantial biological activity (consuming CO2) is observed in coastal polynyas around the Antarctic continent (Arrigo and van Dijken, 2003).

## **3.2 L38-39:** To what is this sentence referring? Everything outlined in the paragraph is important with respect to CO2 flux estimates, no?

The aim of this sentence was to conclude the paragraph with the message that coastal polynyas are important to consider in  $CO_2$  flux estimates of polar regions. However, we can see the confusion caused by the way the sentence is phrased. We have thus clarified this it in the following way:

Original text: This makes them important with regard to air-sea CO2 flux estimates.

Revised text: Their prolonged ice-free conditions and biological productivity mean that it is important to accurately represent the air-sea CO<sub>2</sub> flux of coastal polynyas.

**3.3 L40-45: I found this paragraph full of general statements that don't really say much** – can the authors be more precise, for instance by giving examples or specifics? We have incorporated this comment into our response to comment 3.6.

### 3.4 L51: "...that has been exchanged with the atmosphere..." – do you mean acquired from the atmosphere?

We did not mean "acquired", as natural CO<sub>2</sub> may be released from the ocean to the atmosphere as well. This comment prompted us to change the sentence slightly in the following manner (which we think is indeed clearer):

Original text: "... along with any CO<sub>2</sub> that has been exchanged with the atmosphere at the continental shelf."

Revised text: ... along with any **modifications to the CO<sub>2</sub> content through gas exchange** with the atmosphere at the continental shelf.

**3.5 L60: "separate and independent" – I think these two descriptors are redundant.** We agree and have omitted "separate and independent" from the sentence.

Original text: We will present <u>biogeochemical</u> observations for two separate and independent tidal sampling campaigns ...

Revised text: We will present <u>biogeochemical</u> observations **for two** tidal sampling campaigns ...

3.6 In general, I think the introduction would be strengthened with some more specific information on what has been shown previously with regards to CO2/carbonate state variables (or even just biogeochemistry and/or hydrography that affects the carbonate system) in coastal polynyas even if the tides have not been considered.

We have adapted the introduction to incorporate this helpful and constructive feedback. It required some restructuring of the introduction to maintain a good flow of the text. We have added examples with additional references and replaced sentences that were rather vague with more concrete ones. Please see the revised introduction section in the revised version of the manuscript.

### **3.7 L75-76: Given the subsequent sentence, it doesn't seem particularly informative to state the average area of polynyas.**

We agree that this sentence can indeed be removed (and we indeed did so).

Original sentence removed: Coastal polynyas in the eastern Weddell Sea have an average area of 7.75 x 103 km<sup>2</sup> in the summer and 1.12 x 103 km<sup>2</sup> in winter (coastal polynyas numbers 12-17 in Arrigo and van Dijken (2003)).

However, we think it might be useful to the reader to put the size of the polynya in the case studies into perspective relative to other polynyas in the region. This why we have slightly modified the sentence on line 81-82 of the original manuscript in the following manner:

Original sentence: Generally, the polynya during both tidal observations at this location is considered to be relatively small.

Revised sentence: Given that the average area of coastal polynyas in the eastern Weddell Sea in summer is  $7.75 \times 10^3 \text{ km}^2$  (coastal polynyas numbers 12-17 in Arrigo and van Dijken (2003)), the polynya during both tidal observations at this location is considered to be relatively small.

We think that in the revised text, the selected information from the omitted sentence is more useful to the reader.

#### 3.8 L89: Sentence seems out of place.

The purpose of this sentence was to make clear to the reader where the Ekström Ice Shelf and the sea ice were relative to the polynya/sampling site, as this is important to understand for the interpretation of the results (for example, it is important to know that there was no sea ice between the polynya and the ice shelf). We agree with the reviewer that its placement in the text does break the flow a bit. We have therefore moved the sentence on line 89 to line 74 in the original manuscript:

Moved sentence: The polynya is bordered by the Ekström Ice Shelf along its southern edge, and by sea ice along the rest of its perimeter.

We think that this is a better place in the text for this information, as this paragraph already contains information about the location of the polynya.

## 3.9 LL92-93: Was the oxygen calibration good? And please can you clarify what you mean in the following sentence by "...malfunctioning on every other cast..."; what are the implications of this?

Yes, the oxygen calibration was good (see precisions in Table C1). To clarify: The CTD casts were alternated between the CTD from AWI and an Ultra Clean CTD (UCC) from NIOZ. The oxygen optode on UCC from NIOZ malfunctioned, which is why we cannot include the oxygen data from these 4 casts. The oxygen data on the AWI CTD was fine. We thought an explanation of the two different CTD systems was perhaps a little irrelevant to include in the manuscript (as most of their system is the same between them), which is why we wrote that the optode malfunctioned during "every other cast".

The implication of this is that, for dissolved oxygen and fluorescence, we only have half the number of data for the PS117 tidal observation. This means that the resolution in time is lower and we would miss out on some of the variability in the water column through time. However, we decided to still show the water column data for oxygen and fluorescence, because the lack of variability in other variables, such as nutrients, DIC/TA, and salinity, indicate that there is not a lot of variability in the oxygen data that we could be missing out on due to the missing oxygen profiles from the UCC.

The same counts for fluorescence, for which we only have data from the AWI CTD. We have now included this in the text (see below).

We recognise that it is necessary to elaborate on this topic. We have therefore revised the lines highlighted by the reviewer to clarify the use of different rosettes (on one of which the optode malfunctioned), and refer to added text in the results section in which we explain the minor implication of this.

Original text: The oxygen optode sensor was malfunctioning on every other cast during the PS117 tidal observation period and thus its data had to be excluded from further analysis.

Revised text: During the PS117 tidal observation period, two different CTD rosettes with their own set of sensors were used in alternation. On one of these two CTD rosettes, the oxygen optode sensor malfunctioned and thus its data had to be excluded from further analysis. The fluorescence data for this particular rosette is also not available. The minor implication of this is addressed in Section 3.3.

Added text on line 202 of the original manuscript (at the end of section 3.3):

Due to complications with the data for dissolved oxygen and fluorescence on four of the CTD casts of the PS117 tidal observation, these data were excluded from analysis. The implication of this reduced temporal resolution is that we risk losing representation of water column variability in our dataset for these two variables. However, the low water column variability over time for the physical and other biogeochemical variables (for which we do have data from every cast) strongly suggest that there likely is not a lot of variability in the dissolved oxygen or fluorescence content that we are missing out on due to missing profiles.

## **3.10 L99-105: Presumably these measured nutrient concentrations were used in the carbonate system calculations?**

The measured nutrient concentrations were indeed used in the carbonate system calculations. We have now included this in the text in Section 2.2 (lines 129-130 in the original manuscript), where we explain how the seawater fCO2 was determined.

Original text: The fCO2 of surface seawater (fCO2sw) is determined from the DIC and TA concentrations of the shallowest discrete seawater values ...

Revised text: The fCO2 of surface seawater (fCO2sw) is determined from **the DIC**, **TA**, **nitrate**, **and phosphate content**, **as well as the temperature and salinity**, of the shallowest discrete seawater samples ...

#### 3.11 Figure 1 caption – where are the bathymetry data from?

The bathymetry is from IBSCO Version 1.0. This information was supposed to be included in Table B1, but we now noticed that it was missing. We thank the reviewer for pointing this out. We have included the source of this data in Table B1 and also in the caption of Figure 1:

Original text: Weddell Sea with bathymetry.

Revised text: Weddell Sea with bathymetry: IBSCO Version 1.0 (Arndt et al., 2013).

**3.12** Table 1 (and text): For PS117, is eight CTD casts really enough? For PS89, why were two casts conducted on 8 January not included in the case study?

For PS117: A CTD cast was done every ~3 hours and during times of both ebbing and rising tide. We believe that this is indeed enough to capture a representative variability of the water column during this (very short) time period. We have included the following line in the caption for Table 1 to clarify this:

## Added text: For both observation periods, casts were lowered into the water during times of ebbing and rising tide.

For PS89: The two casts from 8 January were not included in the case study, because they were too far removed in time from the other observations to be able to interpolate between them. We decided that including them would not substantially contribute to the message we aim to discuss. However, we have added a note to the footer of table 1, and have now also included the CO<sub>2</sub> flux based on the discrete surface seawater sample on the 8<sup>th</sup> of January in Fig. 8, because the underway data gives context to that "lonely" datapoint.

### 3.13 L125: where is Syowa Station?

Syowa Station is a Japanese permanent station on the Antarctic coastline at  $69^{\circ}$ S latitude. We used their atmospheric xCO<sub>2</sub> time series data, because it is relatively close (in terms of stations that maintain a time series) to our study site. We compared the time series to the xCO<sub>2</sub> time series from the South Pole, but there was no consistent difference between the two datasets and insignificant difference between the two, especially for the monthly averages. This indicates that the atmosphere is very well mixed for CO<sub>2</sub> on Antarctica and along the coastlines. We therefore opted to use the data from Syowa Station, also because it is at the coast and closer in proximity to our study site.

We have included the coordinates for Syowa Station when it is first mention in the text (line 125 in original manuscript).

### 3.14 L135-136: How important might these discrepancies be?

Discrepancies between the measured and calculated  $fCO_2$  values are important to consider (and to resolve/understand) when deciding which data to use to accurately determine air-sea  $CO_2$  flux calculations. The main purpose of our study is to illustrate the relative variability of the system (and therefore also the  $CO_2$  flux), and therefore *small* discrepancies would not discredit the messages that we are trying to convey. However, as can be seen in Fig. 8, the  $CO_2$  flux results based on the measured and calculated  $fCO_2$  values actually agree very well, despite the small discrepancies. We therefore consider them not to be very important. To make this clearer to future readers of the manuscript, we have added the following text on line 136 of the original manuscript:

Added text line 136: As is shown in Section 4.2, these discrepancies are not large enough to affect the agreement between the CO<sub>2</sub> flux estimates based on these two sets of fCO<sub>2</sub> data.

**3.15** Figure 2 caption – Towards the end of line 2, a space a missing between "The" and "u".

Corrected.

**3.16 L168: Why the choice of a density change of 0.02 kg m-3 to define the MLD when the standard is typically 0.03 kg m-3 (sensu de Boyer Montégut et al. 2004)?** 

We calculated the mixed layer depth using a range of density differences to test the robustness of the final result for the MLD. The results for MLD did not differ substantially when using density differences between 0.01-0.05 kg m<sup>-3</sup>. We were not aware that 0.03 kg m<sup>-3</sup> is considered a standard, and because a density of 0.02 kg m<sup>-3</sup> seemed to capture the changes in MLD sufficiently well, we decided to use this. We agree that it is better to stick to more commonly used methods, and so we have now recalculated the mixed layer depths and updated the markers in Fig. 3. The MLD results (and conclusions based on them) did not change.

0.02 kg m-3 has been changed to **0.03** kg m-3 on line 167 of the original manuscript and in the caption of Fig. 3.

### **3.17 L174: I don't think the amplitude of variability for salinity can really be considered "striking"**

Replaced "striking" with "much".

Original text: ... the amplitude of variability for salinity is strikingly smaller compared to PS89.

Revised text: ... the amplitude of variability for salinity is **much** smaller compared to PS89.

3.18 L190 (and elsewhere): The idea that physical processes such as mixing (rather than biogeochemical processes such as photosynthesis, respirations, and/or calcium carbonate formation/dissolution) are primarily responsible for the observed variability in DIC, TA, and fCO2 is alluded to in numerous places in the manuscript. However, the reasoning behind this conclusion is never fully articulated. Since the readership of Ocean Sciences is going to include people not intimately familiar with the drivers of carbonate system variability, I suggest the authors more clearly lay out their logic in this regard, and here may be the place to do it.

We agree with the reviewer that this is a concept that could have been better introduced. We decided to include it in line 189 of the original manuscript. We allude back to it in lines 281-282 (see our response to comment 3.31).

Original text line 189-191: Salinity-normalised DIC (nDIC) and TA (nTA) profiles (according to Friis et al., 2003) lose much of the semi-diurnal variability, suggesting that physical processes, such as advection and mixing, are the dominant drivers of the observed variability (Fig. G1).

#### Revised text:

In the ocean, changes to salinity are driven by oceanographic processes, such as dilution, ice formation, and mixing. These physical processes also impact DIC and TA, which is why DIC and TA are often strongly correlated to salinity (Middelburg et al., 2020). This is also the case in our dataset. However, DIC and TA content are additionally a function of biological (e.g. photosynthesis, respiration, and remineralisation) and chemical (e.g. CaCO<sub>3</sub> dissolution and precipitation) processes (Zeebe & von Wolf-Gladrow et al., 2001). To be able to study the role of biogeochemical processes on DIC and TA content, it is useful to separate the effect of physical processes, such as dilution and mixing of different water masses, from the rest. This can be done by normalising the DIC and TA values to the salinity, which we have done here according to methods by Friis et al. (2003). The salinity-normalised DIC (nDIC) and TA

(nTA) **profiles lose** much of the semi-diurnal variability seen in the profiles **of the non-salinity-normalised values**, suggesting that physical processes are the dominant drivers of the observed variability **in DIC and TA** (Fig. G1).

### **3.19 L192-194:** Can you estimate how much of an effect the increase in atmospheric CO2 might have had? Since the sampling weren't conducted that far apart in time.

To be able to estimate the contribution of atmospheric CO<sub>2</sub> to the DIC of seawater, we would need to know how much the water has equilibrated with the atmosphere. Given that a) this area is mostly sea ice covered during the year, b) the area and duration of the polynya is variable in the summer, and c) our current work has shown that it is a very dynamic system, we cannot estimate the degree of equilibration.

However, we can make a rough estimation for the upper bound to the contribution of atmospheric CO<sub>2</sub> increase to the increase in DIC by assuming equilibration and assuming all other variables (TA, salinity, temperature, nutrients) remain the same. The increase in atmospheric fCO<sub>2</sub> between January 2015 (377  $\mu$ atm) and January 2019 (387  $\mu$ atm) is 10  $\mu$ atm.

We used the average values of the upper 10 m during PS89 for salinity, temperature, TA, seawater fCO<sub>2</sub> (originally calculated from TA and DIC), and nutrients to calculate the surface DIC content. We then repeated the calculation, but added 10  $\mu$ atm to the average seawater fCO<sub>2</sub> (to simulate equilibration), and subtracted the former from the latter. The result is ~6  $\mu$ mol kg<sup>-1</sup> increase in DIC.

We have added this upper-bound estimate to the manuscript:

Line 192-194 of original manuscript: A part of this increase in nDIC over time could be result of the increase in atmospheric  $CO_2$ , assuming at least partial equilibration with the atmosphere.

Revised version: A part of this increase in nDIC over time could be result of the increase in atmospheric CO<sub>2</sub>, assuming at least partial equilibration with the atmosphere. The atmospheric fCO<sub>2</sub> increase (10  $\mu$ atm) alone could contribute ~6  $\mu$ mol kg<sup>-1</sup> to the surface DIC content if all other variables remained the same. This upper-bound estimate is based on average values of the top 10 m during PS89 and assumes equilibration of the surface water with the atmosphere.

**3.20** L196: **a)** Fluorescence is presented here almost as an afterthought, and only for PS117; if these data are going to be shown in the manuscript, the authors should elaborate. **b)** I additionally found the text here about silicate to be confusing – why is this meaningful? I feel that if the authors want to draw so much attention to what they consider anomalous or unexpected observations with regard to silicate, they should probably offer an explanation for these observations.

a) We agree that more attention could have been given to the fluorescence. We decided not to elaborate too much on fluorescence in the Results section, because we have now revised parts of the text in the Discussion section to better incorporate the relevance of the fluorescence data into the support of our arguments. Please see the third part of our response to comment 3.27 for the details. We have, however, revised line 196 to at least compare the fluorescence

during PS117 explicitly to that during PS89. Note that this revision is merged with revisions made in response to part b) (3.20 b).

Original text line 196: Fluorescence was barely detected during PS117 (Fig. 6).

Revised text line 196: Fluorescence is here used as a proxy for the presence of photosynthetic cells. While the rising tide increased fluorescence in the water column during PS89, it was barely detected during PS117 (Fig. 6).

b) Note: While addressing this comment (3.20 b), we are also addressing comment 3.46, because we feel that both comments are on the same topic. We agree with the reviewer that more needs to be said about the nutrient (incl. silicate) concentrations and how they contribute to our arguments. We have double checked the silicate data and have found no analytical errors. We have confidence in the values that we have presented. Silicate does not behave the same way as nitrate or phosphate, as its concentrations are mainly altered by diatom growth (incorporated into opal) or remineralisation, whereas nitrate and phosphate are strongly affected by photosynthesis and respiration. Silicate remineralisation happens only in the deep waters and in sediments. We can thus expect a different relationship for phosphate and nitrate, vs. silicate. These relationships may be different in different years.

While we are unable to fully explain the nutrient content differences between the two case studies (because we do not have all the necessary biological measurements to be able to do so) we have added a small discussion.

Our revisions to the text in response to this comment are merged to the revisions made in response to part a) (3.20 a).

Revised text on page 10 of the *revised* manuscript:

PS117 nitrate (28.9 - 30.1 umol kg<sup>-1</sup>), phosphate (2.0 - 2.1 215 umol kg<sup>-1</sup>), and dissolved oxygen (322.0 - 333.2 umol kg<sup>-1</sup>) concentrations throughout the water column have similar values as those at the bottom of the water column during PS89 (Fig. 6, G2, G4). This is not the case for silicate, for which its PS117 values lie around the mean silicate values measured for PS89 (60.0 ±1.1 umol kg<sup>-1</sup>; Fig. G4). This observation illustrates that silicate behaves differently than phosphate and nitrate, as its content is primarily affected by other processes, i.e. by diatom growth and remineralisation at depth or in the sediment rather than by photosynthesis and biological respiration (Sarmiento, 2013). Similarly to nDIC and nTA, the nutrients were salinity-normalised (following Friis et al., 2003). Consistent to nDIC and nTA, no obvious deviations from the mean salinity-normalised values are observed that could indicate a dominant biological influence. It supports the observation made above that the dominant driver of the variability observed *within* each tidal case study is mostly physical. For the salinitynormalised silicate content, the averages of both tidal observations are similar to each other  $(59.5 \pm 0.5 \text{ umol kg}^{-1} \text{ for PS89 and } 59.2 \pm 0.2 \text{ umol kg}^{-1} \text{ for PS117; Fig. G5}),$ indicating that processes affecting silicate content did not differ much between the two case studies. However, a consistent offset between the case studies is observed for the salinity-normalised values for nitrate and phosphate, where PS117 values are on average higher by 1.6 umol kg<sup>-1</sup> and 0.1 umol kg<sup>-1</sup>, respectively. Therefore, even though biogeochemical processes might not be able to explain the variability *within* each tidal observation, these results suggest that the polynya may have had a higher input and/or a lower loss of nitrate and phosphate during January 2019 compared to January 2015.

Fluorescence is here used as a proxy for the presence of photosynthetic cells. While the rising tide increased fluorescence in the water column during PS89, it was barely detected during PS117 (Fig. 6). In the absence of active cells that can photosynthesise/respire, remineralisation enhancing the nitrate and phosphate content may have been an important process in the water observed during PS117.

We then allude to the higher salinity normalised values for nitrate, phosphate, and DIC, on page 16 of the *revised* manuscript, where we build our argument that PS117 had more influence from the ice shelf cavity water. This required us to shuffle a few lines (i.e. lines 275-280 of original manuscript), to avoid unnecessary repetition and maintain a good flow of the text. For the same reasons, we have started a new paragraph (at line 316 of original manuscript) to improve the structure of the text.

### 3.21 L199: What is meant by "salinity-normalized" nutrient concentrations?

We mean that the nutrients have been normalised to salinity using the linear regression method by Friis et al. (2003), similarly to how we normalised DIC and TA to salinity. As a response to comment 3.18, we have introduced the reasoning behind normalising DIC and TA to salinity. We think that this, in combination with the following minor change to the text, has improved the clarity that this comment addresses.

Original text: Whereas the salinity-normalised concentrations for nitrate and phosphate during PS117 have an average that is significantly higher ...

Revised text: Whereas the salinity-normalised concentrations for nitrate and **phosphate** (following Friis et al., 2003, similarly to nDIC and nTA) during PS117 have an average that is significantly higher ...

## 3.22 Figure 4 caption – why the choice to highlight pH = 8.05? Similarly, the $\Omega$ aragonite = 1.3; what is the significance of this isoline?

We chose pH = 8.05 and  $\Omega$ aragonite = 1.3 arbitrarily and only to give a sense of the vertical variability in the water column over time. We have added text at lines 324 and 325 of the original manuscript to better introduce and explain the relevance of pH and  $\Omega$ aragonite (shown in Figure 4) and pH and  $\Omega$ calcite (shown in in figure G1). Please see our response to comment 2.1. The added lines, as well as the captions of Figures 4 and G1, also more clearly state that these values are essentially arbitrary but serve the purpose to illustrate how the depth of these horizons can vary. The range of values for pH,  $\Omega$ aragonite,  $\Omega$ calcite are also given in the respective captions.

#### 3.23 L216: What is meant here by "induced"?

The line was missing a part of the sentence, probably got lost in the reiterations of the revisions of the manuscript. We have now completed this sentence:

Original text: induced by intrusions of warmer water, such as mWDW and AASW, underneath the ice shelf ...

Revised text: **formed by melting of glaciers, and of ice shelves** induced by intrusions of warmer water, such as mWDW and AASW, underneath the ice shelf ...

**3.24** Figure 5 caption – on the second line, remove "or" between "during" and "ebbing" Done.

3.25 L227: What was the wind here? In general, I think a more systematic treatment of the winds is required. The values seem to be presented for the first time at random places in the Discussion, which makes it confusing. These values could perhaps be presented in the results?

We recognise that this is confusing. We have now included the minimum, maximum, and average wind speed in Table 1 in the methods section, where we first mention that the minimum, maximum, and mean wind speeds are used in the calculation of the CO<sub>2</sub> flux. We refer to the table in lines 117-118 (of the original manuscript).

In the discussion section, we have now included a reference to Table 1 in line 227, in the caption of Figure 8, and in line 342. We kept the repetition of the range of wind speeds mentioned for each tidal observation period in lines 235 and 245.

We hope that the reader will find this more consistent and can more easily look up the wind speed values now that they are displayed in Table 1.

In doing so, we have slightly altered the caption of Table 1: Original text: Details of the tidal observations made with repeat CTD casts ... Revised text: Details of the tidal observations **based on** repeat CTD casts ...

We also corrected a typo that we found during revisions in the wind speed unit on line 246 of the original manuscript: Original text:  $(3 - 10 \text{ m}^{-1})$ 

Corrected:  $(3 - 10 \text{ m s}^{-1})$ 

**3.26 L232:** The idea of a "salinity front" is an important one that crops up throughout the Discussion. However, I don't think it is introduced and explained in a systematic way (unless I missed something). The authors should introduce this idea clearly early on in their Discussion so that its later significance is obvious to the reader.

We agree with this constructive input by the reviewer. Line 224 in the original manuscript is where we mention a salinity front for the first time (with reference to Skogseth et al., 2013). The next line is where we aimed to link it back to our polynya case study. We have adapted lines 229-232 in the original manuscript to give a better introduction.

Original text lines 229-232:

... In the latter study, the tidal variability was characterised by a cold salinity front that moved back and forth with the tide.

In our case study, the input of fresher water with lower DIC and TA content is likely advection of AASW from the north-east of the front (and sampling site), influenced by the summer sea ice melt.

Revised text:

... In the latter study, the tidal variability was characterised by a cold salinity front that moved back and forth with the tide. This "salinity front" is characterised by lower and higher salinities in the water column on either side of a sharp horizontal salinity gradient. A salinity front of this description might have been moving back and forth with the tide over the sampling site in the Ekström polynya, which from a Eulerian perspective resulted in the properties of the water column changing as shown in Fig. 3 and 4. In our case study, the fresher water with lower DIC and TA content on the northern side of the salinity front (and sampling site) is likely advection of AASW, influenced by summer sea ice melt.

Line 250 changed from "The other side of the front ..." to "The other side of the **salinity** front ..."

3.27 Figure 6: a) Is the lack of fluorescence variability during PS117 the result of the colour scale chosen? b) Also, why are some of the data missing from panel C? c) Finally, the fluorescence data in panel E seem to me to support the authors' arguments about tidal mixing but they're not discussed at all, nor integrated into the authors' arguments – I think they probably should be.

a) The fluorescence values measured during PS117 are similar to those measured in the deep ocean at CTD stations where the depth is >>2000 m, even though they vary at values < 0.1. We decided to put the PS117 data on the same scale as for PS89, because it highlights the contrasts in variability between them. Even when we plot the fluorescence for PS117 on its own scale, the variability over time is not very obvious. As the variability in the PS117 for fluorescence is very small and the number of PS117 profiles we have for this parameter is less than for the others (see comment 3.12), we think that changing the colour scale will not contribute enough to the messages of the manuscript. However, to clarify the range of variability in the PS117 data, we have added the following to the caption of Fig. 6:

#### Added text to caption Figure 6: Fluorescence during PS117 varied at values < 0.09.

b) We have a lower number of casts from which we have fluorescence data than for other parameters. Please see our response to comment 3.12, where we provide the explanation.

c) We agree with the reviewer that we can better incorporate the fluorescence results into the discussion to support our arguments. To do so, we have made the following changes, which include addition of text on lines 231-234, a minor change to the structure of the text by moving lines 256-258 down to line 266 and adding a few lines, and also making minor revisions to lines 310 and 320. Note that some of the revisions include those made in response to comment 3.26.

#### Original text lines 231-234:

In our case study, the input of fresher water with lower DIC and TA content is likely advection of AASW from the north-east of the front (and sampling site), influenced by the summer sea ice melt. In addition to a dilution effect, the accompanying increased fluorescence signal during rising tide on PS89 suggests that photosynthesis in this water has likely contributed to its lower DIC, TA, and nutrient content (Fig. 4, 6), which is sustained by solar radiation.

Revised text lines 231-234:

In our case study, the fresher water with lower DIC and TA content on the northern side of the salinity front (and sampling site) is likely advection of AASW, influenced by summer sea ice melt. Based on the fluorescence increase during rising tide for PS89 (Fig. 6E), the water on this side of the front seems to be richer in phytoplankton cells compared to the southern side of the front. In addition to a dilution effect, the accompanying increased fluorescence signal during rising tide suggests that photosynthesis in this water has likely contributed to its lower DIC, TA, and nutrient content (Fig. 4, 6), which is sustained by solar radiation.

Original text lines 256-258 moved down to line 266:

In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated compared to the AASW and to have relatively higher nutrient and DIC content, and lower dissolved oxygen content, as a result of net remineralisation (Fig. 4, 6).

Revised text lines 266-268:

In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated compared to the AASW and to have relatively higher nutrient and DIC content, and lower dissolved oxygen content, as a result of net remineralisation. Due to the lack of exposure to the atmosphere, phytoplankton cells (for which we use fluorescence as a proxy) are expected to be mostly absent. This description of water properties is consistent for the properties observed during ebbing tide (Fig. 4, 6). It therefore seems feasible that less ventilated, colder water from underneath the ice shelf with lower oxygen and higher nutrient and DIC content can extend to the edge of the ice shelf during ebbing tide and into the polynya.

Added text on line 310: This also applies to times at rising tide in the PS89 observation period when the fluorescence signal increases in the water column, suggesting advection of phytoplankton cells into the polynya.

Original text on line 320: Outflow and mixing of ice shelf melt water might have been stronger during PS117 than PS89.

Revised text on line 320: Earlier, we noted that southerly winds during PS117 may have counter-acted some of the advection of fresher, more ventilated water from the northeast during rising tide. However, the nutrient and oxygen content, as well as the very low fluorescence during PS117, suggest that the outflow and mixing of ice shelf melt water might have been stronger during PS117 than PS89, as well.

### 3.28 L240: See above about "salinity front".

Indeed, please see our response to comment 3.26. In addition, we have adapted line 243-244.

Original text lines 243-244: If a salinity front existed during PS117, it may have been located further away from the sampling site and closer to the sea ice edge of the polynya.

Revised text lines 243-244: If a salinity front existed during PS117, it could have been located further away from the ice shelf edge, and the sharp horizontal salinity gradient might therefore not have passed directly over the sampling site during PS117 as it did during PS89.

**3.29 L258: And presumably also due to a lack of exchange with the atmosphere?** Agreed! We have amended the text to include this point.

Original text: In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated

compared to the AASW and to have relatively higher nutrient and DIC content, and lower dissolved oxygen content, as a result of net remineralisation (Fig. 4, 6).

Revised text: In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated

compared to the AASW and to have relatively higher nutrient and DIC content, and lower dissolved oxygen content, as a result of net remineralisation **and lack of exchange with the atmosphere** (Fig. 4, 6).

### **3.30 L260:** What do you mean here by "drill sites"? I think this is another example of an idea that needs to be better introduced.

We agree with the reviewer that this idea can be better introduced. Smith et al. (2020a) measured the temperature and salinity profiles underneath the ice shelf by drilling through the ice shelf (with hot water) at various locations and lowering a CTD cast through it.

We have amended the text in a way that better introduces the work by Smith et al., before linking it to the relevance of our study. We have also added text to the caption of Figure 7 to improve clarity.

**Original text:** It is possible that the ebbing tide draws out water from underneath the ice shelf which is expected to be colder. Indeed, the study by Smith et al. (2020a) attributed variability in two repeat profiles at one of the drill sites (EIS-4) to tidal influences extending underneath the ice shelf.

Revised text: It is possible that the ebbing tide draws out water from underneath the ice shelf which is expected to be colder. Indeed, this possibility is supported by findings in Smith et al. (2020a), which includes a repeat profile of the Ekström Ice Shelf's cavity water at one of the measurement stations on the ice shelf (EIS-4; Fig. 7). These two repeat profiles were taken 11 hours apart. The difference observed in the vertical salinity and temperature profile between these two casts was attributed to tidal influences extending underneath the ice shelf (Smith et al., 2020a).

Original text caption Fig. 7: A) Temperature salinity diagram for PS89 (circles) and PS117 (diamonds) tidal observation periods, coloured according to dissolved oxygen concentrations, and the hot water drill CTD profiles through the ice shelf from Smith et al. (2020a) (coloured lines). Colours for hot water drill profiles correspond to the coloured marker locations on the map (B).

Revised text caption Fig. 7: A) Temperature-salinity diagram for PS89 (circles) and PS117 (diamonds) tidal observation periods, which are coloured according to dissolved oxygen concentrations. **CTD profiles of the ice shelf's cavity water were collected and made** available by Smith et al. (2020a) (coloured lines). The cavity CTD profiles were taken by hot water drilling through the ice at various locations on the ice shelf, which are shown on the map in (B) in corresponding colours to the profiles in (A).

3.31 L281-282: a) Here again, it is not apparent to anyone not deeply familiar with the carbonate system why the nDIC and nTA data suggest that physical processes explain the observed variability. The rationale either needs to be explained here, or explained earlier (see my comment above) and then alluded to here. This is a pretty concept in support of the arguments made in the paper. b) Additionally, I got to the end of this paragraph as a whole (L293) and wasn't really sure what I should take away from it.

a) We have now included an explanation for the rationale in section 3.3 (see our response to comment 3.18). The sentence that the reviewer refers to here has been moved and modified to incorporate revisions in response to the second part of this comment (see below). As part of those revisions, we have inserted a reference to the explanation we newly provided in section 3.3.

b) We thank the reviewer for this comment. Upon re-reading the paragraph that the reviewer is referring to, we agree. We have moved this paragraph down, because we think it improves the flow of the discussion. We have placed it after discussing the influence of sub ice shelf water in the polynya. As we made a few other revisions to this section (in response to the first part of this comment, comment 3.32, and comment 2.2), we would like to refer the reviewer to pages 15 and 17 of the <u>revised manuscript</u> to see the result of the combined revisions made to this part of the text.

#### Page 15 of the revised manuscript:

As explained in Section 3.3, the salinity normalisation removes the impact of physical processes from the DIC and TA data. Therefore, any variability that remains in the nDIC and nTA results needs to be explained according to other processes. These processes are represented in Fig. 5 by theoretical lines that indicate how nTA and nDIC would change relative to each other as a result of photosynthesis/respiration, CaCO<sub>3</sub> dissolution/precipitation, and CO2 uptake/release (Zeebe & von Gladrow, 2001). For example, factors that could be relevant to net photosynthesis are variable sea ice cover affecting light availability, nutrient replenishment during ebbing tide, and mixing of phytoplankton cells into deeper water during rising tide (Gleitz et al., 1994). Yet, none of these processes seem particularly dominant in changing the nTA and nDIC content (Fig. 5). The results in Fig. 5 show a legacy of processes that may have occurred in the past weeks to months, as the **marine carbonate** system's equilibration time with the atmosphere is slow, especially in sea ice covered regions. Additionally, the data during rising tide might also reflect processes that happened in the sea ice, which will have affected the carbonate chemistry of the sea ice melt water and thus the properties of the AASW. While we here consider the tides to transport a salinity front back and forth across the sampling site, we must also recognise that the sampled mass of water on each side of the front is not exactly the same during each tidal phase, which contributes to the variability observed in the dataset.

### Page 17 of the revised manuscript:

In this study, we have argued that the DIC variability in the coastal polynya is driven by back-and-forth movement of water under the force of tidal currents across the sampling site located in a region where there is a horizontal gradient in DIC content: lower DIC content to the north-east, influenced by summer sea ice melt, and higher DIC content to the south-west, influenced by unventilated ice shelf cavity water. This led us to investigate whether there is evidence in our dataset for a tidally-driven horizontal DIC pump. For example, net transport away from the ice shelf could transport DIC and nutrients (and perhaps even iron) from the ice shelf towards surface waters on the continental shelf that are exposed to sea ice and the atmosphere. Subsequent biological carbon uptake will then remove DIC. However, when we calculate the trajectory of a water parcel (using the ship's position as a starting point and the average current velocity of the water column) the net transport is south/south-east, i.e. towards the ice shelf (not shown). This implies that surface waters would be modifying the properties of the water underneath the ice shelf over time (instead of the other way around), for example by dilution. If this is the case, we would expect to see a trend in the DIC content of the polynya during ebbing tide. However, this is not the case and the net change in DIC

content over six hour periods (including ebbing and rising tide) is zero (Fig. G4 for PS89). Our observations are a snapshot of a highly dynamic system and consequently they do not provide enough data to analyse such modifications of the seawater physico-chemical properties. Nevertheless, they can be the beginning of future studies into this topic.

#### **3.32 L297: Please explain the significance of the nTA:nDIC ratio.**

By referring to the nTA:nDIC ratio, we aimed to refer to how nTA relates to nDIC in Fig. 5. However, we now understand that this may have been confusing because we only use the term "nTA:nDIC ratio" once and have not given specific introduction to the theoretical lines in Fig. 5, which represent processes that would change the relationship of nTA to nDIC along these lines. This is a comment that relates to comment 2.2 (by reviewer #2), which suggested to give an introduction to these processes. We think that our minor edit to line 297, combined with the changes we made in response to comment 2.2, improve the clarity.

Original text line 297: Yet, none of these processes seem particularly dominant or persistent in the nTA:nDIC ratio (Fig. 5).

Revised text: Yet, none of these processes seem particularly dominant in changing the nTA and nDIC content (Fig. 5).

#### 3.33 L299: The word "data" is plural.

"This data ..." has been corrected to "These data ...".

#### 3.34 L313: What do you mean by "light stability" in this context?

We recognise that the original phrasing is unclear. We meant that sustained primary productivity needs enough light availability in the upper part of the water column that does not vary too much on a short time scale. However, as this is driven by the MLD (affecting the depth of phytoplankton cells) and we are referring in the text to drivers of *low* primary productivity (and not drivers of high primary productivity), we have removed "light stability" in the sentence:

Original text: ... and the most likely drivers of low primary productivity are increased MLD, light stability, and grazing pressure (Arrigo and van Dijken, 2003).

Revised text: ... and **important** drivers of low primary productivity are increased **MLD** and **grazing** pressure (Arrigo and van Dijken, 2003).

# **3.35 L334: I think this section might benefit from a sentence at the end here summing up what we have learned from the new data presented here rather than simply ending the section after outlining everything we don't know.**

We like this suggestion! We have added the following at the end of this section:

Added text on line 334 of the original manuscript:

Despite the unknowns outlined above, the case studies presented in this work show that strong tidal influences on the physical structure and biogeochemical properties of the water column can be expected along the Weddell Sea coastline (and other polar regions subject to strong tides), especially in close proximity to ice shelves and regions of sea ice melt. They also show that local winds and ice shelf meltwater outflows can increase the complexity of the tidal impact within in a region such as a coastal polynya. In addition to studies on the physical role of tides on (for example) basal ice shelf melt, ecological, biogeochemical, and air-sea gas exchange studies can benefit from a better understanding of tidal impacts on the water column.

3.36 L345: "...fluctuates between the bottom (incoming tide) and... (outgoing tide)" – the meaning of this sentence is unclear. We have improved the sentence, as shown below:

Original text: However, the depth at which the fCO2 of the seawater is equal to that of the atmosphere (marked by a dashed line in Fig. 4A) fluctuates between the bottom (incoming tide) and the surface (outgoing tide).

Revised text: However, the depth at which the fCO2 of the seawater is equal to that of the atmosphere (marked by a dashed line in Fig. 4A) fluctuates **from near the bottom of the water column during incoming tide to the surface during outgoing tide.** 

**3.37 L351: In general, I think it's better to avoid hyperbolic terms such as "drastic".** We have replaced "even more drastic" with "even stronger".

Original text: ... an even more drastic fluctuation ... Revised text: ... an even **stronger** fluctuation ...

3.38 Figure 7 – a) I believe that the use of PSU for practical salinity and outdated and such data should be presented with units. Alternately, absolute salinity should be used.
b) Additionally, what is AB? c) And finally in the 5th line of the caption, should the reference to "single purple markers" actually be to "single whitecrosses"?
a) We have now updated this in Fig. 7.

b) AB stands for Atka Bay, where Smith et al. (2020a) also took some profiles. We have now incorporated an explanation in the caption:

Added text in caption of Figure 7: B) Map of measurement locations of the Ekström Ice Shelf cavity CTD profiles by Smith et al. (2020a), denoted by "EIS\_", a measurement location in Atka Bay by Smith et al. (2020a) denoted with "AB", and the sampling location of the tidal observations indicated by the yellow star.

c) Indeed. "Single purple markers" have been changed to "**single white crosses**" in the caption of Figure 7.

**3.39 L378: There's some odd repetition here that makes the sentence confusing – please revisit for clarity.** 

We thank the reviewer for noticing this. We have re-written these lines to remove the odd repetition and to improve the clarity.

Original text: We emphasise the potential misrepresentation of the role of coastal polynyas in the Weddell Sea CO2 uptake if tidal influences are not accounted for using two extreme scenarios from the hypothetical case where samples are collected only during rising or ebbing tide of the PS89 tidal observation: samples are only taken at either peak rising tide or peak ebbing tide, which lead to an overestimation or underestimation of the CO<sub>2</sub> flux, respectively (see above).

Revised text: We emphasise the potential misrepresentation of the role of coastal polynyas in the Weddell Sea  $CO_2$  uptake if tidal influences are not accounted for. For this, we again use the two extreme scenarios based on the PS89 observations that were also used above to illustrate the maximum potential over- and underestimation of the  $CO_2$  uptake. I.e., we use the hypothetical cases where seawater samples are either collected at peak rising tide (overestimation of  $CO_2$  uptake) or at peak ebbing tide (underestimation of  $CO_2$  uptake).

# 3.40 Figure 8 – where is the "dotted line" referred to in the 3rd line of the caption? And if the filled shading indicates the range, does the black line indicate the average wind speed?

The line with the information on the "dotted line" was accidentally left in the caption, but should have been removed. The parameterisation by Sweeney et al. (2007) was used in the  $CO_2$  calculations by Brown et al. (2015). Since we are making a comparison to their work, we wanted to use the same parameterisation. However, the results show no clear difference and we have therefore omitted it from the plot. We have now removed this line from the caption.

The full black, green, and orange lines indeed indicate the fluxes based on the average wind speeds. We have now included this information in the caption.

Original caption: Air-sea CO<sub>2</sub> flux (in mmol m<sup>-2</sup> day<sup>-1</sup> on the left y-axis and in mol m<sup>-2</sup> year<sup>-1</sup> on the right y-axis) determined from the discrete surface seawater sample measurements for the PS89 (green) and PS117 (orange) tidal observation periods, and from the PS89 underway fCO2 measurements (black), which started on the 7th of January 2015. Dotted lines use the parameterisation by Sweeney et al. (2007), which was used in calculations by Brown et al. (2015). The filled shading indicates the range of the flux calculated using the minimum and maximum wind speed measured during PS89 and PS117, respectively. Negative flux represents CO2 uptake by the ocean.

Revised caption: Air-sea CO<sub>2</sub> flux (in mmol m<sup>-2</sup> day<sup>-1</sup> on the left y-axis and in mol m<sup>-2</sup> year<sup>-1</sup> on the right y-axis) determined from the discrete surface seawater sample measurements **and average wind speed** for the PS89 (green) and PS117 (orange) tidal observation periods, and from the PS89 underway fCO<sub>2</sub> measurements (black), which started on the 7th of January 2015. The filled shading indicates the range of the flux calculated using the minimum and maximum wind speed measured during PS89 and PS117, respectively (**Table 1**). Negative flux represents CO<sub>2</sub> uptake by the ocean.

#### 3.41 L414: What do you mean by "mediating effects"?

We recognise that this sentence is unclear. We also realised that "mediating" is the wrong word for what we meant to express. A better word is "modulating". The line has been revised, as shown below:

Original text: The datasets here are too small to explore the mediating effects of these processes.

Revised text: The datasets of the two short case studies presented here are too small to fully explore the modulating effects of these processes on the water column variability.

# **3.42** L415: What is meant by "repeats are required"? Also, I found the inclusion of "carbonate chemistry" a little incongruous here since that is what is presented in this manuscript. Can you clarify your meaning?

We meant that case studies such as these tidal observations would have to be repeated to verify and study interacting processes. "Carbonate chemistry" was included in the list, because we meant to convey that an array of measurements and samples, in addition to carbonate chemistry measurements, are required to constrain relevant interacting processes. We have modified the text as shown below to improve the clarity.

Note: the modified text follows the text edited according to comment #3.41 (see above). Also note: we have inserted a break in the paragraph after the modified text, because we think it improves the readability of the text.

Original text: Longer tidal observations and repeats are required, along with measurements of micro-nutrients, carbonate chemistry, biological productivity, and oxygen isotopes, to be able to constrain interacting processes. A better understanding of the carbonate chemistry of the water underneath the ice shelf - although challenging to obtain - would help understand the influence of this water during ebbing tide.

Revised text: To be able to do so, longer tidal observations are required that cover different parts of the spring-neap tidal cycle, and at different times of the year to capture varying wind and ice melt/growth conditions. Alongside carbon system state variables, an array of co-collected measurements, such as micro-nutrients, biological productivity, and oxygen stable isotopes, can help to constrain interacting processes. An understanding of the carbonate chemistry of the cavity water underneath the ice shelf - although challenging to obtain - would help understand the influence of this water on the polynya during ebbing tide.

### **3.43 L424: Please see my comments above about the "salinity front".**

Please see our response to comment 3.26. Additionally, we have revised line 423-424:

Original text lines 423-424: It may also help identify the formation and characteristics of - what is described here as - a salinity "front" that moves back and forth with the tide.

Revised text lines 423-424: It may also help identify the formation and characteristics of **a horizontal coastal salinity gradient – here referred to as a "salinity front"** – that moves back and forth with the tide.

## **3.44 Data availability: is it acceptable to the journal for the data to only be accessible by contacting the corresponding author? This seems unusual.**

We believe there might have been a slight misunderstanding caused by the manner in which we had originally written our statement for the data availability and would like to clarify. As stated in our data availability statement, our PS117 data will be made available online on the Pangaea database. We were still working on this at the time of initial submission of the manuscript (also coordinating how the rest of the data of PS117 will be published). The data used in the current work has since been submitted to Pangaea and we have received the preliminary citation for it, which should be finalised before finalisation of the manuscript. The editors are aware of this.

Original text: For data access, contact the corresponding author. DIC and TA datasets will be made available online on the Pangaea database (in progress).

#### Revised text: Data are available on Pangaea: https://doi.org/10.1594/PANGAEA.946363.

## **3.45** Figure A1-A4 – what does the pink star denote? This information should be included in the caption.

The pink start denotes the sampling location within the polynya during the PS89 and PS117 tidal observations. We have now included this in the captions for Figures A1-A4.

3.46 Figure G4 – I think the authors should offer a reason for the anomalous silicate data from PS117. Are they certain it's not an analytical error? If not, might it shed some light on the water mass encountered during PS117? I found it a little odd that all these data were presented, the inconsistency highlighted, and then no discussion/explanation offered. Same comment applies to Figure G6. The silicate data from PS117 are not anomalous. There are different relationships between salinity and all three nutrients for PS89 and PS117 (i.e. not only for silicate). Obviously, the water masses present in 2015 (PS89) and in 2019 (PS117) had different characteristics. This is shown in G4, G5, and G6. We have not found any measurement errors, and based on the data also have no reason to presume that.

It is indeed expected that nitrate and phosphate will be more similar to each other because the processes in which they are involved are similar (i.e., utilization and remineralization of organic matter). This is different for silicate, as it is incorporated in opal. Opal is formed and dissolved independent on the organic matter processes in which nitrate and phosphate are changed. We can therefore expect different relationships for PO4/NO3 on the one side and silicate on the other; and these relationships may be different in different years.

Please see our response to comment 3.20, part b), in which we explain the changes made to the manuscript. After incorporating the revisions, we decided to remove figure G6, as the reviewer's comments made us realise that it causes more confusion than clarification. We feel that it no longer adds any important information that Figs. G4 and G5 do not already provide and would support our argument, which we have now clarified (as shown in response to comment 3.20b).

### The **role influence** of tides **and sea ice** on the **marine** carbonate chemistry **in** of a coastal polynya in the south-eastern Weddell Sea

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#### Abstract.

Tides significantly affect polar coastlines by modulating ice shelf melt and modifying shelf water properties through transport and mixing. However, the effect of tides on the marine carbonate chemistry in such regions, especially around Antarctica, remains largely unexplored. We address this topic with two case studies in a coastal polynya in the south-eastern Weddell Sea,

- 5 neighbouring the Ekström Ice Shelf. The case studies were conducted in January 2015 (PS89) and January 2019 (PS117), capturing semi-diurnal oscillations in the water column. These are pronounced in both physical and biogeochemical variables for PS89. During rising tide, advection of sea ice melt water meltwater from the north-east created a fresher, warmer, more deeply mixed water column with lower dissolved inorganic carbon (DIC) and total alkalinity (TA) content. During ebbing tide, water from underneath the ice shelf decreased the polynya's temperature, increased the DIC and TA content, and created a
- 10 more stratified water column. The variability during the PS117 case study was much smaller, as it had less sea ice melt water meltwater input during rising tide and was better mixed with sub-ice shelf water. The contrasts in the variability between the two case studies could be wind and sea ice driven, and underline the complexity and highly dynamic nature of the system.

The variability in the polynya induced by the tides results in an air-sea  $CO_2$  flux that can range between a strong sink (-20-24 mmol m<sup>-2</sup> day<sup>-1</sup>) and a small source (73 mmol m<sup>-2</sup> day<sup>-1</sup>) on a semi-diurnal time scale. If the variability induced

15 by tides is not taken into account, there is a potential risk of overestimating the polynya's  $CO_2$  uptake by 9867 % or underestimating it by 10873 % (mistaking it for a source instead of a variable sink), compared to the average flux determined over several days. Depending on the timing of limited sampling, the polynya may appear to be a source or a sink of  $CO_2$ . Given the disproportionate influence of polynyas on heat and carbon exchange in polar oceans, we recommend that future studies around the Antarctic and Arctic coastlines to consider the timing of tidal currents in their sampling strategies and analyses. This will help constrain variability in oceanographic measurements and avoid potential biases in our understanding of these highly complex systems.

#### Copyright statement.

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#### 1 Introduction

Coastal regions are subject to tidal forces, which modify the water column through enhanced mixing (Padman et al., 2009).
Tides in polar regions have recently gained increasing attention in investigations focusing on understanding the physical interaction between the ocean and sea ice (e.g., Dmitrenko et al., 2012; Kirillov et al., 2013; Skogseth et al., 2013) and how they affect ice shelf melt (e.g., Makinson et al., 2011; Mueller et al., 2018; Padman et al., 2018; Huot et al., 2021)(e.g., Padman et al., 2009; Makinson Tidal effects on the biogeochemistry along polar coastlines, however, have not yet received similar attention, even though tides have been shown to affect the chemical properties and the fugacity of seawater CO<sub>2</sub> (fCO<sub>2</sub>) in other regions (Rogachev et al., 2021).

30 2001; Andersson and MacKenzie, 2012; Sims et al., 2022).

Areas of open water in the middle of an otherwise sea ice covered region, also known as polynyas, are common features along polar coastlines. They are well known for their contribution to sea ice formation (Renfrew, 2002) and both heat and carbon exchange with the atmosphere (Hoppema and Anderson, 2007). They have been described as "windows" between the ocean and the atmosphere (Barber and Massom, 2007), enabling strong interaction between these two spheres. The tides in the

- 35 Weddell Sea are the largest in the Southern Ocean (Padman et al., 2018). Here, relatively warm, carbon-rich Warm Deep Water (WDW) upwells in the east and is physically and chemically altered along its route towards the western Weddell Sea, a hotspot for Antarctic Bottom Water (AABW) formation and carbon sequestration (Fahrbach et al., 1994; Anderson et al., 1991; Huhn et al., 2013). Water on the eastern shelf also has the potential to be exported to the deep ocean by northward transport into the Upper Circumpolar Deep Water (uCDW) (Orsi et al., 2002), along with any modifications to the dissolved inorganic carbon (DIC)
- 40 content on the continental shelf. Studying processes that modify the physical and chemical properties of these water masses on the shelf, such as tides, will enable a better understanding of the transport of carbon to the deep ocean.
   A common feature along the Antarctic coastline are coastal polynyas, described as areas of open water where sea ice cover

is expected. Absence of sea ice enables strong direct interaction between the ocean and the atmosphere in regions and at times of the year when sea ice cover would otherwise restrict it . They and strong gradients between ocean and atmosphere exist.

45 Polynyas are therefore thought to have a disproportionally large impact on the polar oceans considering their relatively small surface area (Barber and Massom, 2007). The prolonged ice-free conditions allow direct gas exchange to oceur, a longer time window for equilibration direct exposure of the ocean to the atmosphere has an impact on the marine carbonate system, altering the seawater  $fCO_2$  and thus the capacity for ocean  $CO_2$  uptake. Whether the polynya is a source or a sink of  $CO_2$  with the atmosphere, as well as prolonged biological productivity (Hoppema and Anderson, 2007). Substantial biological activity is observed in coastal polynyas around the Antarctic continent (Arrigo and van Dijken, 2003). This makes them important with regard to air-sea strongly depends on the interplay between processes that increase the seawater  $fCO_2$  flux estimates, beyond the atmospheric  $fCO_2$ , and those that decrease it. For example, polynyas can have an enhancing role in sea ice production as they can release heat directly to the atmosphere (Renfrew, 2002). In this process, brine, including DIC, is rejected from the sea ice matrix into the ocean (Rysgaard et al., 2011; Skogseth et al., 2013). In the summer, dilution by sea ice melt and calcium

- 55 carbonate (CaCO<sub>3</sub>) dissolution draws down CO<sub>2</sub> (Rysgaard et al., 2011). Additionally, enhanced light availability supports biological productivity (Arrigo and van Dijken, 2003), which consumes CO<sub>2</sub> that can thereby typically generate a strong CO<sub>2</sub> sink (Yager et al., 1995; Arrigo et al., 2008). The prolonged ice-free conditions also potentially allow enough time for the polynya to take up as much CO<sub>2</sub> as is necessary to reach equilibrium with the atmosphere (Hoppema and Anderson, 2007). However, biological productivity is found to be variable among Antarctic coastal polynyas (Arrigo et al., 2015), and in some
- cases is not sufficient to keep a polynya from outgassing CO<sub>2</sub> (Arroyo et al., 2019). Tides can displace water on short timescales (Skogseth et al., 2013; Llanillo et al., 2019) and modify the water column structure through enhanced mixing (Padman et al., 2009). On the one hand, tidal mixing in coastal polynyas can replenish nutrients at the surface (Tremblay et al., 2002), stimulate biological production, and thereby enhance CO<sub>2</sub> drawdown. On the other hand, mixing with CO<sub>2</sub>-rich deep water can increase surface water *f*CO<sub>2</sub> (Rogachev et al., 2001), or in some cases erode a stable mixed layer necessary to support phytoplankton
- 65 growth (Arrigo and van Dijken, 2003).

In shallow and coastal regions, tides can have an important role in modulating the physical and biogeochemical properties of the polynya's water column, especially along its margins. In particular, the effect. The effects of tides on the marine carbonate chemistry remains of these biogeochemically impactful regions along the Antarctic coastline remain largely unexplored. Understanding the tidal influence may help us to quantify some of the variability observed in biological productivity

70 around Antarctica (Arrigo et al., 2015) and among Antarctic polynyas, such as the variability in the biological productivity (Arrigo et al., 2015) as well as the capacity of coastal polynyas to absorb or release atmospheric CO<sub>2</sub> (Arroyo et al., 2019). Practically, understanding the role of tides this improved understanding can help develop more reliable sampling activities that consider the timing and strength of tidal currents, thereby obtaining representative data of a highly dynamic system.

The tides in the Weddell Sea are the largest in the Southern Ocean (Padman et al., 2018). Here, relatively warm, carbon-rich
75 Warm Deep Water (WDW) upwells in the east and is physically and chemically altered along its route towards the western
Weddell Sea, a hotspot for Antarctic Bottom Water (AABW) formation and natural earbon sequestration (Fahrbach et al., 1994; Anderson e
Water on the eastern shelf is modified through ventilation with the atmosphere and also has the potential to be exported to the
deep ocean by northward transport into the Upper Circumpolar Deep Water (uCDW) (Orsi et al., 2002), along with any CO<sub>2</sub>
that has been exchanged with the atmosphere at the continental shelf. Studying processes that modify the physical and chemical

80 properties of these deep water masses, such as tides, will enable a better understanding of the transport of anthropogenic carbon to the deep ocean.

In this work, we illustrate the effect of tides on the seawater carbonate chemistry marine carbonate system with two case studies in a coastal polynya in the south-eastern Weddell Sea that neighbours the Ekström Ice Shelf (Fig. 1). This coastal polynya regularly forms in the summer months (Boebel, 2019; Arrigo and van Dijken, 2003; Arrigo et al., 2015). Coastal polynyas in

- 85 this region are typically formed by katabatic winds from the continent that advect the newly produced sea ice away from the coastline in the spring and summer (Eicken and Lange, 1989; Renfrew, 2002). At the Ekström Ice Shelf, a number of grounded ice bergs to the east can also create a sea-ice free lee downstream from the westward-flowing coastal current (Boebel, 2019). We will We present biogeochemical observations for two separate and independent tidal sampling campaigns in the austral summer: one in January 2015 and the other in January 2019. To the best of our knowledge, this is the first time that tidal
- 90 influences on the seawater carbonate chemistry are studied in a coastal Antarctic polynya. We discuss the variability induced by tidal forces and explore the differences between the two tidal observations in terms of their physical and biogeochemical characteristics, and what it means for ocean  $CO_2$  uptake.

#### 2 Methods

#### 2.1 Sample collection and measurementsSampling location

- 95 The data were collected during two repeat hydrographic expeditions in the Weddell Sea with the German icebreaker *R.V. Polarstern*: expedition PS89 (2 December 2014 31 January 2015; Cape Town Cape Town; (Boebel, 2015)) and expedition PS117 (12 December 2018 7 February 2019; Cape Town Punta Arenas; (Boebel, 2019)). During both expeditions, the tidal cycle was recorded by means of repeat CTD casts at the same location at a frequency that was high enough to constrain the tidal oscillation in the water column. These recordings will hereafter be referred to as *tidal observations*. The tidal observations
- 100 were performed at the same site in a coastal polynya, 56 km west of Atka Seaport, directly at the edge of the Ekström Ice Shelf (Fig. 1), the geometry of which is thought to be representative of most ice shelves of Dronning Maud Land (Smith et al., 2020a).

The polynya is bordered by the Ekström Ice Shelf along its southern edge, and by sea ice along the rest of its perimeter. It regularly forms in the summer months (Boebel, 2019; Arrigo and van Dijken, 2003; Arrigo et al., 2015). Coastal polynyas in

- 105 the eastern Weddell Sea have an average area of 7.75 x 10<sup>3</sup> km<sup>2</sup> in the summer and 1.12 x 10<sup>3</sup> km<sup>2</sup> in winter (coastal polynyas numbers 12-17 in Arrigo and van Dijken (2003)). this region are typically formed by katabatic winds from the continent that advect the newly produced sea ice away from the coastline in the spring and summer (Eicken and Lange, 1989; Renfrew, 2002). At the Ekström Ice Shelf, a number of grounded ice bergs to the east can also create a sea-ice free lee downstream from the westward-flowing coastal current (Boebel, 2019).
- The size and shape of the polynyas at the Ekström Ice Shelf are highly variable, depending on the wind direction and speed. For the PS89 tidal observations, the average width (between the ice shelf and sea ice) of the Ekström polynya is about 0.8 km, estimated from Synthetic Aperture Radar (SAR) images (Fig. A1). The length was approximately 12 km. During the PS117 tidal observation, the polynya was substantially larger, having an approximate average width of 3 km and a length of about 40 km (Fig. A3). GenerallyGiven that the average area of coastal polynyas in the eastern Weddell Sea in summer is
- 115  $7.75 \times 10^3$  km<sup>2</sup> (coastal polynyas numbers 12-17 in Arrigo and van Dijken (2003)), the polynya during both tidal observations at this location is considered to be relatively small.

Information about the tidal observations is shown in Table 1. Sources of supporting data used in this study can be found in the Supplementary Materials (Table B1). Both tidal observations were made at the same time of year (i.e. mid-January). The sampling during PS89 (75 hours) lasted  $\sim$ 3 times longer than during PS117 (22 hours). The exact location of the hydrographic

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stations differed slightly between the two expeditions due to shifting of the Ekström Ice Shelf extent between 2015 and 2019. The sampling sites for PS117 were chosen in such a way that the distance to the ice shelf was approximately the same as during PS89. Due to other ongoing scientific activities on board during the PS117 tidal observation, the exact location of sampling within the coastal polynya varied slightly per CTD cast, but the casts remained within a maximum distance of 300 m from each other. The polynya is bordered by the Ekström Ice Shelf along its southern edge, and by sea ice along the rest of its perimeter.

#### 125 2.2 Hydrographic and biogeochemical observations

In addition to a SBE911plus CTD sensor, each rosette sampler (SBE32, 24 x 12 L bottles) was equipped with a fluorometer (EcoFLR, Wetlabs), an oxygen optode (SBE43, Seabird Electronics), and an Acoustic Doppler Current Profiler (ADCP) system (2x 300 kHz RDI Workhorse ADCPs) (Table C1). The oxygen measurements were calibrated using discrete oxygen samples from deep CTD casts only, analysed with the Winkler method (Boebel, 2015, 2019; Rohardt and Tippenhauer, 2020). The oxygen optode sensor was malfunctioning on every other cast during During the PS117 tidal observation period, two different

- CTD rosettes with their own set of sensors were used in alternation. On one of these two CTD rosettes, the oxygen optode sensor malfunctioned and thus its data had to be excluded from further analysis. The fluorescence data for this particular rosette is also not available. The minor implication of this is addressed in Section 3.3.
- Dissolved inorganic carbon (DIC) and total alkalinity (TA) samples were collected following Dickson et al. (2007). DIC and TA samples were analysed on a VINDTA 3C system (Mintrop, 2016), which uses coulometry for DIC and potentiometric titration for TA determination. TA was calculated according to Dickson et al. (2007) for PS89 and using the Python package Calkulate (Humphreys and Matthews, 2022) for PS117. On PS89, dissolved phosphate ( $PO_4^{3-}$ ), silicate (SiO<sub>4</sub>), and nitrate ( $NO_3^{-}$ ) analyses performed by UV-Vis spectrophotometric methods were carried out on board with a SEAL Analytical continuous-flow AutoAnalyzer (Boebel, 2015). During PS117, nutrient samples were analysed simultaneously for  $PO_4^{3-}$ ,
- 140 SiO<sub>4</sub>, nitrite (NO<sub>2</sub><sup>-</sup>), and the combination of NO<sup>3-</sup> + NO<sub>2</sub><sup>-</sup> on board on a continuous gas-segmented flow TRAACS 800 Auto-Analyzer (Technicon, a.k.a. SEAL Analytical) within 4-5 hours after sampling (Boebel, 2019). Samples were calibrated with standards diluted in low nutrient sea water seawater within the salinity range of the Southern Ocean. Analytical uncertainties can be found in Tables C2 and C3.

To complement the ADCP data, a tidal model (Model CATS2008) was used to determine the times of high (rising) and low (ebbing) tide during the tidal experiments. This model has been optimised for the Antarctic seas, using available measurements and including ice shelf cavities to improve performance (Padman et al., 2002). All tidal constituents, which represent each mode of the tidal oscillation on a different time-scale, are used (e.g. M2, S2, K1). The modelled currents are averaged over the entire water column for tidal currents only, i.e. they are not total currents. Total currents (measured by the ADCP) include contributions from, for example, mean flow along the continental shelf.



**Figure 1.** Map of study site: A) Weddell Sea with bathymetry: <u>IBSCO Version 1.0 (Arndt et al., 2013)</u>. Grey regions represent the Antarctic continent and land-fast ice, white regions represent ice shelves. B) Enlarged map of coastal study site along the Ekström Ice Shelf. Yellow star shows location of tidal measurements. See Table 1 for coordinates.

 Table 1. Details of the tidal observations made with based on repeat CTD casts and discrete seawater sampling during the two hydrographic

 expeditions: PS89 and PS117. For both observation periods, casts were lowered into the water during times of ebbing and rising tide. Depth of the polynya was around 165 m and 200 m during PS89 and PS117, respectively.

	PS89	PS117
Start observations [UTC]	21:09 9 Jan. 2015 <sup>a</sup>	14:27 11 Jan. 2019
End observations [UTC]	01:00 11 Jan. 2015	11:57 12 Jan. 2019
Location latitude	70° 31 <u>°</u> 24 <u>"</u> " S	70°31 <u>°-</u> ′_19.56 <u>"-</u> ″ S
Location longitude	8° 45 <u>-</u> ′34.2 <u>"-</u> ′′ W	8°46 <u>~</u> 6.76 <u>"-</u> "W
Deepest depth of CTD cast $[m]$	160 - <del>m</del> -	190.5 - 201.5 <del>- m</del> -
No. of CTD casts	40	8
No. DIC/TA bottle samples	260	67
Mean (min max.) wind speed $[m s^{-1}]$	10.7 (4-16)	<u>6.6 (3-10)</u>

<sup>*a*</sup> Two casts done on the 8<sup>*th*</sup> of January have not been included into this case study, as they were too disconnected from the rest of the time series. However, the CO<sub>2</sub> flux based on any discrete measurements available from these casts has been included in Fig. 8. ADCP measurements started on the 7th of January. The underway  $fCO_2$  measurements started on the 7<sup>*th*</sup> of January at 23:00 (Fig. D1).

#### 150 2.3 The marine carbonate system and CO<sub>2</sub> flux calculations

The air-sea CO<sub>2</sub> flux was calculated according to:

$$F = kK_0(fCO_{2sw} - fCO_{2atm})$$

(1)

F is the CO<sub>2</sub> flux in mol m<sup>-2</sup> hr<sup>-1</sup>, k is the gas transfer velocity,  $K_0$  is the CO<sub>2</sub> solubility at *in situ* temperature and salinity, and  $fCO_2$  is the fugacity of  $CO_2$  in seawater (sw) and in the atmosphere (atm). The gas transfer velocity is calculated

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according to the parameterisation of Wanninkhof (2014). Minimum, maximum, and average wind speed for the duration of the tidal observation period, as measured on board and reported at 10 m above sea level, were used as input to this parameterisation (Table 1). For the Schmidt number, i.e. the parameter that relates the gas transfer velocity of different gases, we use Wanninkhof (2014), which gives a refitted polynomial updated from Wanninkhof (1992) to cover a temperature range of -2 to 40 °C and is virtually the same as the parameterisation by Ho et al. (2006). The  $CO_2$  solubility is calculated according to Weiss (1974). The

- fugacity of CO2 is numerically similar to the partial pressure of CO2 (pCO2), but accounts for the non-ideal behaviour of the 160 gas. The  $fCO_{2atm}$  is calculated using the virial- and cross-virial coefficients from Weiss (1974) in the equation to convert the atmospheric CO<sub>2</sub> mole fraction to  $fCO_2$  by Weiss and Price (1980). It requires the dry air mole fraction of CO<sub>2</sub> ( $xCO_2$ ), for which we use discrete air sample measurements from Syowa Station at 69° 0' 16"/S, 39° 34' 54"E (Dlugokencky et al., 2019), and the water vapour pressure, which is derived from *in situ* seawater temperature and salinity in the parameterisation of Weiss
- 165 and Price (1980). We use the average xCO<sub>2</sub> of January 2015 and 2019 for the PS89 and PS117 experiment, respectively, and shipboard atmospheric pressure reported at sea level.

The  $fCO_2$  of surface seawater ( $fCO_{2sw}$ ) is determined from the DICand TA concentrations, TA, nitrate, and phosphate content, as well as the temperature and salinity, of the shallowest discrete seawater values samples (typically between 15 and 5 m deep), using PyCO2SYS (Version 1.3) (Humphreys et al., 2022), based on the original work of Lewis and Wallace (1998).

- 170 Parameterisations by Lueker et al. (2000) were used for the carbonic acid equilibrium constants, by Dickson (1990) for the bisulfate ion dissociation constants, by Uppström (1974) for the boron:salinity relationship, and by Dickson and Riley (1979) for the hydrogen fluoride dissociation constants. Additionally, continuous surface water  $fCO_2$  was measured at the ship's seawater supply with an intake at 11 m depth by a General Oceanics pCO2 analyser on board, for the PS89 tidal observation only. The discrete surface seawater samples were collected at the same depth as the underway water intake depth ( $\sim 11$  m) or shallower
- $(\sim 5 \text{ m})$ . The measured and calculated  $f \text{CO}_2$  values are comparable for the periods where they overlap (Fig. D1). Small discrep-175 ancies between the measured and calculated values are likely due to the difference in depth and spatial and temporal variability. As is shown in Section 4.2, these discrepancies are not large enough to affect the agreement between the CO<sub>2</sub> flux estimates based on these two sets of  $fCO_2$  data. Alongside  $fCO_2$ , the PyCO2SYS package simultaneously resolves other carbonate system parameters with DIC, TA, and auxiliary data (listed above) as input parameters (Zeebe and Wolf-Gladrow, 2001; Humphreys and M
- These include the saturation state for calcite and aragonite (polymorphous forms of calcium carbonate) and pH. 180

#### 3 Results

#### **Tidal current** 3.1

The *u* (east-west) and *v* (north-south) components of the current velocity measured by the ADCP are significantly positively correlated to each other (Fig. F1). They synchronously alternate sign roughly twice a day throughout the water column (Padman et al., 2002), resulting in a barotropic (depth-averaged) component of the flow that matches the modelled tidal velocity (Fig. 185

2). The semi-diurnal tidal currents are thus a dominant component of the total current velocity at this sampling location. The vertical grey areas in Fig. 2 (and in other figures) indicate the time and duration of ebbing tide, here defined as the time when both the u and v components of the modelled current velocity are positive, i.e. the direction of the current is towards the northeast. When both components are negative, the direction is towards the south-west and here considered to be rising tide. Note that the white vertical areas in the figures include the rising tide as well as times when either the modelled u or v component is negative.

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The velocity profiles are generally homogeneous during ebbing tide. More vertical structure is seen in both velocity components after peak velocities are reached during rising tide during PS89. These baroclinic (depth-dependent) flows induce short-lived vertical shear between the surface and subsurface layers before velocity profiles homogenise again towards the north-east (ebb). The range of current velocities is slightly larger during the PS89 tidal observation than during PS117 (Fig. F1), which is mainly due to the higher velocities in the morning of 10 January 2015. The modelled tidal current at this time is not particularly stronger than at any other time point in the observation period, including PS117. The stronger current in the

first half of 10 January 2015 is thus likely the result of other enhancing factors, such as wind speed and direction. Both the PS89 and PS117 discrete tidal observations were made five days after spring tide, although the spring tide prior

- to the PS89 observations was at full moon (5 January 2015) and the spring tide prior to the PS117 observations was at new 200 moon (6 January 2019; dates obtained from https://tidesandcurrents.noaa.gov/historic tide tables.html). The tidal observations of both case studies are thus set at a similar time in the spring-neap tidal cycle. Peak-to-peak tidal heights in this region are around 2 m, but may increase by a factor of two during spring tides (Padman et al., 2002, 2018). Our datasets only capture a small fraction of time, and we cannot judge the relative strength of the tide beyond its time limits. However, considering that the dominant constituent of tidal oscillations in the Weddell Sea is the semi-diurnal constituent (Padman et al., 2002) and that 205
- the modelled velocities are similar between both tidal observations, we regard the two case studies as comparable in terms of tidal influence on the system.

#### 3.2 Physical variability

A clear semi-diurnal tidal cycle is observed in the physical properties of the water column during the PS89 tidal observation period in January 2015 (Fig. 3). Over the depth horizons, salinity increases and temperature decreases throughout the water 210 column during ebbing tide. Isopycnals rise to the surface, resulting in a shallow stratification. A mixed layer forms at the surface during ebbing tide with relatively uniform properties and an average depth of  $\sim 20$  m. The mixed layer depth (MLD) is determined by a  $\frac{0.020.03}{0.020.03}$  kg m<sup>-3</sup> density difference with the average of the top 10 m. During rising tide, the MLD tends to either deepen or the mixed layer breaks down altogether as the density decreases. When a steep density gradient is absent, 215

which typically occurred during rising tide, the water column is considered to be relatively well mixed. The isolines for salinity and temperature deepen as the surface water becomes fresher and warmer. These semi-diurnal fluctuations occur throughout the water column, down to the bottom at almost 200 m depth.

While a similar tidal pattern is also recorded in the salinity and temperature profiles of the shorter PS117 tidal observation, the amplitude of variability for salinity is strikingly-much smaller compared to PS89. The salinity values for PS117 range only


**Figure 2.** Current velocity for PS89 (A, C, E, G) and PS117 (B, D, F, H). Modelled *u* component of the tidal currents is shown in panels A and B. The modelled *v* component is shown in G and H. Modelled tidal velocities are averaged over the full water column. The *u* component of the ADCP profile data is shown in C and D. The *v* component of the ADCP data is shown in E and F. Vertical grey-grey-shaded areas indicate times of ebbing tide, here identified as times when the *u* and *v* components in the modelled tidal current are both positive, i.e. the direction of the current is north-east. Directions associated to the positive and negative values of the *u* and *v* components are indicated by the red letters next to the colour bars: N (north), S (south), E (east), W (west).

220 between 34.13 and 34.29, while they range between 34.03 and 34.34 for PS89. With values between -1.58 °C (at the surface) and near freezing -1.89 °C (at the bottom), the temperatures measured during PS117 have a smaller range and are generally lower than those measured for PS89 (-1.42 to -1.85 °C). In contrast to PS89, no mixed layer was identified at any point during the PS117 tidal period, as a steep density gradient was absent and the entire water column was better mixed.

#### 3.3 Biogeochemical variability

225 Despite the lower vertical resolution <u>compared to the continuous sensor measurements</u>, the discrete bottle measurements capture the variability in the water column well, as shown by comparing the discrete bottle and continuous profile measurements for density (Fig. E1). We are therefore confident that the discrete biogeochemical measurements are also representative of the variability in the water column at the time of sampling.

The DIC and TA content mimic the tidal signature as seen for salinity (Fig. 4): their content decreases throughout the wa-230 ter column when the tide comes in, and increases as the tide goes out. The variability is, again, much lower during PS117 than during PS89. For the PS89 tidal observation, the DIC (TA) varied between 2174.3 and 2217.9  $\mu$ mol kg<sup>-1</sup> (2307.3 and 2327.1  $\mu$ mol kg<sup>-1</sup>) at the surface (<50 m) and between 2186.8 and 2222.7  $\mu$ mol kg<sup>-1</sup> (2312.3 and 2328.7  $\mu$ mol kg<sup>-1</sup>) at



**Figure 3.** A , and B ) Salinity show the salinity for PS89 and PS117, respectively. Green markers in A indicate the mixed layer depth (MLD) for casts where a mixed layer could clearly be identified according to a strong density gradient. MLD is identified as the depth at which the density difference with the average density values in of the top 10 m is 0.020.03 kg m<sup>-3</sup>. Temperature profiles are shown in C (PS89) and D (PS117). White contour lines represent isopycnals in kg m<sup>-3</sup>. Vertical grey-coloured grey shaded areas indicate times of ebbing tide.

greater depths (>50 m). During PS117, DIC and TA content overall ranged between from 2202.6 — to 2220.1  $\mu$ mol kg<sup>-1</sup> and 2311.5 — to 2322.3  $\mu$ mol kg<sup>-1</sup>, respectively. Salinity-normalised DIC (In the ocean, changes to salinity are driven by

- 235 oceanographic processes, such as dilution, ice formation, and mixing. These physical processes also impact DIC and TA, which is why DIC and TA are often strongly correlated to salinity (Middelburg et al., 2020). This is also the case in our dataset. However, DIC and TA content are additionally a function of biological (e.g. photosynthesis, respiration, and remineralisation) and chemical (e.g. CaCO<sub>3</sub> dissolution and precipitation) processes (Zeebe and Wolf-Gladrow, 2001). To be able to study the role of biogeochemical processes on DIC and TA content, it is useful to separate the effect of physical processes, such as dilution
- 240 and mixing of different water masses, from the rest. This can be done by normalising the DIC and TA values to the salinity, which we have done here according to methods by Friis et al. (2003). The salinity-normalised DIC (nDIC) and TA (nTA) profiles (according to Friis et al., 2003) lose much of the semi-diurnal variability seen in the profiles of the non-salinity-normalised values, suggesting that physical processes , such as advection and mixing, are the dominant drivers of the observed variability in DIC and TA (Fig. G1). PS117 nDIC values are markedly higher than those for most PS89 samples (Fig. 5). A part of this
- increase in nDIC over time could be result of the increase in atmospheric CO<sub>2</sub>, assuming at least partial equilibration with the atmosphere. The atmospheric  $fCO_2$  increase (10 µatm) alone could contribute ~6 µmol kg<sup>-1</sup> to the surface DIC content if

all other variables remained the same. This upper-bound estimate is based on average values of the top 10 m during PS89 and assumes equilibration of the surface water with the atmosphere.

- PS117 nitrate (28.9 30.1  $\mu$ mol kg<sup>-1</sup>), phosphate (2.0 2.1  $\mu$ mol kg<sup>-1</sup>), and dissolved oxygen (322.0 333.2  $\mu$ mol kg<sup>-1</sup>) concentrations throughout the water column have similar values as those at the bottom of the water column during PS89 (Fig. 6, G2, G4). Fluorescence was barely detected during This is not the case for silicate, for which its PS117 (Fig. 6). Silicate has an offset between both case studies (Fig. ??). The silicate concentration is also relatively uniform in the water column during PS117 (58.3 - 59.8  $\mu$ mol kg<sup>-1</sup>; Fig. G2). Instead of values close to the upper part of the PS89 silicate range (as is the case for nitrate and phosphate), the PS117 silicate values lie around the mean silicate values measured for PS89 (60.0 ± 1.1  $\mu$ mol kg<sup>-1</sup>;
- 255 Fig. G2, G4). Whereas the This observation illustrates that silicate behaves differently from phosphate and nitrate, as its content is affected by other processes, i.e. by diatom growth and remineralisation at depth or in the sediment rather than by photosynthesis and biological respiration (Sarmiento, 2013). Similarly to nDIC and nTA, the nutrients were salinity-normalised concentrations for nitrate and phosphate during PS117 have an average that is significantly higher (29.7(following Friis et al. (2003)). Consistent to nDIC and nTA, no obvious deviations from the mean salinity-normalised values are observed
- 260 that could indicate a dominant biological influence (Fig. G5). It supports the observation made above that the dominant driver of the variability observed within each tidal case study is mostly physical. For the salinity-normalised silicate content, the averages of both tidal observations are similar to each other (59.5  $\pm$  0.10.5  $\mu$ mol kg<sup>-1</sup> and 2.0  $\pm$  0.01 $\mu$ mol kg<sup>-1</sup>, respectively) than those for PS89 (28.1and 59.2  $\pm$  0.30.2  $\mu$ mol kg<sup>-1</sup> and 1.9  $\pm$  0.04  $\mu$ mol kg<sup>-1</sup>), the for PS117; Fig. G5), indicating that processes affecting silicate content did not differ much between the two case studies. However, a consistent offset between the
- 265 case studies is observed for the salinity-normalised silicate averages are similar ( $59.5 \pm 0.5$ -values for nitrate and phosphate, where PS117 values are on average higher by 1.6  $\mu$ mol kg<sup>-1</sup> for PS89 and 59.2  $\pm$  0.2 and 0.1  $\mu$ mol kg<sup>-1</sup> for, respectively. Even though biogeochemical processes might not be able to explain the variability within each tidal observation, these results suggest that the polynya may have had a higher input and/or a lower loss of nitrate and phosphate during January 2019 compared to January 2015. Fluorescence is here used as a proxy for the presence of photosynthetic cells. While the rising tide increased
- 270 fluorescence in the water column during PS89, it was barely detected during PS117 ; Fig. G5). (Fig. 6). In the absence of active photosynthetic cells, remineralisation enhancing the nitrate and phosphate content may have been an important process in the water observed during PS117.

Due to complications with the data for dissolved oxygen and fluorescence on four of the CTD casts of the PS117 tidal observation, these data were excluded from analysis. The implication of this reduced temporal resolution is that we risk losing

275 representation of water column variability in our dataset for these two variables. However, the low water column variability over time for the physical and other biogeochemical variables (for which we do have data from every cast) strongly suggest that there likely is not a lot of variability in the dissolved oxygen or fluorescence content that we are missing out on due to missing profiles (Fig. 6).



Figure 4. DIC content at the sampling site during the PS89 (A) and PS117 (B) tidal observations. TA content for the PS89 (C) and PS117 (D) observations. White contour lines indicate sigma-t in kg m $^{-3}$ . Vertical grey shaded areas indicate periods of ebbing tide, as defined in the text. Red dashed line in A and B represents the depth at which the seawater  $fCO_2$  is equal to the atmospheric  $fCO_2$ , which is 377  $\mu$  atm in January 2015 and 387  $\mu$ atm in January 2019. Seawater shallower than this depth is undersaturated in fCO<sub>2</sub> compared to the atmosphere. For PS117 (B), the seawater is mostly oversaturated in  $fCO_2$  compared to the atmosphere. The red dotted line in C and D represents the depth at which the seawater pH  $\Omega_{ar} = \frac{8.05}{1.3} \Omega_{ar}$  is lower at depths below this line. The value 1.3 is arbitrary to illustrate the vertical variability in the water column.  $\Omega_{ar}$  ranges between 1.22-1.52 and 1.21-1.34 for PS89 and PS117, respectively.

#### 4 Discussion

#### 280 4.1 Water masses and biogeochemistry

Hydrographically, the water measured during both tidal observations is identified as Eastern Shelf Water (ESW), which is found south of the Antarctic Slope Front (ASF) where pycnoclines slope downwards towards the south at the edge of the narrow continental shelf of the Dronning Maud Land coastline (Heywood et al., 1998). ESW is characterised by salinities between 34.28 and 34.4 and temperatures close to freezing point (Carmack, 1974). ESW itself is a mixture of the following (Fahrbach et al., 1994):

- Winter Water (WW, winter surface water capped by a warmer summer stratification; characterised by a subsurface temperature minimum (Nicholls et al., 2009))

<sup>285</sup> 



Figure 5. Salinity-normalised TA (nTA) and DIC (nDIC) plotted against each other for PS89 (circles) and PS117 (diamonds) tidal data. Samples collected during or ebbing (black circles and yellow diamonds) or rising tide (grey circles and white diamonds) are differentiated by different marker colours. Theoretical process lines are drawn for CaCO3 dissolution/precipitation, photosynthesis/respiration, and CO2 uptake/release (Zeebe and Wolf-Gladrow, 2001).

- Antarctic Surface Water (AASW, derived from WW that has been freshened by sea ice melt and heated by solar radiation in the spring and summer)
- 290 - modified Warm Deep Water (mWDW, which is the result of mixing between WW and WDW along the ASF (Ryan et al., 2020))
  - glacial melt water meltwater (GMW, formed by melting of glaciers, and of ice shelves induced by intrusions of warmer water, such as mWDW and AASW, underneath the ice shelf (Fahrbach et al., 1994; Zhou et al., 2014)).

However, the oscillations in the physical and biogeochemical properties induced by the incoming and outgoing tide suggests 295 that the tide is enabling movement and possibly mixing of water masses, which is especially pronounced in the PS89 dataset (Fig. 3). While water in the Ekström polynya can broadly be categorised as one water mass (i.e. ESW) according to the physical properties, we will here explore the deepening and shoaling of the isopyncals, as well as the changing water physico-chemical properties.

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At rising tides during PS89, the tide brings in water from the north-east that is fresher and warmer compared to the water present at the sampling location during low ebbing tide (Fig. 3 A, C). A well-defined mixed layer with relatively uniform properties is seen at the surface during ebbing tide ( $\sim 20$  m depth), which tends to disappear or deepen when the tide comes in and the water column density decreases. Similar observations in of tide-driven shoaling and deepening of isopycnals have been made in



**Figure 6.** Same as Fig. 43, but for dissolved  $O_2$  (A and B),  $NO_3^-$  (C and D), and fluorescence (E and F). Fluorescence during PS117 varied at values < 0.09.

other Antarctic coastal systems, although in lower wind conditions (Llanillo et al., 2019,  $<4 \text{ m s}^{-1}$ )(Llanillo et al., 2019,  $<4 \text{ m s}^{-1}$ , see TA destabilising (stabilising) water column has previously been associated with the rising (ebbing) tide observed in coastal

- 305 polynyas in the Arctic (Skogseth et al., 2013). In the latter study, the tidal variability was characterised by a **eold**-salinity front that moved back and forth with the tide. This "salinity front" is characterised by lower and higher salinities in the water column on either side of a sharp horizontal salinity gradient. A salinity front of this description might have been moving back and forth with the tide over the sampling site in the Ekström polynya, which from a Eulerian perspective resulted in the properties of the water column changing as shown in Fig. 3 and 4.
- 310 In our case study, the input of fresher water with lower DIC and TA content is likely advection of AASW from the north-east of the on the north-eastern side of the salinity front (and sampling site) is likely advection of AASW, influenced by the summer sea ice melt. Based on the fluorescence increase during rising tide for PS89 (Fig. 6E), the water on this side of the front seems to be richer in phytoplankton cells compared to the south-western side of the front. In addition to a dilution effect, the accompanying increased fluorescence signal during rising tide on PS89 suggests that photosynthesis in this water has likely
- contributed to its lower DIC, TA, and nutrient content (Fig. 4, 6), which is sustained by solar radiation. The advection of fresher, lower DIC and TA sea water seawater from the north-east during rising tide is likely enhanced by high winds (4 - 16 m s<sup>-1</sup>) that consistently came from the north-east during - and in the week prior to - the PS89 tidal observation (Fig. H1A and H2A ).

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tide, thereby highlighting the interannual variability of the system. Instead, the entire water column is much more uniform with very few vertical gradients during the observation period. Differences in shape and size of the polynya between the two case studies may have affected the proximity of a salinity front to the sampling site. Even though the average sea ice concentration in the immediate vicinity of the sampling site was highly variable in the two months leading up to both PS89 and PS117 (not shown), the polynya was at least three times larger and more well-defined during PS117 than during PS89 (Section 2.1, Fig. A1 and A3). If a salinity front existed during PS117, it may could have been located further away from the sampling

In comparison to PS89, the sampling site during PS117 has less pronounced freshening of the surface water during rising

- site and closer to the sea ice edge of the polynyaice shelf edge, and the sharp horizontal salinity gradient might therefore not 325 have passed directly over the sampling site during PS117 as it did during PS89. Moreover, winds during PS117 may not have had the same enhancing effect on the advection of fresher, diluted water during rising tide compared to PS89. Whereas high winds during PS89 consistently came from the north-east, the wind speeds during PS117 were lower (3 - 10 m s<sup>-1</sup>) and their direction was more variable, mainly coming from the ice shelf side in the south-east (Fig. H1B and H2B). Modulating effects
- 330 of winds on tidally-induced changes in physical water column properties, whether enhancing or counter-balancing, have also been observed in coastal systems at the Antarctic Peninsula (Llanillo et al., 2019).

The other side of the salinity front (i.e from the south-west) brings in higher salinity and lower temperatures into the polynya during ebbing tide. This water seems is less ventilated than AASW and shares physical properties with ice shelf water. Ice shelf water is characterised by potential temperatures of <-1.8 °C and salinity >34.6 (Carmack, 1974). However, recent work

335 by Smith et al. (2020a) has shown that the temperature and salinity from a number of CTD profile measurements underneath the Ekström Ice Shelf in the same summer season as PS117 (2018/2019) ranged from -2.08 to -1.83 °C and 34.21 to 34.38, respectively (Fig. 7). These values overlap with the temperature and salinity at measured within  $\sim 10$  m of the bottom of the sampling site during both tidal observations, especially when the tide goes out. In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated compared to the AASW and to have relatively higher nutrient and DIC eontent, and lower dissolved oxygen content, as a result of net remineralisation (Fig. 4, 6). 340

It is possible that the ebbing tide draws out water from underneath the ice shelf which is expected to be colder. Indeed, the study by Smith et al. (2020a) attributed variability in two repeat profiles this possibility is supported by findings in Smith et al. (2020a), which includes a repeat profile of the Ekström Ice Shelf's cavity water at one of the drill sites measurement stations on the ice shelf (EIS-4); Fig. 7). The two repeat profiles at EIS-4 were taken 11 hours apart. The small difference

- 345 observed in the vertical salinity and temperature profile between these two casts was attributed to tidal influences extending underneath the ice shelf (Smith et al., 2020a). As well as some vertical displacement of the ice shelf by the tidal force (Legrésy et al., 2004), horizontal displacement also occurs underneath the ice shelf. Another study found 12-hourly and 14-day fluctuations in a temperature time series 70 m underneath the Ekström Ice Shelf (June 2012 to February 2013), ranging between -1.94 and -1.6  $^{\circ}C$  (Hoppmann et al., 2015). It also described effects of the tide on the glacial melt water meltwater outflow,
- which could be seen in the orientation and growth of platelet ice crystals in Atka Bay (Hoppmann et al., 2015), adjacent to the 350 Ekström Ice Shelf and east of the sampling site in the current study. In terms of biogeochemical properties, the sub-ice shelf water is expected to be less ventilated compared to the AASW and to have relatively high nutrient and DIC content, and lower

dissolved oxygen content, as a result of net remineralisation and lack of exchange with the atmosphere. Due to the lack of exposure to the atmosphere, phytoplankton cells (for which we use fluorescence as a proxy) are expected to be mostly absent.

355 <u>This description of water properties is consistent for the properties observed during ebbing tide (Fig. 4, 6)</u>. It therefore seems feasible that less ventilated, <u>colder</u> water from underneath the ice shelf with lower oxygen and higher nutrient and DIC content can extend to the edge of the ice shelf during ebbing tide and into the polynya.

Even though mWDW is a source for eastern shelf water (Nicholls et al., 2009), we do not see a direct signal of mWDW in our dataset. The bathymetry of the cavity underneath the Ekström Ice Shelf slopes from about 450 m depth at the ice shelf edge

- 360 to a maximum depth of 1100 m southwards towards the grounding-line (Smith et al., 2020a). Although troughs sculpted into the cavity's bathymetry (Smith et al., 2020a) potentially allow WDW (or its modified form) to enter it (Fahrbach et al., 1994) (a process that may be enhanced by tides), the warmer water is usually restricted to the north of the continental shelf in this region by prevailing easterly winds (Heywood et al., 1998; Thompson et al., 2018). The cavity is instead likely influenced by ESW that enters through Ekman transport (Zhou et al., 2014)of which a thin layer along the base of the ice shelf is colder and
- 365 more buoyant, indicating outflows of ice shelf melt water (Smith et al., 2020a) (Fig. 7). Influence from ice shelf water seems to dominate the water properties in front of the ice shelf during PS117, despite the tides, which may be explained by the variable wind direction from the south-east (Fig. H2B) and potentially a large distance between a salinity front and the sampling site. In contrast, winds from the north-east enhance the influence of fresher, more ventilated ESW during PS89, and the sea ice conditions may have led to a salinity front that is closer to the sampling site.
- 370 The As explained in Section 3.3, the salinity normalisation removes the impact of physical processes from the DIC and TA data. Therefore, any variability that remains in the nDIC and nTA results indicate that most of the variability observed in this short time series is due to the physical movement of water masses by the tidal current, rather than biogeochemical processeshappening *in situ* (Fig. G1). Net transport away from the ice shelf could create a tidally-driven horizontal DIC pump, whereby the sub-ice shelf water is a source of DIC that is transported away from the ice shelf into surface waters where it is
- 375 exposed to the sea ice and the atmosphere. These conditions are supportive of biomass production, which will decrease the DIC content only if the biological carbon uptake is more efficient than the advection of higher DIC waters. However, when we calculate the trajectory of a water parcel using the ship's position as a starting point and the average current velocity of the water column, the net transport is southneeds to be explained according to other processes. These processes are represented in Fig. 5 by theoretical lines that indicate how nTA and nDIC would change relative to each other as a result of photosynthesis/south-east,
- 380 i. e. towards the ice shelf (not shown). This implies that the surface waters could be modifying the water underneath the ice shelf over time. The advection of lower DIC and salinity water might dilute the DIC content, but respiration of organic material might increase it over longer time periods. However, the total DIC content in the water column does not show a trend over time in this dataset and the net change in DIC content over six hour periods (including ebbing and rising tide) is zero (Fig. G3 for PS89). Our observations are a snapshot of a highly dynamic system and consequently we cannot analyse such modifications of
- 385 the water physico-chemical properties with this dataset.

Variability in the salinity-normalised DIC and TA content could be the result of respiration, CaCO<sub>3</sub> dissolution/precipitation, and CO<sub>2</sub> uptake/release (Zeebe and Wolf-Gladrow, 2001). For example, factors that could be relevant to net photosynthesis

are variable sea ice cover affecting photosynthesis by modified light availability light availability, nutrient replenishment during ebbing tide, and mixing of phytoplankton cells into deeper water during rising tide (Gleitz et al., 1994), CaCO<sub>3</sub> dissolution

- 390 (Fig. 5), temperature changes affecting CO<sub>2</sub> solubility, and possible nutrient replenishment during ebbing tide... Yet, none of these processes seem particularly dominant or persistent in the nTA:nDIC ratio in changing the nTA and nDIC content within each tidal observation (Fig. 5). The results in Fig. 5 show a legacy of processes that may have occurred in the past weeks to months prior to sampling, as the carbonate chemistry system' marine carbonate system's equilibration time with the atmosphere is slow, especially in sea ice covered regions. Additionally, this data the data during rising tide might also reflect processes that
- happened in the sea ice, which will have affected the carbonate chemistry of the sea ice melt water meltwater and thus the 395 properties of the AASW. While we here consider the tides to transport a salinity front back and forth across the sampling site, we must also recognise that the sampled mass of water on each side of the front is not exactly the same during each tidal phase, which. This contributes to the variability seen in the data. observed in the dataset. Finally, even though there is good agreement between the high vertical resolution sensor data and the discrete bottle data for salinity and temperature (exemplified
- 400 with density in Fig. E1), biogeochemical processes could imprint additional variability in the DIC and TA profiles that are not reflected in salinity and temperature measurements. We must therefore consider that the discrete seawater samples might not have captured the full scale of the variability in the polynya, limiting our interpretation of relevant biogeochemical processes.

Coastal polynyas have been described as ""the most productive waters in the Southern Ocean" (Arrigo et al., 2015). Their chlorophyll a levels are found to peak in January, roughly coinciding with the peak of coastal polynyas' area of open water

- 405 (Arrigo et al., 2015). In polynyas around Antarctica, iron supplied by basal melting of ice shelves is a major contributing factor to the variability in phytoplankton biomass (Arrigo et al., 2015). Considering that the observations in the current study were made in a coastal polynya of variable size directly adjacent to the Ekström Ice Shelf with an estimated basal melt rate of 4.2 Gt year<sup>-1</sup> (Rignot et al., 2013), the lack of observable *in situ* nutrient and inorganic carbon uptake by primary productivity at the surface is perhaps unexpected. This also applies to times at rising tide in the PS89 observation period when
- 410 the fluorescence signal increases in the water column, suggesting advection of phytoplankton cells into the polynya. Tidal mixing that replenishes nutrients at the surface has been described to drive phytoplankton productivity in other tidal regions (Rogachev et al., 2001). However, primary productivity and its peak in the summer has have been shown to be highly variable among Antarctic coastal polynyas, and the most likely important drivers of low primary productivity are increased MLD, light stability, deep MLD and grazing pressure (Arrigo and van Dijken, 2003). These are likely highly relevant factors in our case
- 415 study. High phytoplankton growth rates require water column stability that lasts several weeks (Gleitz et al., 1994), which is absent during the case studies presented here. Even during ebbing tide, when the water column stratifies at a shallower shallow depth during PS89, the duration of stratification is too short to support substantial in situ DIC and nutrient uptake by growth and primary production.

In a study in the Amundsen Sea, stations close to the Pine Island Glacier were characterised by a deep MLD and low phytoplankton biomass and Chl a despite high dissolved Fe availability (Alderkamp et al., 2012), suggesting that upwelling 420 of Fe-rich basal meltwater mixed the water at the ice shelf's edge (Alderkamp et al., 2012; Gerringa et al., 2012). Outflow and mixing of ice shelf melt water might have been stronger during PS117 than PS89. The water A colder, more buoyant layer along the base of the Ekström Ice Shelf similarly indicates outflows of ice shelf meltwater (Smith et al., 2020a). The temperature and salinity at the bottom of the profile profiles during PS117 indeed has a temperature and salinity that is more

- 425 similar to the temperature and salinity compare to those measured near the base of the ice shelf (mean of top 350 m of the ice shelf CTD casts EIS4-8 (Smith et al., 2020a)). The water underneath the shelf is directly affected by basal melt. During PS89, the bottom water temperature and salinity values resembled for PS89 resemble more closely those deeper in the cavity (e.g. the mean of the water deeper than 350 m of the ice shelf CTD casts EIS4-8; Fig. 7). Earlier, we noted that southerly winds during PS117 may have counter-acted some of the advection of fresher, more ventilated water from the north-east during rising
- 430 tide. The comparisons to the work by Smith et al. (2020a) support the idea that in addition to less sea ice meltwater input from the north-east - outflow and mixing of ice shelf meltwater might have been stronger during PS117 than PS89, dominating the polynya water properties. Along with a more mixed water column, this difference in connectivity to the ice shelf cavity is consistent with the less ventilated water of the polynya during PS117, and can be responsible for the higher nDIC (and salinity-normalised nitrate and phosphate) content, compared to PS89.
- From an ecological perspective, it is relevant to consider the effect of the carbonate system variability on the diversity, structure, and production of pelagic-benthic organism communities. Calcifying organisms, such as pteropods, foraminifera, and coccolithophores, depend on the seawater calcium carbonate saturation state to form their shells and skeletons, which are made from CaCO<sub>3</sub> (Orr et al., 2005). The pH in the Ekström polynya varied between 8.02-8.12 and 8.02-8.06 for PS89 and PS117, respectively (see Fig. G1 for vertical variability). The saturation state of aragonite ( $\Omega_{av}$ ; the less stable polymorph
- 440 compared to the other common CaCO<sub>3</sub> polymorph: calcite) concurrently varied between 1.22-1.52 and 1.21-1.34, respectively. A contour in Fig. 4C and D at an arbitrary value of 1.3 for  $\Omega_{ar}$  gives a sense of the vertical variability driven by tides. Even at the lowest pH values recorded here, the  $\Omega_{ar}$  does not fall under 1, which means that the marine chemical environment does not thermodynamically promote CaCO<sub>3</sub> dissolution. The dynamic nature of the polynya might foster a resilience among the pelagic and benthic organism communities to rapid (semi-diurnal) changes of  $\Omega_{ar}$ . However, even at a carbonate saturation level > 1,
- the rate of biogenic calcification has been shown to be affected by the CaCO<sub>3</sub> saturation state (Feely et al., 2004). The Southern Ocean is especially vulnerable to ocean acidification driven by marine anthropogenic CO<sub>2</sub> uptake (Orr et al., 2005; Negrete-García et al., 20 Tidally induced variability may increase the sensitivity of high-latitude coastal systems to shoaling aragonite and calcite saturation state horizons. Alongside ecological impacts of tides along the Antarctic coastline, future studies can look into the tidal impacts on long-term changes of the vulnerability of pelagic-benthic organism communities.
- 450 In this study, we have argued that the DIC variability in the coastal polynya is driven by back-and-forth movement of water under the force of tidal currents across the sampling site located in a region where there is a horizontal gradient in DIC content: lower DIC content to the north-east, influenced by summer sea ice melt, and higher DIC content to the south-west, influenced by unventilated ice shelf cavity water. This led us to investigate whether there is evidence in our dataset for a tidally-driven horizontal DIC pump. For example, net transport away from the ice shelf could transport DIC and nutrients (and perhaps
- 455 even iron) from the ice shelf towards surface waters on the continental shelf that are exposed to sea ice and the atmosphere. Subsequent biological carbon uptake will then remove DIC. However, when we calculate the trajectory of a water parcel (using the ship's position as a starting point and the average current velocity of the water column) the net transport is south/south-east,

i.e. towards the ice shelf (Fig. F2). This implies that surface waters would be modifying the properties of the water underneath the ice shelf over time (instead of the other way around), for example by dilution. If this is the case, we would expect to see

- 460 a trend in the DIC content of the polynya during ebbing tide. However, this is not the case and the net change in DIC content over six hour periods (including ebbing and rising tide) is zero (Fig. G3 for PS89). Our observations are a snapshot of a highly dynamic system and consequently they do not provide enough data to analyse such modifications and trends of the seawater physico-chemical properties. Nevertheless, they can be the beginning of future studies into this topic.
- While a tidal movement of a salinity front or gradient across the sampling site is a possible and realistic explanation for the oscillations observed in the water column, validating it would require physico-chemical profiles between the Ekström Ice 465 Shelf and the edge of the continental shelf. Without them, other relevant physical processes, such as regional circulation, tidal straining, or mixing, cannot be excluded. For the same reason, the distance from the ice shelf at which the tidally-driven deepening and shoaling of the isolines (most clearly seen for PS89) can be observed remains uncertain. The distance will depend on the strength of the tidal current and would have to be investigated with repeat transects from the ice shelf towards
- 470 the open ocean at various points in the tidal cycle. Other mediating factors, such as winds and internal tidal waves generated by uneven bathymetry, would have to be additionally considered (Llanillo et al., 2019). Moreover, tidal mixing may erode fronts and modify water masses (such as at the ice shelf edge or of the ESW) over time, adding a temporal dimension to the effect of the tide on the shelf waters in this region.

Despite the unknowns outlined above, the case studies presented in this work show that strong tidal influences on the physical

475 structure and biogeochemical properties of the water column can be expected along the Weddell Sea coastline (and other polar regions subject to strong tides), especially in close proximity to ice shelves and regions of sea ice melt. They also show that local winds and ice shelf meltwater outflows can increase the complexity of the tidal impact within in a region such as a coastal polynya. In addition to studies on the physical role of tides on (for example) basal ice shelf melt, ecological, biogeochemical, and air-sea gas exchange studies can benefit from a better understanding of tidal impacts on the water column.

#### 480 4.2 Air-sea CO<sub>2</sub> exchange

The tidally-induced variability in the water column implies that the timing of sampling matters when estimating the relative contribution of coastal regions to the total CO<sub>2</sub> flux of the Weddell Sea. We first present the variability in the CO<sub>2</sub> flux during the tidal observation periods. We then illustrate that bias can be introduced in our understanding of the relative importance of coastal regions along the Weddell Sea if sampling strategies do not take tidal influences into account.

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The difference in the  $fCO_2$  of the seawater and the atmosphere is what drives a positive or negative  $CO_2$  flux at the air-sea interface. For the flux calculations, we used the average wind speed recorded during the PS89 and PS117 tidal observation periods: 10.7 and 6.6 m s<sup>-1</sup>, respectively (Table 1). This choice implies that the computed variability in the flux results is solely mainly driven by the air-sea gradient of  $fCO_2$ . During the PS89 tidal observation period in January 2015, the surface water at the Ekström Ice Shelf was undersaturated in  $fCO_2$  relative to the atmosphere (Fig. 4), creating a  $CO_2$  sink (Fig. 8). 490 However, the depth at which the  $fCO_2$  of the seawater is equal to that of the atmosphere (marked by a dashed line in Fig. 4A)

fluctuates between the bottom (incoming tide ) and the surface (outgoing tide) from near the bottom of the water column during



Figure 7. A) Temperature salinity Temperature-salinity diagram for PS89 (circles) and PS117 (diamonds) tidal observation periods, which are coloured according to dissolved oxygen concentrations, and the hot water drill. CTD profiles through of the ice shelffrom 's cavity water were collected and made available by Smith et al. (2020a) (coloured lines). Colours for The cavity CTD profiles were taken by hot water drill profiles correspond to drilling through the coloured marker ice at various locations on the ice shelf, which are shown on the map in (B) in corresponding colours to the profiles in (A). AASW = Antarctic Surface Water, ESW = Eastern Shelf Water, ISW = Ice Shelf Water. The average temperature and salinity of water deeper and shallower than 350 m underneath the ice shelf are plotted as single purple markers white crosses. Contour lines indicate sigma-t in kg m<sup>-3</sup>. Black line indicates freezing point at mean atmospheric pressure. B) Map of measurement locations of the Ekström Ice Shelf cavity CTD profiles by Smith et al. (2020a) denoted by "EIS\_", a measurement location in Atka Bay by Smith et al. (2020a) denoted with "AB", and the sampling location of the tidal observations indicated by the yellow star. C) Temperature profiles for PS89 (circles) and PS117 (diamonds) tidal observation periods, coloured according to oxygen concentrations, and for the hot water drill CTD profiles underneath the ice shelf from Smith et al. (2020a).

incoming tide to near-surface during outgoing tide. Direct  $fCO_2$  measurements were made using the vessel's underway system (at 11 m depth) during (as well as 2.5 days prior to the start of) the discrete seawater sampling, i.e. the start of the PS89 tidal observation period (Fig. D1).  $fCO_2$  correlates very well with the salinity, again indicating that physical movement of water is the dominant driver of the variability.  $CO_2$  fluxes determined from the underway measurements a) compare well with the 495 fluxes calculated from the discrete seawater carbonate chemistry results where they overlap in time, and b) show an even more drastic stronger fluctuation on the 7<sup>th</sup> and 8<sup>th</sup> of January 2015, when the flux status of the sampling site swung between a sink (rising tide) and a source (ebbing tide) of CO<sub>2</sub> twice within 24 hours (Fig. 8). This suggests that water with higher DIC content reached the surface during ebbing tide. The CO<sub>2</sub> sink during PS89 is as large as -19.9 23.6 mmol m<sup>-2</sup> day<sup>-1</sup>, while the largest  $CO_2$  source reaches 6.93.1 mmol m<sup>-2</sup> day<sup>-1</sup> (Fig. 8). 500

During PS117, the entire water column has a higher seawater  $fCO_2$  than also dips below the atmospheric value , except for a patch between 50 and 20 m depth at at times of rising tide. However, the  $fCO_2$  gradient and the start and end of the tidal observation period wind speed are much lower compared to PS89 (Fig. 4B).-, resulting in a low CO<sub>2</sub> flux (Fig. 8). Even though not all PS117 CTD cast measurements started as shallow as those from PS89, the few casts that did have measurements starting <20 m showed a lack of a strong gradient in the DIC and TA content at the surface. The shallowest discrete carbonate chemistry water samples are therefore considered to be representative enough of the water properties at the surface. Accordingly, the site is likely to have been a small source of had a relatively neutral CO<sub>2</sub> flux at this time in January 2019. Using the  $fCO_2$  results based on the discrete water sampling, the average CO<sub>2</sub> uptake during the PS89 tidal observation period is -8.0-11.7 ± 3.7 mmol m<sup>-2</sup> day<sup>-1</sup> (± 1 $\sigma$ ). For PS117, the average CO<sub>2</sub> release to the atmosphere is 1.4-0.1 ± 0.70.9 mmol m<sup>-2</sup> day<sup>-1</sup>. Even though the size of the coastal polynya was variable, the sampling site was free of sea ice during the tidal observations and it is assumed to have been ice free for the entire summer. We therefore have not scaled the gas transfer velocity with the fraction of open water area. At times during the summer when the site does get covered by sea

The importance of strategic seawater sampling for the purpose of obtaining reliable air-sea gas exchange values in regions

515 , such as the Ekström coastal polynya , is illustrated by the following. Assuming the scenario we know for the PS89 tidal observation period, if discrete water samples had unknowingly only been collected during ebbing tide (higher seawater  $fCO_2$ ), the calculated CO<sub>2</sub> flux (0.6-3.1 mmol m<sup>-2</sup> day<sup>-1</sup>) would have underestimated the strength of the CO<sub>2</sub> uptake by the polynya by up to 10873 %, compared to the average uptake (-8.0-11.7 mmol m<sup>-2</sup> day<sup>-1</sup>), i. e. actually mistaking it for a small source rather than a sink of CO<sub>2</sub>. However, if samples had only been collected during times of rising tide (lower seawater  $fCO_2$ ),

ice, the amplitude of the CO<sub>2</sub> flux would be subdued.

- 520 the capacity of the polynya to take up CO<sub>2</sub> (-15.9-19.6 mmol m<sup>-2</sup> day<sup>-1</sup>) would have been overestimated by up to 9867 %, compared to the average uptake value. Since the variability of the CO<sub>2</sub> flux during PS117 was much lower (a CO<sub>2</sub> release ranging between 0.2 2.2 1.2 and 0.8 mmol m<sup>-2</sup> day<sup>-1</sup>), samples collected at any time during this 24 hour period would have been relatively representative of this tidal observation period, but not necessarily of the month or the entire summer season.
- We emphasise the potential misrepresentation of the role of coastal polynyas in the Weddell Sea  $CO_2$  uptake if tidal influ-525 ences are not accounted for<del>using.</del> For this, we again use the two extreme scenarios from the hypothetical case where samples are collected only during rising or ebbing tide of the based on the PS89 tidal observation: samples are only taken at either observations that were also used above to illustrate the maximum potential over- and underestimation of the  $CO_2$  uptake. I.e., we use the hypothetical cases where surface seawater samples are either collected at peak rising tide or (overestimation of  $CO_2$  uptake) or at peak ebbing tide , which lead to an overestimation or underestimation of the (underestimation of  $CO_2$
- flux, respectively (see above). uptake). We constrain results and comparisons to the summertime, assume that all coastal polynyas in the south-eastern Weddell Sea are influenced by the same water masses present in the Ekström polynya during the PS89 tidal observation, and assume the same wind speed to highlight the role of the seawater  $fCO_2$  variability. Using the total area of polynyas along the south-eastern Weddell Sea coastline in the summer of  $49 \times 10^3$  km<sup>2</sup> (as estimated by Arrigo and van Dijken (2003)), the total net CO<sub>2</sub> flux-uptake for all polynyas along the south-eastern coastline

535 would be  $-0.78-0.97 \times 10^9$  mol day<sup>-1</sup>(net CO<sub>2</sub> uptake), if data had only been collected during rising tide. It would have been  $0.03-0.15 \times 10^9$  mol day<sup>-1</sup>(net CO<sub>2</sub> release), if data had only been collected during ebbing tide.

Brown et al. (2015) estimated a summer marine uptake of  $CO_2$  for the entire Weddell Sea of -0.044 to -0.058  $\pm$  0.010 Pg C yr<sup>-1</sup>, based on a summertime ocean inversion. In our hypothetical, biased upscaling case of collecting carbonate chemistry samples during ebbing tide, we would determine that the contribution of eastern shelf polynyas to Brown et al.'s upper summer  $CO_2$ 

- 540 uptake estimate is 0.21.2 % (using the same area for the Weddell Sea:  $6.2 \times 10^{12}$  m<sup>2</sup> and scaling the daily flux up to the whole year). If seawater samples had only been collected during rising tide, the contribution of the eastern shelf polynyas would have been estimated at 5.97.3 % to the total summer CO<sub>2</sub> uptake of the Weddell Sea. This is quite substantial considering that the area used here for the south-eastern coastal polynyas is less than 0.8 % of the total Weddell Sea area (including regions covered and not covered by sea ice). If the average CO<sub>2</sub> flux of PS89 had been used in this simplistic upscaling exercise
- instead of the extreme high- and low-end scenarios, then the total CO<sub>2</sub> flux of all Weddell Sea coastal polynyas would be -0.4-0.58  $\pm$  0.18  $\times$ 10<sup>9</sup> mol day<sup>-1</sup> (3.04.4 % of Weddell Sea flux) for January 2015. There is an order of magnitude difference if Results are two orders of magnitude lower when the same upscaling exercise is done with the average flux for the PS117 experiment: 0.07case study: 0.003  $\pm$  0.034  $\times$ 10<sup>9</sup> mol day<sup>-1</sup> (0.50.02 % of Weddell Sea flux).
- The <u>purpose of the</u> above exercise is <u>simply to to simply</u> highlight the variability in these coastal systems. Given both the scarcity of data in these regions and the challenges in reaching them, tides may be an important aspect to consider to explain some of the variability seen in previous and future oceanographic data. Although the Weddell Sea is considered to be an albeit small - annual net CO<sub>2</sub> sink (Hoppema et al., 1999; Bakker et al., 2008; Brown et al., 2015), its CO<sub>2</sub> uptake is sensitive to the balance of physical, chemical, and biological processes, such as sea ice growth/melt, regional wind strength/patterns, circulation, and biological CO<sub>2</sub> drawdown (Brown et al., 2015). The coastal marine regions and the processes that govern their water properties may be equally sensitive and their changes on time-scales of hours to weeks or months may be mediated by the tides.

#### **5** Conclusions

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We present the significant semi-diurnal influence of tides on the water properties and carbonate chemistry at the margins of a coastal polynya hugging the Ekström Ice Shelf in the south-eastern Weddell Sea. Advection of lower DIC and TA waters from the north-east during rising tide influenced by sea ice melt, decreases the salinity and  $fCO_2$  at the sampling site and results in CO<sub>2</sub> draw-down from the atmosphere. As the sampling site is located directly next to the ice shelf, it sees the extension of the water underneath the ice shelf, which is drawn out from underneath during ebbing tide. This water is less ventilated and has a higher DIC and TA content (and therefore a higher  $fCO_2$ ) compared to the water to the north-east, which decreases the strength of the CO<sub>2</sub> sink and can even reverse it the direction of the CO<sub>2</sub> air-sea flux on a semi-diurnal time scale.

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Differences in the variability between the two tidal observations between January 2015 and January 2019 suggests suggest a complex interaction between timing of the tide, local and regional sea ice melt, polynya area, basal melt, and local forces, such as wind speed and direction. The datasets of the two short case studies presented here are too small to explore the



**Figure 8.** Air-sea CO<sub>2</sub> flux (in mmol  $m^{-2}$ day<sup>-1</sup> on the left y-axis and in mol  $m^{-2}$ year<sup>-1</sup> on the right y-axis) determined from the discrete surface seawater sample measurements and average wind speed for the PS89 (green, bottom x-axis) and PS117 (orange, top x-axis) tidal observation periods, and from the PS89 underway  $fCO_2$  measurements (black, bottom x-axis), which started on the  $7^{th}$  of January 2015. Dotted lines use The CO<sub>2</sub> flux based on a discrete surface seawater sample collected on the parameterisation by Sweeney et al. (2007), which was used in calculations by Brown et al. (2015)7<sup>th</sup> of January 2015 is also shown with a green marker. The filled shading indicates the range of the flux calculated using the minimum and maximum wind speed measured during PS89 and PS117, respectively (Table 1). Negative flux represents CO<sub>2</sub> uptake by the ocean.

mediating fully explore the modulating effects of these processes . Longer tidal observations and repeats are required , along with measurements of micro-nutrients, carbonate chemistry, on the water column variability. To be able to do so, longer

570 tidal observations are required that cover different parts of the spring-neap tidal cycle, and at different times of the year to capture varying wind and ice melt/growth conditions. Alongside carbonate system state variables, an array of co-collected measurements, such as micro-nutrients, biological productivity, and oxygen isotopes, to be able to stable isotopes, can help to constrain interacting processes. A better An understanding of the carbonate chemistry of the cavity water underneath the ice shelf - although challenging to obtain - would help understand the influence of this water on the polynya during ebbing tide.

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The observations presented here were obtained from a stationary sampling site. Without knowing the hydrological conditions in the surrounding area at various time points in the tidal cycle, we must consider that our conclusions only apply to a very local area, the margins of polynyas, or the edges of ice shelves. Hydrographic transects between the ice shelf and out towards the edge of the continental shelf (across the polynya and underneath the sea ice ) well into the sea ice cover at ebbing and rising tide can help identify the extent to which the tidal oscillation, as seen in the case studies, is relevant further away from

580 the coastline and from the polynya's margins. It may also help identify the formation and characteristics of --what is described here as - a salinity a horizontal coastal salinity gradient -- here referred to as a "salinity front" -- that moves back and forth with the tide.



Figure A1. Sentinel-1 SAR image of the Ekström Ice Shelf and polynya on 12.01.2015 (PS89) (ESA, 2021). The pink star indicates the sampling location for the PS89 tidal observation.

This case study has shown that tides can swing the status of coastal polynyas on the south-eastern continental shelf of the Weddell Sea from a strong sink to a source of  $CO_2$  on a semi-diurnal time-scale. Seawater  $CO_2$  uptake can be underestimated by  $\frac{10873}{585}$  % and overestimated by  $\frac{9867}{585}$  %, if these tidal changes are ignored. Awareness of the tidal impacts is required to implement strategic sampling techniques to obtain representative data in these extremely variable - and rarely accessible - systems that play a role in the sensitive balance of the Weddell Sea's net air-sea  $CO_2$  exchange.

Data availability. Data are available on Pangaea: https://doi.org/10.1594/PANGAEA.946363.

Appendix A: Sentinel images of Ekström polynya



**Figure A2.** Sentinel-1 SAR image of the Ekström Ice Shelf and polynya on 12.01.2015 (PS89), zoomed in (ESA, 2021). The pink star indicates the sampling location for the PS89 tidal observation.



**Figure A3.** Sentinel-1 SAR image of the Ekström Ice Shelf and polynya on 10.01.2019 (PS117) (ESA, 2021). <u>The pink star indicates the</u> sampling location for the PS117 tidal observation.



**Figure A4.** Sentinel-1 SAR image of the Ekström Ice Shelf and polynya on 10.01.2019 (PS117), zoomed in (ESA, 2021). The pink star indicates the sampling location for the PS117 tidal observation.

Table B1. References to all supporting data and data sources used in this work.

Data Type	Data Source	Reference
PS89 and PS117 DIC/TA data	Pangaea	(González-Dávila et al., 2022)
PS89 physical oceanographic data AWI CTD (continuous)	Pangaea	(Rohardt and Boebel, 2015a)
PS117 physical oceanographic data AWI CTD (continuous)	Pangaea	(Rohardt and Boebel, 2020)
PS89 CTD bottle data, incl. nutrient data (discrete)	Pangaea	(Rohardt and Boebel, 2015b)
PS117 CTD bottle data, incl. nutrient data (discrete)	Pangaea	(Rohardt et al., 2020)
PS89 ADCP	Pangaea	(Witte and Boebel, 2018)
PS117 ADCP	Pangaea	(Boebel and Tippenhauer, 2019)
PS89 wind speed	Pangaea	(König-Langlo, 2015)
PS117 wind speed	Pangaea	(Schmithüsen, 2020)
xCO <sub>2</sub> Syowa	ESRL NOAA	(Dlugokencky et al., 2019)
Antarctica boundaries	SCAR ADD	(Gerrish et al., 2020)
Ekström CTD data	Pangaea	(Smith et al., 2020b)
Sentinel 1 - SAR	European Space Agency	(ESA, 2021)
Southern Ocean Bathymetry	IBSCO Version 1.0, Pangaea	(Arndt et al., 2013)

# 590 Appendix B: Data references

Table C1. CTD sensor precisions.

Variable	Sensor or method	Expedition	Precision	Reference
Conductivity	SBE4c	PS89, manufacturer specification	$0.003 \text{ mSc m}^{-1 a}$	(Driemel et al., 2017)
Salinity	SBE4c	PS117	$0.0004^{b}$	(Rohardt and Tippenhauer, 2020)
Temperature	SBE3plus	PS89, manufacturer specification	0.001 $^{\circ}$ C $^{a}$	(Driemel et al., 2017)
Temperature	SBE3plus	PS117	0.00000 °C $^a$	(Rohardt and Tippenhauer, 2020)
Pressure	Digiquartz with TC	PS89, manufacturer specification	0.015~% full scale	(Driemel et al., 2017)
Fluorescence	Wetlabs EcoFLR	PS89 and PS117	-	(Rohardt and Tippenhauer, 2020)
Dissolved O <sub>2</sub>	SBE43	PS89	$0.43^c \text{ ml } \mathrm{L}^{-1}$	(Boebel, 2015)
Dissolved O <sub>2</sub>	SBE43	PS117	$0.42^d \text{ ml } \mathrm{L}^{-1}$	(Rohardt and Tippenhauer, 2020)

<sup>*a*</sup> Average of the residual of post-calibration by Sea-Bird Scientific. <sup>*b*</sup> Standard deviation of the residual of the difference between the sensor measurements and the Optimare Precision Salinometer samples analysed on board. <sup>*c*</sup> Standard deviation of the difference in dissolved oxygen Winkler samples analysed on a potentiometric detection system and on a photometric end-point system on board. <sup>*d*</sup> Standard deviation of the residual of the difference between the sensor measurements and Winkler titration samples.

Table C2. Analytical uncertainty of the DIC and TA analyses using the variability of the CRM measurements per CRM batch. n refers to the number of CRMs that were run to obtain the measured values. Values listed for CRMs are certified values by Prof. Andrew Dickson's laboratory at the Scripps Institution of Oceanography of the University of California, San Diego (https://www.ncei.noaa.gov/access/ ocean-carbon-acidification-data-system/oceans/Dickson\_CRM/batches.html). Net coulometer counts were calibrated against the certified DIC values of the reference material, which was run before and after the sample runs per analysis day. This gave a value for counts per  $\mu$ mol, for each CRM run. These were averaged and used (along with density and volume) to obtain the concentration of DIC per sample in  $\mu$ mol kg<sup>-1</sup>.

Dataset	CRM Batch No.	n	DIC [ $\mu$ mol kg <sup>-1</sup> ]		TA [ $\mu$ mol kg <sup>-1</sup> ]	
			CRM	Measured	CRM	Measured
PS89	137	25	$2031.90\pm0.62$	$2031.90\pm1.22$	$2231.59\pm0.32$	$2231.71 \pm 1.09$
PS117	176	133	$2024.22\pm0.82$	$2024.22\pm3.32$	$2226.38\pm0.53$	$2226.30\pm3.18$
PS117	185	17	$2029.88\pm0.62$	$2029.88\pm2.88$	$2220.67\pm0.58$	$2221.09\pm0.85$

Appendix C: Sampling at study site

 Table C3. Analytical precisions for nutrient concentrations.

Dataset	$\mathrm{NO}_3^-$ [ $\mu\mathrm{mol}~\mathrm{kg}^{-1}$ ]	$\mathrm{PO}_4^{3-}$ [ $\mu \mathrm{mol} \ \mathrm{kg}^{-1}$ ]	$SiO_4 \ [\mu mol \ kg^{-1}]$
$PS89^a$	0.15	0.02	1.0
$PS117^b$	0.041	0.008	0.057

 $^{a} \pm 1 \sigma$  of replicate samples for PS89.  $^{b} \pm 1 \sigma$  of repeat measurements of working standard at similar concentrations as average values for the tidal observation period of PS117: 30, 2, 60  $\mu$ mol kg<sup>-1</sup> for NO<sub>3</sub><sup>-</sup>, PO<sub>4</sub><sup>3-</sup>, and SiO<sub>4</sub>, respectively.



**Figure D1.** A comparison of measurements between the continuous measurements from the on-board underway system and the discrete samples of the surface seawater for PS89. A) Depth at which the surface discrete samples were collected during the tidal observation. The horizontal black line indicates depth at 11 m, which is the depth of the intake for the continuous  $fCO_2$  measurements. B) The  $fCO_2$  continuous measurements from the on-board underway system (black line) and the calculated  $fCO_2$  from the discrete surface samples (circles). C) Same as B), but for temperaturesalinity. D) Same as B), but for salinitytemperature. The grey areas indicate periods of ebbing tide (where the *u* and *v* components of the modelled tidal currents are both positive).

#### **Appendix D: Underway measurements**



**Figure E1.** A) High vertical resolution profile <u>of</u> sigma-t <u>measurements</u> for PS89. B) High vertical resolution profile <u>of</u> sigma-t <u>measurements</u> for PS117. C) Discrete (low vertical resolution) profile measurements at bottle sampling depth for PS89. D) Discrete (low vertical resolution) profile measurements at bottle sampling depths are shown in white markers in C and D.

#### Appendix E: Continuous profile vs. discrete bottle density measurements

To study the tidal cycle, profile measurements from the CTD casts are interpolated over time and depth. The high vertical resolution profile measurements for salinity and temperature are collected at a 1 dbar resolution on the down-cast, which is higher than the resolution of the discrete bottle samples and measurements that are collected on the up-cast. Difference in resolution and natural variability in the water column result in a slight difference between the high vertical resolution profile (down-cast) and discrete (low vertical resolution) bottle measurements (up-cast) at equal depth. To ensure that the bottle data with the lower vertical resolution is sufficiently representative, we compare the time and depth-interpolated bottle data to the high vertical profile measurements interpolated over time for the physical variables. As an example, we show the comparison for density (Fig. E1). It shows that the resolution of the bottle data sufficiently captures the same features in the water column as seen in the high resolution profile data. The bottle measurements are therefore reliable for interpretation of the chemical variables. As the higher vertical resolution profile measurements capture more detail of the features in the water column, these are used for the time series interpolations wherever applicable.



**Figure F1.** Correlations of the *u* and *v* components of the ADCP data for the tidal observations during PS89 (green diamonds) and PS117 (blue circles) between 0 - 50 m (A), 50 - 100 m (B), 100 - 150 m (C), and 150 - 200 m (D). All correlations are significant (p-value < 0.05) and positive, as shown with the black (PS89) and white (PS117) linear regression lines. A)  $v = 0.63 \times u + 0.014$  (PS89);  $v = 0.58 \times u - 0.01$  (PS117). B)  $v = 0.56 \times u - 0.02$  (PS89);  $v = 0.66 \times u - 0.05$  (PS117). C)  $v = 0.65 \times u - 0.03$  (PS89);  $v = 0.54 \times u - 0.08$  (PS117). D)  $v = 0.29 \times u - 0.034$  (PS89);  $v = 0.20 \times u - 0.05$  (PS117).

605 Appendix F: Currents



Figure F2. The hypothetical distance that a water parcel could have travelled relative to a starting point at the ship's position (indicated by the yellow star) at the starting time of sampling during the PS89 (green) and PS117 (orange) tidal observations. Full lines show the distance travelled using the water column mean ADCP current data. Dashed values show the distance travelled using the modelled water column mean tidal current data. Black arrows indicate the direction of the currents. These calculations assume that the mean currents apply to the larger shelf and polynya region, disregards topographic influences, and ignores the presence of the ice shelf, which is located directly south of the sampling site.



**Figure G1.** Salinity-normalised DIC content at the sampling site during the PS89 (A) and PS117 (B) tidal observations, as well as salinitynormalised TA content for the PS89 (C) and PS117 (D) observations. White contour lines indicate sigma-t in kg m<sup>-3</sup>. Vertical grey shaded areas indicate periods of ebbing tide, as defined in the text. Dashed red lines in A and B indicate the depth at which the pH = 8.05. Dotted red lines in C and D indicate the depth at which the aragonite calcite saturation state ( $\Omega_{ca}$ ) = 1.32.05. These are arbitrary values, used to illustrate the variability in the water column. pH ranged between 8.02-8.12 and 8.02-8.06 for PS89 and PS117, respectively.  $\Omega_{ca}$  ranged between 1.95-2.43 and 1.92-2.13 for PS89 and PS117, respectively.

## Appendix G: Tidal variability

Phosphate (red) and silicate (blue) concentrations plotted against nitrate concentrations for the PS89 (circles) and PS117 (diamonds) tidal observations.



Figure G2. As for Fig. G1, but instead for phosphate and silicate (excluding content and not including the pH and calcite saturation contours) that are shown in Fig. G1.



**Figure G3.** Left y axis: total water column DIC content between 10 and 120 m during the PS89 tidal observation. Right y axis: total DIC content between 10 and 120 m for the entire PS89 polynya, using the estimated dimensions in the text and assuming an ellipsoidal area.



**Figure G4.** Nitrate (<u>A</u>, black), phosphate (<u>B</u>, red), and silicate (<u>C</u>, blue) content plotted against salinity for the PS89 (circles) and PS117 (diamonds) tidal observations, including linear regression lines.



**Figure G5.** Salinity-normalised (following Friis et al. (2003)) nitrate (A, black), phosphate (B, red), and silicate (C, blue) content plotted against salinity for the PS89 (circles) and PS117 (diamonds) tidal observations.



**Figure H1.** A) Wind speed measured at Neumayer III Research Station (black) in the time prior and during the PS89 tidal observation, as well as the ship-board wind speed measurements during the PS89 tidal observation (red). B) Wind speed measured at Neumayer III Research Station in the time prior and during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black), as well as the ship-board wind speed measurements during the PS117 tidal observation (black).



**Figure H2.** A) Wind direction measured at Neumayer III Research Station in the time prior and during the PS89 tidal observation (black), as well as the ship-board wind direction measurements during the PS89 tidal observation (red). B) Wind direction measured at Neumayer III Research Station in the time prior and during the PS117 tidal observation (black), as well as the ship-board wind direction measurements during the PS117 tidal observation (black), as well as the ship-board wind direction measurements during the PS117 tidal observation (black), as well as the ship-board wind direction measurements during the PS117 tidal observation (black), as well as the ship-board wind direction measurements during the PS117 tidal observation (red). Grey areas indicate the duration of the tidal observations. Horizontal dashed lines indicate 90°, 180°, and 270°. North, East, South, and West directions are indicated by the red initials at the right side of the plots.

### Appendix H: Wind

- 610 Author contributions. ESD developed the concept for this manuscript, led the writing process, and collected/analysed/processed the PS117 DIC and TA samples. DCEB, MH, GDO, BQ, HJV, MGD, and JMSC provided valuable input and guidance for the development of this work. MGD and JMSC independently collected/analysed/processed the PS89 DIC and TA samples. BQ processed the PS117 ADCP data. DS and SO collected/analysed/processed the PS89 and PS117 nutrient data, respectively. GR ran the tidal model. STK collected and analysed the Winkler O<sub>2</sub> samples for the calibration of the dissolved O<sub>2</sub> sensors on PS117. All authors contributed to the manuscript.
- 615 Competing interests. The authors declare that they have no conflict of interest.

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