Combined authors response and changes-tracked revised manuscript of OS_2016_09.

In the following we provide a detailed point-by-point response to all referee comments and specify all changes in the revised manuscript. The response to the Referees includes comments from Referees (in black) and author's response and author's changes in manuscript (in blue). In addition, we provide a marked-up manuscript version showing the changes.

Reviewer 1 (Dr. M. Ribas-Ribas).

The present paper under review for Ocean Science describes seasonal cycles and controlling factors on Aragonite saturation states and pH and proposes a nice way to monitore Ocean Acidification from continuous underway *p*CO2 measurements. I appreciate the effort to maintain the VOS line for so long and the extra sampling cruise. Together, makes a valuable dataset! It is also really easy to read as it flows. I will recommend the publication after moderate corrections/clarifications.

Response: We thank the reviewer for encouraging and constructive comments as well as for suggested corrections and improvements.

However, I have two major concerns about the current version of the manuscript:
1. Statistical analysis need to be better explained and improved to have more robust conclusion. For example, fig. 2 B (8-249, 9-264) explain that they are UW and RF are really similar but I would like to know the slope and if this slope is statistically different than 1 (same apply for B and D). I would add other stats comments and the list of general comments.

Response: We agree with the reviewer on this point.

In the revised manuscript, the statistics of all comparisons are presented. An additional table (Table 3) summarizing the statistics of the comparisons on Fig. 2 is included. Further, in order to introduce how these statistics is used the following paragraph has been added to the beginning of section 3.1 *"In this section we present the regression equations identified in this study in addition to validating the various estimation procedures used by comparing the estimated values with those measured/computed. The results of these comparisons are summarized in Table 3. For each comparison, the coefficient of determination (R^2) and the significance level (p-value) are used as metrics for the goodness of the correlation while the associated root-mean-square error (rmse) is benchmarked against the maximum target uncertainties developed by the Global Ocean Acidification Network (GOA-ON) and the California Current Acidification Network (C-CAN) of ±0.2 for Ω_{Ar} (McLaughlin et al., 2015), which corresponds to maximum uncertainties of ±0.02, ±1.25 or ±1.8 in pH, SST, or SSS, respectively."*

2. I would like to know more about interannual variability. This is also somehow what I expect after reading introduction (3-91). But still we only have some sentences at the end of section 3.3. Related to this, I don't understand why you choose VOS data since 2009 but then you have CS since 2010, a cruise in 2015 and a sensor in 2012. I understand it's not easy to treat data from VOS as quick as they are generated but at least some words of cautions will be nice.

Response: we agree with the reviewer to write more about the interannual variations (IAV), although the focus of the study is on the seasonal variations.
In the revised manuscript, IAV have been computed as the standard deviations of monthly means. The results are summarized in additional table (Table 4) and results commented in the end of section 3.3.
Regarding the temporal coverage of the datasets, we used all underway data that has been available from the VOS line which was in operation in the period September 2005 to September 2009. Cruise data with dates beyond the operating period of the VOS line has been used in order to maximize the data (in terms of number of data points as well as in spatial and temporal coverage) available from the study area to identify the regional SSS/SST – Alkalinity relationship (Eq. 2 in the manuscript). In order to clarify the above points, the first paragraph of section 2.1 in the revised ms, includes the sentence *"The VOS line was in operation in the period September 2005 to September 2009."*

My comments will be with format page-line (so 5-3 means page 5, line 3); page-line:line (so 7-7:9 means page 7 from line 7 until line 9).
1-17 What coherent means in this contest?
Response: with "Spatially Coherent" we mean that seasonal changes with similar magnitudes occur everywhere at the same time.

1-21 (and elsewhere in the ms) Please choose as many decimal place you want to report according to your method accuracy and error propagation and stick to them. Here you start with 2 and then past to 1 but further in the ms, suddenly there is 4-5 digits (9-272, 10-284).
Response: in the revised ms, pH values are presented with three decimal points while two decimals are used for the saturation state.

2-36 What is Peters reference referring to? It looks strange.
Response: this has been replaced with more relevant reference (Le Quéré et al., 2015) for updated assessment of global emissions.

2-51-54 Long paragraph
2-61 "Only few studies" I expect at the end of the sentence some citation
Response: in the revised ms (page 3), this sentence has been extended to *"However, only a few studies on the carbon cycle of Norwegian fjords exist in the literature, and these are from the high Arctic at Svalbard (Fransson et al., 2014; Omar et al., 2005)."*

3-75:80 I think that should flow better with a bit of rearranging to avoid repetition together with 1-61:2-68
I really like this part where it is explain the importance of the study, to "fill the gap". It is indeed extremely important to fill these coastal gaps. I think it will also be nice to mention that this study set the baseline for future studies to evaluate OA and how this change could affect.
Response: we thank the reviewer for a good suggestion.
In the revised ms (page 3), we have rearranged the first sentence as suggested. We have also extended the paragraph with *"Observations of the carbon cycle dynamics in the fjord system will not only further our understanding and ability for prediction, but they will also serve as benchmarks against which future changes are compared."*

5-130 “coastal open ocean” is somehow misleading, although I understand might be good to rephrase.
Response: in the revised ms, the phrase “coastal open ocean” has been replaced with “adjacent coastal North Sea”.

5-143:146 Economic important could be also tourist and other ecosystem functions?
Response: we tried to stick to the natural ecosystems only. However, we agree that we needed to elaborate the economic significance. Thus, in the revised ms (end of section 1.1), we extended the paragraph with *“The fjord system also contributes to the important aquaculture production that, with its annual fish production of >700 tonnes, ranks Norway within the tenth place worldwide. About one fifth of this is produced in the Hordaland County where the fjord system studied here is situated (http://www.diercke.com).”*

5-149 “of” is double CO_2 is without subscript (also in equation 3 and 4 and 12-360 and some references)
Response: corrected.

5-151 webpage without hyperlink, like for example 6-166 (some happens in 7-197)
Response: corrected.

6-166 knowing the authors, I suppose there are plan to submit the remaining data to SOCAT, right?
Response: the reviewer is right. Actually, the data is submitted as mentioned in revised ms (last sentence of section 2.1).

6-176 (and elsewhere in the ms, for example table 1 or 7-195), unify dates format
Response: done.
7-197 It will be nice to state here a few details from sensor, like accuracy or/and precision, as it is important to propagate the other uncertainties in the calculations.
Response: done.

7-217 Here an important point, TA-SSS algorithm comes only from summer values, right? Please clarify and add some sentence of caveat about it.
Response: we agree with the reviewer.
In the revised ms, we have discussed this issue in connection with the comparison between wintertime pH estimates and in situ pH measurements from January 2012. In the end of section 3.1 we conclude *“It must be noted that the above total error was derived from all available observational data including the in situ sensor data (shown in Fig. 2c and in described section 2.3), which are the only wintertime measurements used in this study. This is important because the lack of wintertime data in the CS dataset which was used for the identification of AT-SSS/SST relationship (Eq. 2) means that wintertime AT(sst) might be overestimated so that corresponding pH(sst) values would be overestimated. In fact, during the aforementioned comparison between pH(sst) and measured pH we noted that for this particular dataset pH(sst) overestimated the measurements. However, the estimates were consistent with the observations to within the total error of ±0.01 pH units. Thus, by utilizing the above total errors, we also accounted for the effect of this possible caveat of Eq. 2 arising from the lack of wintertime TA measurements.”*

8-222 Which other ancillary parameters? Where they come from?

Response: in the revised ms (page 8), this sentence has been modified to *"The UW fCO2 together with TA (sst), UW SST, and SSS(sst) were then used to characterize the full seawater CO2 chemistry using CO2SYS (Lewis and Wallace, 1998; van Heuven et al., 2011), with K1 and K2 constants from Lueker et al. (2000)."*

8-244 You haven't describe RMS before. Salinity is undimension. It will be nice to have some idea here of what this 0.81 could means in terms of pH or OmegaAr, with initial error propagation
Response: in the revised ms, statistics of equations and comparisons clarified, and rmse is defined. Additionally, the errors in pH, SST, and SSS that can produce the maximum target uncertainty of ±0.2 for Ω_{Ar} developed by the C-CAN and GOA-ON have been estimated (see 1st paragraph of section 3.1).

10-281 Fig. 2 should read Fig. 3. Also normally better to start the sentence in more direct way. I would like to know more details how is this data collapsed: what we see is means? What about std? This comment is together with this interannual variation maybe.
Response: what we show on Fig. 3 is gridded data based on weighted averages.
In the revised ms (section 3.2, and tables), a table showing the interannual variations has been added (Table 3). Additionally, the first paragraph of section 3.2 is modified to *"In order to present the mean distributions across the different fjords throughout the annual cycle, we collapsed the data into one virtual year by projecting it onto non-equidistant rectangular grids using the "weighted-average gridding" method of the Ocean Data View software (Schlitzer, 2015). As evident from Fig. 3, there is a clear seasonality in both pH(sst) and Ωar (sst)."*

10-284 text said maximum is 8.2 but figure goes until 8.35
Response: winter pH values are typically about 8.25, but extreme pH values of >8.3 occurred during the winter of 2008.
In the revised ms (section 3.2, and tables), this is clarified by stating that pH *"..varies between minimum values (8.05) around New Year to typical maximum values of around 8.25, which occur during the late winter and/or spring (March-April)."* Additionally, a table showing the interannual variations has been added (Table 3).

I like this comparison with C-CAN 💻
10-311 Could you add a sentence in methodology or somewhere explaining how DIC is normalize, which salinity has been used, which reference? Also note OmegaAr (sst) has something between t and). Also extra space before brakets ini 11-313
Response: corrected.

11-314 State the table or fig that is showing that (I think Fig. 4)
Response: done as suggested by the reviewer.

11-315 Maybe nice to state the basics about Lauvset methods. Also note extra brakets before Lauvset and missing before the year.
Response: done as suggested by the reviewer.
In the revised ms (page 12), we added the sentence *"This method estimates the monthly pH changes expected from corresponding changes observed in SST, SSS, DIC, and TA as well as their sum."*
11-316 Left panels maybe better for state the letters (a, c…)
Response: done as suggested by the reviewer.

11-319 Fig. 4 c, d, e (mismatch of figure number, spaces missing after comma and letters in the figure are capital and in the test are not, please unify). Also amend for 11-321,11-333, 12-369 and 11-322.
Response: corrected as suggested by the reviewer.

11-324:325 This sentence need more explanation. Although I agree, somehow contradict the idea of if we measure pCO_2 and temperature we can estimate OA parameters.
Response: The sentence is not about our ability to estimate OA parameters. It is about our ability to analyze the controls of OA parameters for which measured SSS and AT are best. If estimated AT(sst) is used, on the other hand, the magnitude of the alkalinity control will be more uncertain while its form will resemble that of SST.
In the revised ms (page 13), the sentence is extended to *"This emphasizes the need for measured SSS and TA values when the objective is to analyze the controls of pH and Ω_{Ar}(sst) variations."*

11-334 I think that should read Fig. 4F
After reading this twice, an idea can be to do some "Multiple linear regression" to support your analysis in a statistical way.
Response: here we disagree with the reviewer. First, "Fig. 4" is correct i.e. that is where the seasonal amplitude of Ω_{Ar}(sst) is shown. Secondly, we have already verified that multiple linear regressions are not a better alternative for our analyses. Such regression would only give us indication on how well the Ω_{Ar}(sss) values can be modelled from a given set of parameters, but the values of the regression coefficients would NOT necessarily reflect sensitivity of Ω_{Ar}(sss) to the associated parameters.

11-337 impact. (extra space before point) Also in 11-342 before sst).
Response: corrected as suggested by the reviewer.
12-359 equations 5 and 6 or equation 3 and 4 (somehow not easy to understand)
Response: we agree with the reviewer. The ambiguity arised as result of a typo.
In the revised ms (page 14), the sentence is corrected to *"This, together with the fact that equations 3 and 4 can…"*
12-366 another stats comment, how significantly is this significantly?

12-371 there are two commas before R2
13-372 there is extra point after (6)
Response: Thank you! Both the above typos have been corrected in the revised text.

13-373 or somewhere else, just though that another importance to use VOS pCO_2 is that they are more frequent that normal oceanography cruises in winter, especially in these regions.
Response: Good idea! This is implemented in the revised manuscript (page 15).

A note of caution about the slopes, we need some +- because if we took the slope of red square will be really different. But still I like the comparison with RCP scenarios.
Response: we agree with the reviewer.
In the revised ms (end of section 3.4), an uncertainty of ±0.2 in the Ω_{Ar} estimates is included and the text has been changed accordingly.

13-387 cannot
Response: we are not sure what this comment means, but the word "cannot" was used intentionally in the original manuscript.

13-401 extra : at the end of captions
Response: corrected.
14-420:423 I miss some words of what this low omegaAr 1.3 could mean for calcifying organism. Some studies point that there's no need to be below 1 to have some affect in organism. Some "bio"-words could expand the readers-users of these nice results.
Response: ….

14-424:425 Maybe I miss something but this sentence is not really new or surprising, right?
Response: in the revised text (page 17), this sentence has been modified to *"Strong correlations of pH and* Ω_{Ar} *with* fCO_2 *and* $fCO_{2@meanSST}$ *(*fCO_2 *adjusted to the mean temperature), respectively provide an approach to interpolate pH and* Ω_{Ar} *over large areas in the fjords of western Norway where underway measurements of* fCO_2*, SST, and SSS are available."*

Table 1 What's the different between 1 and 5 m. Are they both underway water?
Response: The RF dataset are averages over measurements five depths 1-5 m. This is clarified in the revised manuscript (page 7, and Table 2 and its caption)
22-607 Should be table 2
Response: corrected.

Figure 1 may benefit from a more global map, for no European readers. Also if possible add the meaning of the arrows (NCC) in the figure, so we don't have to read legend.
Response: a more global map is used in the revised manuscript.

Fig. 2A, is colour scale and x-axis the same SST
Response: No, the color scale shows months. This is clarified in the revised manuscript (Fig. 2A).

Fig. 3 is missing A-D and parameter and unit on the colour scale. Also unify decimal units
Response: The missing legends "A-D" has been added to Fig. 3 of the revised manuscript.

Fig. 4 You explain good that SST and TA are not independent. So question is, could you still use this method with dependent variables? Also careful because labels are cutting x-axis.
Response: Yes, we can use this procedure even if TA is based on SST data. This is because the decomposition procedure computes the effect of changes in each driver (i.e. changes in SST, SSS, TA, and DIC) separately. Moreover, the seasonal changes in TA and SST are opposite i.e. TA decreases when SST increases and vice versa, and the magnitude of the former is about ten times bigger. Thus, even though the similarity of Fig. C and E (in from) is as expected, the magnitudes of the resulting effects from the two drivers can be different (these are currently nearly equal by coincidence) if, for instance, we use a TA Revelle Factor slightly different form the global value of -10.

Dr. Reviewer 2 (E.M. Jones)
Comment:
"This study presents seasonal cycling and controlling factors of the ocean acidification parameters, aragonite saturation and pH, in fjords of western Norway. The data and discussions are an important contribution to CO2 research in a relatively undersampled

region and the methods used to determine the whole carbonate system from underway pCO2 data form a novel approach and are complimentary to future studies in this field. The choice of the journal fits very well and I recommend publication of this article. In the version reviewed here there are a number of ameliorations that can be made in terms of clarity, coherence and rigour before proceeding with publication. The authors may find comments, questions and linguistic corrections analytically below."

Response: We thank the reviewer for these encouraging and constructive comments as well as for the suggested corrections and clarifications.

C: 1. A very minor comment regarding language; as it is a European journal I would suggest replacing the use of "fall" with "autumn".
Response: done as requested by the reviewer.

2. Make sure it is clear how TA is derived from SSS(sst) and SST, i.e, how strong is a relationship between SSS and SST to make such a derivation and secondly what steps are carried out to determine TA?
Response: this has been clarified as suggested by the reviewer.
In the revised manuscript (page 10), it is stated *"To estimate a corresponding TA value for each UW fCO2 observation obtained from MS Trans Carrier, we used salinity values estimated from UW SST data by using Eq.1. The results (denoted as SSS(sst)) were then inputted into Eq.2 to obtain TA(sst) (Table 2). The fact that TA(sst) are based on SSS(sst) rather than measured SSS values introduced an additional error in the estimated pH(sst) and ΩAr(sst). In order to assess this error…."*

3. Include a clear statement of the precision and accuracy of the measured parameters. This would fit well before the detailed description of the propagation of errors and further place them in context.
Response: in the revised ms, the measurements accuracy of DIC, TA, and pH is stated (section 2.2 and 2.3).

4. The influence of sea ice and glacial ice dynamics has not been explicitly considered. Is this area free from ice influences and if so perhaps state this or does sea ice formation in winter and melt during spring-summer contribute to the correlation in SST and SSS?
Response: the study area is free from ice influence.
In the revised ms (section 1.1), this is clarified by stating "*..snow melt and run-off are the main local sources for freshwater since the fjord system is generally ice free.*"

5. For salinity normalised DIC, the terms DICS and nDIC are both used. Perhaps try and use one term for consistency and clarity throughout the paper and include a statement of how the normalisation was carried out, i.e., what salinity reference is used, if the standard correction was made or non-zero endmembers were included, as described in Friis et al. (2003).
Response: "DICS" was found in Eqs. 3 and 4 in the original the manuscript. However, this is referring to the product "DIC" times the parameter "S". The latter has been defined in Egleston et al. (2010) as referenced in the text.
In the revised manuscript, all abbreviations used DIC, nDIC are properly defined. Additionally, an overview of the symbols used for quantities estimated and/or derived from the measurement-based variables is given on Table 2.

6. Figure 2: in relation to the various regression analyses made, a statement on the interpretation of the regression and the significance of the relationships is required. This would make the comparisons of the parameters more relevant and strengthen the choice of those used in other calculations.

Response: we thank the reviewer for the suggested improvement.

In the revised manuscript, the statistics of all equations and comparisons are presented, and an additional table (Table 3) summarizing the statistics of the comparisons on Fig. 2 is included.

7. Check Table numbering; Table 2 is absent.

Response: corrected.

Specific comments:

Abstract

Page 1

Line 9 write "carbon dioxide (CO_2)" in full (first time use in main text). Line 10 insert "the" between "lowers" and "aragonite saturation state". Line 19 change to "carbonrich". Line 24-25 replace "brings up" with "enables" and add "reach" between "to" and "the". Line 32 define "SSS" for first time use.

1. Introduction

Page 2

Line 38 replace "incur" with "cause". Line 39 replace "ocean" with "oceanic". Line 43 insert "," after the reference. Line 51 insert "," after "regions". Line 63 insert "a" between "is" and "prerequisite".

Page 3

Line 64 remove the "s" on "latitudes". Line 65 insert "CO_2" between "be" and "sources". Line 76 delete "important" to refrain from using the same word twice in one sentence. Line 81 delete "the" between "in" and "surface". Line 89 insert "the" between "present" and "mean".

1.1 The Study Area

Page 3

Line 93 instead of capital letters use lower case "n" and "s" for "north" and "south", respectively. Line 95 replace "at" with "along".

Page 4

Line 103 delete "the" at the end of the line. Line 106 replace "it" with "Korsfjord" to reduce the use of generic "it" and be specific to the subject under description. Line 108 remove full-stop and replace with and to join sentences for better flow. Line 109 correct "witch" to "which". Line 118 replace "mix" with "mixes". Line 119 insert second bracket ")" after "(NCC". Line 121 change "wind" to "winds" and insert "the water in" after "circulation of". Line 122 replace "that follows" with "following". Line 124 suggestion to add "forcing" after "wind". Line 125 replace "," with "and inputs of". Line 125-126 between "seasonal time scales," and "during spring-summer" replace text with "salinity drives stratification". Line 126 add "the water column is" between "and" and "more".

Page 5

Line 129 specify what "the temperature" refers to, i.e., a certain depth or depth range in the water column or certain location in the fjord. Line 131 delete “the” start line with “Water”. Line 132 following “oxygen” insert “to the area”. Line 132-133 delete “the fjords enhance their” and insert “is enhanced in the fojrd” between “production” and “which”. Line 133 replace “enables them to host” with “supports”. Line 137 replace “decisive” with “dominant controls of” and delete “for the”. Line 140 write “nutrient-rich” and add “on from” after “follows”. Line 142 insert “upper” before “water column”, i.e., assuming that the sub-surface/ deeper waters remain nutrient rich? Line 143 insert 2 “,” either side of “with its adjacent waters”. Line 149 replace the extra “of” with “the” and make the 2 on “CO2” a subscript. Line 152 replace “It” with “The ship”. Line 153 replace “.” after “(Fig. 1)” with “,” and delete “It”.

Line 6

Line 161 replace “in” with “during”. Line 166 add SOCAT reference: Bakker, D. C. E.,

Response: all the above correction have been implemented in the revised text.

Page 7

Line 192 instead of capital letter use lower case “s” for “station”. Line 200 clarify the estimated pH values – estimated from what source? CO2SYS?

Response: this is clarified in the revised ms, by modifying the sentence to *“These sensor data were used to assess the uncertainty in our pH values estimated as described in the next section.”*

2.4 Methods

Page 7

Line 206-207 insert “an” before “empirical” and define the parameters used to derive the empirical relationship.

Response: this is clarified in the revised ms, by modifying the end of the sentence to *“…sea surface salinity (SSS) was determined from empirical relationship with SST.”*

Line 217 replace “Second” with “Secondly”. Line 217 clarify how TA is derived from SSS(sst), see general comments.

Response: see response to the general comments.

3. Results and discussion

3.1 Correlations and validations

Page 8

Line 236 insert “the” before “data”.

Line 237-239 Is sea ice present in the region? see general comments.

Response: see response to the general comments.

Line 274 insert “through the calculations” between “propagated” and “to”.

Response: in the revised text (page 11), the sentence have been modified to *“These two error estimates were combined (as the square root of sum of squares) to determine the total error in our estimates, which were found to be ±0.01 and ±0.1 for pH and ΩAr, respectively.”*

Line 239 clarify where the “runoff” originates. Line 240 insert
“degree of” between “high” and “scatter”. Line 244 reverse order of “indeed is” to “is indeed”. Line 247 delete “a” after “As” and re-write sentence following “verification” as “that the RF SST dataset is spatially representative,”. Line 249 replace “in” with
“across”. Line 256 replace “statics” with “statistics”. Line 257 replace “functions” with “acts” and insert “an” between “as” and “indicator”. Line 259 add a space to separate “with” and “values”. Line 260 add commas to read “data ,i.e., pH(sss)”. Line 265 insert “closely” between “
Ar(sst)” and “reproduce” and delete “very well”. Line 269 replace
“show” with “shown”.

3.2 Spatiotemporal variations

Page 10

Line 281 replace “collapsed” with “condensed”. Line 284 delete “the” following “after”. Line 286 replace “outweighs” with “counteracts”. Line 287 replace “begins” with “begin” and also specify what processes are being referred to. Line 288 insert “the” after September replace “SSTs” with “SST”. Line 289 re-phrase sentence between “mixing,” and “as mentioned” to read “which enables deep, carbon-rich coastal water to penetrate the surface layer,”. Line 290 replace “as” between “and” and “reflected” with “is” and delete “the” before “increasing”. Perhaps specify which DIC values are increasing by the autumnal mixing, i.e., sea surface, surface layer, upper ocean: : : Line 293 replace “drives up the “ with “enriches”. Line 294 insert “the” before “concentration”, delete “the” between “of” and “carbonate” and add an s to read “ions”. Line 296 rephrase to read “due to inputs of run-off” and replace “reinforces” with “enhances”. Line 297 replace “over” with “exhausted”.

Response: all the above corrections have been implemented in the revised text.

Line 298 replace “The” with “However,” and delete
“, on the other hand,”.

Response: we find this sentence clear in the original text.

Line 300 replace “mismatch” with “decoupling of”. Line 307
correct “embody” to “embodied”.

3.3 Controls of seasonal variability and trends

Page 11

Line 310 replace “arranged the data into” with “computed”. Page 11 Line 315 re-write the reference to “Lauvset et al. (2015)”. Line 316-317 replace “are shown on Fig. 4 (left panels) where it can be seen” with “show” – removes the double Fig. reference in the sentence. Line 326 replace “letting one of the drivers” with “varying them independently”.

Line 327 delete “to vary” and replace “drivers” with “controls” – removing double word use in the same sentence. Line 329 replace “for” with “of” and correct “driver” to “drivers”. Line 331 correct “induce” to “induces”. Line 332 insert “other” between “the” and “hand”. Line 333 correct “induce” to “induces”. Line 334-335 re-write to “We therefore conclude that variations in DIC, followed by TA, are the most important

drivers for changes in
Ar(sst).” Line 337 replace “have” with “has” and delete “In
terms of processes” so that the next line starts with “This means”. Line 338 correct
to “carbon-rich”. Line 339 insert “inputs” after “runoff”. Line 343 replace “changes” to
“change”.
Response: all the above corrections have been implemented in the revised text.

The first use of nDIC – how is defined and how are the normalised values determined,
perhaps add reference, e.g., Friis et al. (2003).
Response: in the revised text (page 13), this part of the sentence has been modified to *“..both for SST and DIC normalized to the mean salinity (nDIC) according to Friis et al. (2003)”*

3.4 Inference of OA parameters from VOS underway data
Page 12
Line 353 the use of DICS is not specifically defined in the text and is an additional
term to nDIC – do they both refer to salinity normalised DIC determined in the same
way? Please clarify to be sure.
Response: please see the general comments regarding “DICS”.

Line 362 remove “, while the CO2 system is fully determined only occasionally,” as I don’t
think it adds anything it would reduce the length of the sentence.
Response: we chose to keep “while the CO_2 system is fully determined only occasionally” in
the text in order to emphasize that occasional determination of the full CO2-system is
necessary for the method to work.

Line 355 remove the space after (2010). Line 359
reference to equations 4 and 5 might not be correct, i.e., should it be equations 3 and
4. Please check and amend if necessary.

Line 368 delete the spare “and” after “Fig. 5” and add “to” between “conform” and “tight”.
Line 371 replace extra “,” with “;” after “10.354” in
equation 5.
Page 13
Line 372 check for extra spaces and uses of “,” and/ or “;” in separation of terms and
consistency with equation 5. Line 377 delete “and” before “thus” and replace “min- imise”
with “minimizing”. Line 380 replace “with” by “to”. Line 391 change to “carbonrich”.
Line 392 rearrange the line to read “surface water also reflects the properties
of the deeper water”. Line 394 replace “can” with “could” and insert “to occur” after
“expected”. Line 399 replace “development” with “CO2 concentrations” and replace
“follows” with “follow”. Line 400 add “driving oceanic CO2 uptake” after “atmosphere”.
4. Summary and concluding remarks
Page 14
Line 402 insert “worth” after “four years” and replace “less” with “sporadic”. Line 403
delete “frequent”. Line 413-414 use the same number of decimal places for quoted

numbers. Line 415 insert “the” before “phytoplankton” and replace “, which” with “that” and delete “levels”. Line 417 replace “brings up” with “allows”; correct to “carbonrich”; insert “mix into” between “to” and “the”. Line 418-419 replace “and reinforces the decrease in pH” with “reduces” and delete “, which continuous throughout fall”. Line 430-431 finish sentence after “carbonate system”.

Page 15

Line 435 replace “development” with “concentrations” and remove “f” from “fCO2”, i.e., referring to concentrations of CO2 rather than the concentrations of the fugacity of CO2 that wouldn’t be quite correct. Line 436 finish the sentence after “atmosphere”.

5. Acknowledgements

Page 15

Line 438 replace “supports” with “support” and replace “by” with “from”. Line 440 insert “the” after “and help of”.

Tables

Table 1

Page 20 Line 598 replace “about” with “of”. Line 599 insert “which” after “for”.

Page 21 Line 603 replace “(continue)” with “(continued)”.

Table 3

Page 22 nDIC – “DIC normalised to the mean salinity”; please include somewhere in the main body of the text what value was determined for the mean salinity and how.

Figure texts

Page 23 Line 620 replace “which” with “where” and replace “tick” with “thick”. Line 635 check “ln(nfCO2ts)” – is the “n” correct and currently it doesn’t match with the X-axis labelling in Figure 5 (B).

Figures

Figure 2 (A) Y-axis can be expanded to open up the visual regression trend, i.e., range in SSS of 25-35. Confusion of the colour bar underneath is too close to the X-axis and on first inspection looks like it is referring to SST values. Add “month” as the unit to clarify the colour bar and move it closer to panel (A) if possible. Figure (3) 4 time series panels are presented but only 2 parameters mentioned in the Figure text and all colour bars are unlabelled. Add parameter labels and units (where relevant) to each of the coloured panels.

Response: all the above corrections have been implemented in the revised text.

Aragonite saturation states and pH in western Norway fjords: seasonal cycles and controlling factors, 2005-2009

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Abstract:

The uptake of anthropogenic Carbon Dioxide (CO_2) by the ocean leads to a process known as ocean acidification (OA) which lowers the aragonite saturation state (Ω_{Ar}) and pH, and this is poorly documented in coastal environments including fjords due to lack of appropriate observations.

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Here we use weekly underway data from Voluntary Observing Ships (VOS) covering the period 2005-2009 combined with data from research cruises to estimate Ω_{Ar} and pH values in several adjacent western Norwegian fjords, and to evaluate how seawater CO_2 chemistry drives their variations in response to physical and biological factors.

The OA parameters in the surface waters of the fjords are characterized by strong seasonal and spatially coherent variations. These changes are governed by the seasonal changes in temperature, salinity, formation and decay of organic matter, and vertical mixing with deeper, carbon-rich coastal water. Annual mean pH and Ω_{Ar} values were 8.13 and 2.21, respectively. The former varies from minimum values (≈8.05) in late December - early January to maximum values of around 8.2 during early spring (March-April) as a consequence of the phytoplankton spring bloom, which reduces Dissolved Inorganic Carbon (DIC). In the following months, pH decreases in response to warming. This thermodynamic decrease in pH is reinforced by the deepening of the mixed layer, which ~~brings up~~enables carbon-rich coastal water to reach the surface, and this trend continues until the low winter values are reached again. Ω_{Ar}, on the other hand, reaches its seasonal maximum (>2.5) in mid to late summer (July -Sept), when the spring bloom is over and pH is decreasing. The lowest Ω_{Ar} values (≈1.3-1.6) occur during winter (Jan-Mar), when both pH and Sea Surface Temperature (SST) are low and DIC is highest. Consequently, seasonal Ω_{Ar} variations align with those of SST and salinity normalized DIC~~.~~ (nDIC).

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We demonstrate that underway measurements of fugacity of CO_2 in seawater (fCO_2~~), SST,~~) and ~~SSS~~SST from VOS lines combined with high frequency observations of the complete carbonate system at strategically placed fixed stations provide an approach to interpolate OA parameters over large areas in the fjords of western Norway.

1. Introduction:

The continued emissions of carbon dioxide (CO_2) (~~Peters~~Le Quéré et al., ~~2013~~2015) are of global concern, not only because they are the main drivers of anthropogenic global warming, but also because of the changes in the ocean chemistry they ~~incur~~cause (Ciais et al., 2013). The increase in the atmospheric CO_2 concentration drives a net ocean CO_2 uptake, which leads to higher proton (H^+) concentration i.e. lower pH, lower concentration of carbonate ion ~~(CO_3^{2-})~~(CO_3^{2-}) and, lower saturation state (Ω) for calcium carbonate in seawater. This process is known as ocean acidification (OA) (e.g. Royal Society, 2005), and it has direct and indirect effects on biological activity in the ocean (e.g. Gattuso and Hansson, 2011) including reported inhibition of biogenic calcification by marine organisms which precipitate 0.5–2.0 Gt of carbon as calcium carbonate ($CaCO_3$) in the global ocean every year (Bach, 2015).

For the open ocean, the rate of OA has been relatively well documented and understood during the last decade. Observations from time series stations and volunteer observing ships in different oceanic regions consistently show systematic changes in surface ocean chemistry that result from OA. Specifically, long-term negative trends of pH and saturation state for aragonite (Ω_{Ar}) have been observed (e.g. Lauvset et al., 2015; Bates et al., 2014).

For coastal regions observed rates of pH change largely differ from those expected from oceanic CO_2 uptake alone, as variations in other biogeochemical processes, related for example to changes in nutrient loading and eutrophication, are important as well (Clargo et al. 2015; Provoost et al., 2010; Wootton et al., 2008).

The Norwegian west coast (Fig. 1) is dominated by fjords, narrow and deep estuaries, carved by glacial processes, with a sill in the mouth where they connect to the coastal North Sea. Apart from being important recreation areas and marine pathways, these fjords are important ecosystems and their physics, marine life, and associated environmental pressures have been relatively well studied (e.g. Matthews and Sands, 1973; Erga and Heimdal, 1984; Asplin et al., 2013; Brattegard et al., 2011; Stigebrandt, 2012; and references therein).

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However, only a few studies on the carbon cycle of Norwegian fjords exist in the literature~~.~~, and these are from the high Arctic at Svalbard (Fransson et al., 2014; Omar et al., 2005). This hampers our understanding of the natural variability and controls of seawater carbonate chemistry, which is a prerequisite for sound estimates of OA in these ecosystems. Generally, in the Northern Hemisphere, high ~~latitudes~~latitude coastal regions are thought to be sinks for atmospheric CO_2, while low-latitude regions are thought to be CO_2 sources (Borges et al., 2005; Cai et al., 2006; Chavez et al., 2007; Chen and Borges, 2009). The few existing studies of Norwegian fjords confirm the above picture; they act as an annual net sink for atmospheric CO_2 (Fransson et al., 2014; Omar et al., 2005).

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The carbon cycle of the northern North Sea, to which the western Norway fjords are connected, has been well studied (Thomas et al., 2004; 2005; 2007; 2008; Bozec et al., 2005; 2006; Omar et al., 2010). However, observation-based OA estimates are still scarce. Recently, Clargo et al. (2015) observed a rapid pH decrease in the North Sea, but after accounting for biological processes, they estimated an ocean acidification rate consistent with concurrent atmospheric and open ocean CO_2 increases over the period they studied, 2001-2011.

Filling the knowledge gap on OA (and generally the carbon cycle) in ~~fjords in~~ western ~~Norway has not been described previously. Filling this knowledge gap~~ Norwegian fjords is important because ~~the fjords~~these areas are ~~important~~ spawning grounds for different fish species (Salvanes and Noreide, 1993; Johannessen et al., 2014), productions sites for pelagic calcifiers (Berge, 1962; Erga and Heimdal, 1984; Frette et al., 2004), the home for some coral reefs (e. g. Fosså et al., 2002), and significant food sources due to the aquaculture industry which operates there. Observations of the carbon cycle dynamics in the fjord system will not only further our understanding and ability for prediction, but they will also serve as benchmarks against which future changes are compared.

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In this study, we present first estimates of OA parameters in ~~the~~ surface waters of several adjacent western Norway fjords (Fig. 1), based mainly on weekly underway data from Voluntary Observing Ships (VOS) covering the period 2005-2009. We combine the underway data with available station data from research cruises to facilitate a complete description of the seawater CO_2 chemistry in accordance with the recommendations of OA core principles by McLaughlin et al. (2015). We focus on analyses of Ω_{Ar} and pH values and evaluate their variations in response to the physical and biological factors: summer warming and stratification, spring phytoplankton bloom, and deep mixing during fall and winter. First we

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present the mean distribution across the different fjords (Korsfjord-Langenuen-Hardangerfjord) to understand the spatiotemporal patterns, then we collapse all data into a monthly time series to analyze the seasonal controls and resolve any interannual or multiyear temporal patterns.

1.1 The study area

The study area covers, from ~~North~~north to ~~South~~south, the interconnected Raunefjord (centered around 60.27°N; 5.17°E), the Korsfjord (centered around 60.17°N; 5.21°E), Langenuen, and southern parts of the Hardangerfjord~~,~~, which are all situated ~~at~~along the western coast of mainland Norway (Fig. 1). The area stretches over some 60 km, but the main focus here will be on the area from the Korsfjord to the Hardangerfjord from which the vast majority of the data has been acquired.

The bathymetry and hydrographic conditions of the fjords have been described elsewhere (Helle, 1978; Mathew and Sands, 1973; Bakke and Sands, 1977; Erga and Heimdal, 1984; Asplin et al., 2014). In the following only a brief account, based on the above studies, is given.

The Korsfjord is 690 m deep in its main basin and situated about 25 km south of the Norway's second largest city, Bergen. To the west ~~it~~Korsfjord is relatively well connected to the open coastal ocean of the northern North Sea through a 250 m deep sill at Marsteinen. To the north it connects with ~~-~~the Raunefjord through the 100 m deep strait Lerøysundet - between the islands Sotra and Lerøy. At the eastern end ~~it~~the fjord branches into the smaller and shallower fjords Lysefjord and Fanafjord~~. To~~, and to the southwest it connects with the open coast through the Selbjørnsfjord, ~~witch~~which has a sill depth of 180 m at Selbjørn. To the south it connects to the Hardangerfjord through the 25 km long and 300 m deep strait Langenuen.

The Hardangerfjord is a 179 km long fjord ranking as the fourth longest fjord in the world. It stretches from the coastal open ocean in the southwest to the mountainous interior of Norway. Our study includes the southern parts of the fjord. This is bounded by the larger islands Stord and Tysnesøya in the north, the Haugaland peninsula in the south, and the smaller islands Fjellbergøya and Halsnøya on the south/east side. This part of the fjord is over 300 m deep in its basin (around 59.76N; 5.55E) and connects with the smaller fjords Ålfjord and Bjoafjord in the south.

In the fjord system run-off from land ~~mix~~mixes with salty water originating from the northward flowing Norwegian Coastal Current (NCC~~,~~) to produce a typically salinity stratified water column with a complex circulation, forced both by external and internal factors. In particular, the coastal ~~wind~~winds have a profound influence on the water circulation ~~of~~in western Norwegian fjords producing episodic renewal of the deep water that follows periods of prolonged northerly winds (Svendsen, 1981; Erga and Heimdal, 1984). Besides wind forcing, the hydrography of the fjords is also influenced by winter cooling, summer warming, snow melt and run-off. The fjords also receive freshwater through the NCC, which carries water originating from the Baltic Sea and rivers in the southern North Sea (Skagseth et al., 2011 and references therein). However, snow melt and run-off are the main local sources for freshwater since the fjord system is generally ice free. Thus, on seasonal time scales, ~~the fjords are generally~~ salinity ~~stratified~~drives stratification during spring-summer and the water column is more homogenous during winter. Additionally, Asplin et al. (2014) reported regular episodes of water exchange between Hardangerfjord and the NCC that homogenized the upper 50 m of the fjord by mixing with coastal water. During these events the water temperature inside the Hardangerfjord regularly becomes identical with that of the adjacent coastal ~~open ocean~~North Sea (Asplin et al., 2014).

~~The water~~Water exchange with the NCC is important for the fjord ecosystems as it supplies nutrients and oxygen to the area (Aure and Stigebrandt, 1989). In response, ~~the fjords enhance their~~ primary production is enhanced in the fjords, which ~~enables them to host~~support rich and diverse marine life (Erga and Heimdal, 1984; Erga, 1989; Salvanes and Noreide, 1993).

Erga and Heimdal (1984) studied the dynamics of the spring bloom in the Korsfjord and estimated a total primary production of 74 g C m^{-2} during the period ~~-~~February – June. Further, they reported light regime and water column stability to be ~~decisive for~~dominant controls of the onset of the bloom. They also pointed out that changes in the alongshore wind component are important for the bloom dynamics, with persistent northerly winds inducing upwelling of nutrient~~-~~-rich coastal water that promotes blooming while the opposite situation follows on from persistent southerly winds. During calm periods strong stratification develops, which can ultimately lead to nutrient exhaustion in the upper water column.

The study area, with its adjacent waters, is ecologically and economically important because it covers spawning grounds for a number of different fish species (Lie et al., 1978; Johannessen et al., 2014). Additionally, the largest concentration of coral reefs in western Norway is found in the Langenuen strait (Fosså, 2015). The fjord system also contributes to the important aquaculture production that, with its annual fish production of >700 tonnes, ranks Norway within the tenth place worldwide. About one fifth of this is produced in the Hordaland County where the fjord system studied here is situated (http://www.diercke.com).

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2. Data and methods

2.1 **Weekly underway VOS data**

Weekly underway measurements~~ of~~ of fugacity of CO_2 in seawater (fCO_2) and SST were obtained aboard the containership MS Trans Carrier (operated by Seatrans AS, Norway, www.seatrans.no). During the study period, the ship sailed from Bergen to ports in southwestern Norway on a weekly basis. It passed through several fjords including the Korsfjord and the Hardangerfjord (Fig. 1~~). It~~), then crossed the North Sea mostly along a transect roughly at 5°E longitude to Amsterdam, Netherlands, and then back on the same route (Omar et al., 2010). The measurement method used aboard MS Trans Carrier was described in Omar et al. (2010). The instrument recorded one fCO_2 and SST measurement about every three minutes and automatically shut off when the ship approached ports in Bergen (20-30 km from port ≈60.2°N) and Amsterdam, in order to protect the inlet filter from potentially polluted seawater. Between February and December 2006 the VOS line was serviced by a sister ship, MS Norcliff, which was equipped with the same measurement system ~~in that period.~~

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~~Underway data~~during that period. The VOS line was in operation in the period September 2005 to September 2009. Data acquired between 59.74°N – 60.16°N and 5.17°E – 5.58°E (The Korsfjord, Langenuen, and southern parts of the Hardangerfjord) ~~from September 2005 to September 2009~~ are used for the current analyses. This dataset will be referred to as the UW (e.g. UW fCO_2 and UW SST) which stands for underway. The UW data from the years 2005, 2006, and 2007 are available from the SOCAT database ~~(http://www.socat.info/).~~ (http://www.socat.info/), the 2008 and 2009 UW data has been submitted for the SOCAT Version 4 release.

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2.2 Cruise and fixed station data

We augment the VOS data with station data acquired during scientific cruises in the study area in the period 2007-2010 and in 2015, and during regular visits (1-4 times per month) to a fixed station in the Raunefjord in 2007 and 2008. Table 1 summarizes details of these three datasets, which will be referred to as the CS, 2015 and RF datasets, respectively.

Five of the cruises were conducted in the Korsfjord and the Raunefjord (Fig. 1, Table 1) onboard RV Hans Brattstrøm as part of the EU FP7 educational project CarboSchools (CS) in 2007-2010. The CS dataset covers mainly the spring and summer seasons reflecting the somewhat opportunistic nature of the sampling campaign. The 2015 cruise took place during fall (September 24) as part of the Ocean Acidification project funded by the Norwegian Environment Agency, and measurements were taken at three stations in the Korsfjord, Langenuen and southern Hardangerfjord (Fig.1, red squares).

During each of the above cruises water samples were collected for analyses of parameters including DIC, total alkalinity (TA), salinity and temperature at 1-2 stations. The DIC concentrations were determined by the coulometric method (e.g. Johnson et al., 1993) with a precision of ±1 μmol kg^{-1}. TA was measured by potentiometric titration with strong acid (HCl), and a precision of ±2 μmol kg^{-1}. Accuracy was checked by using Certified Reference Material supplied by A. Dickson (SIO). Once all samples have been corrected with respect to offsets determined from the CRM measurements, the DIC and TA measurements were accurate to within the respective measurement precision (above). Only surface data (depth<=4m) from within the geographical rectangle 59.74-60.34°N and 5.17-5.55°E were used in the current study.

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The Department of Biology, ~~UoB~~University of Bergen has acquired CTD (SAIV) data from a fixed station in Raunefjord (RF) during 27 days in 2007 and 35 days in 2008 as part of a monitoring program close to the Marine Biological field ~~Station at Espegrend~~station at Espegrend. These data contained temperature and salinity profiles with one meter resolution. Averages of the uppermost five meters have been used in this study and will be referred to as the RF dataset.

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2.3 In situ pH sensor data

In January 2012 we carried out an evaluation of two pH sensors of the type Submersible Autonomous Moored Instruments (SAMI_pH, second generation) at the Marine Biological field Station at the eastern shore of the Raunefjord. The sensors were suspended from a wooden frame attached to the floating docks around a raft-house in the fjord –some hundred meters from land. The instruments were submersed at about one meter depth in the fjord and were left for 50 hours starting 24.01.2012 10:00 GMT, recording one measurement each hour. A full description of the measurement method for these instruments is found at http://www.sunburstsensors.com/. In addition to pH, these instruments also recorded the seawater temperature~~.~~ and they have measurement precision and accuracy of <0.001 and +/-0.003 pH units, respectively. During the test, salinity was also recorded using a Seaguard

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RCM from Aanderaa Data Instruments. These sensor data were used to assess the uncertainty in our pH values estimated ~~pH values~~as described in section 3.1.

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2.4 Methods

2.4.1 Complete seawater CO_2 chemistry from SST and fCO_2

A complete description of the seawater CO_2 chemistry from the UW SST and UW fCO_2 data collected onboard MS Trans Carrier has been obtained through a 3-step procedure. This is similar to the procedure described in Nondal et al. (2009) with the main modification being that in the current study, sea surface salinity (SSS) was determined from empirical relationship with SST.

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First, the RF dataset has been used to determine the regional SSS versus SST relationship. The RF data was chosen for this purpose because it covered all seasons well, both in 2007 and 2008. The identified regional SSS-SST relationship allowed us to estimate a SSS value for each UW SST observation from MS Trans Carrier. This step was necessary because the total number of measured SSS values were less than 150 data points, while the available underway SST and fCO_2 data were much more numerous (> 9900 data points), covering most of the study area during the years 2005-2009. The remaining SST and SSS data (CS, and from sensors) were used for evaluation to verify that SST-SSS relationship is valid for the whole study area (section 3.1). Salinity values estimated from SST will be denoted as SSS(sst).

Second, we determined TA from SSS(sst) and SST using an algorithm we identified for the region using the CS dataset. This allows us to estimate a corresponding alkalinity value for each UW fCO_2 observation obtained from MS Trans Carrier. Alkalinity values estimated from measured SSS and SST data will be denoted as TA(sss), whereas TA values estimated from SSS(sst) and SST values will be denoted as TA(sst).

The UW fCO_2 together with TA (sst~~)~~), UW SST, and ~~other ancillary parameters~~SSS(sst) were then used to characterize the full seawater CO_2 chemistry using CO2SYS (Lewis and Wallace, 1998; van Heuven et al., 2011), with K1 and K2 constants from Lueker et al. (2000). The CO2SYS calculation also gives DIC, pH, Ω_{Ar} and all other seawater CO_2 chemistry variables. The data estimated using this three stage procedure will be denoted pH(sst) and Ω_{Ar}(sst) and are the main focus of this study.

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pH and Ω_{Ar} values based on TA(sss) and fCO_2 will be denoted as pH(sss) and Ω_{Ar}(sss), whereas values that are either measured or computed from measured TA and DIC will be denoted as simply pH and Ω_{Ar}. nDIC denotes the DIC values normalized to constant salinity (the mean value) according to Friis et al. (2003) with freshwater end member DIC concentration of 1039 µmol kg^{-1} inferred from the cruise data. An overview of the symbols used for estimated and derived quantities used in this study is given in Table 2.

3. Results and discussion

3.1 Correlations and validations

In this section we present the regression equations identified in this study in addition to validating the various estimation procedures used by comparing the estimated values with those measured/computed. The results of these comparisons are summarized in Table 3. For each comparison, the coefficient of determination (R^2) and the significance level (p-value) are used as metrics for the goodness of the correlation while the associated root-mean-square error (rmse) is benchmarked against the maximum target uncertainties developed by the Global Ocean Acidification Network (GOA-ON) and the California Current Acidification Network (C-CAN) of ±0.2 for Ω_{Ar} (McLaughlin et al., 2015), which corresponds to maximum uncertainties of ±0.02, ±1.25 or ±1.8 in pH, SST, or SSS, respectively.

The regional SST-SSS relationship obtained from the RF dataset is given by Eq. 1 and is depicted in Fig. 2a (filled symbols). Despite a clear covariation between SST and SSS, there is a lot of scatter in the data and the statistics of the regression equation is not particularly strong (Eq. 1). The observed correlation most probably arises from the annual cycles; during summer the study area embodies warm water diluted by runoff, whereas during winter the surface water is colder and saltier due to little or no runoff. The magnitude of these annual variations varies with time and space and this is reflected by the high degree of scatter in the relationship. Consequently, the identified regression model is able to explain only 27% of the salinity variations. Nonetheless, the independent station and sensor data (dots, squares, and stars), which have been acquired from the whole study area~~, fits well~~ in different seasons, falls into a pattern around the relationship described by Eq.1 with ~~an RMS~~a root-squared-mean error of 0.81 psu. Thus, ~~these data confirm~~from here on we assume that Eq. 1 ~~indeed~~ is ~~representative for~~able to estimate the seasonal SSS variations across the whole study region. To verify this we have compared the monthly averages of RF_SSS data with values obtained using Eq.1 and monthly RF_SST. As shown in the last row of Table 3, the estimated values

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were significantly correlated with the monthly RF_SSS (R^2=0.65 and p=0.002) and the resulting rmse of 0.3 was lower than the benchmark values of ±1.8.

$$\cancel{SSS = -0.142SST + 31.09}\ SSS = -0.142SST + 32.09\text{, for SSS>29; } R^2\text{=0.27; n=61;}$$

$$\cancel{\text{rms}}\text{rmse=1.2}\cancel{\text{ psu}}. \qquad (1)$$

As ~~a~~ further verification ~~of the spatial representativeness of~~that the RF SST dataset is spatially representative, we compared it with the chronologically co-located UW SST that have been acquired onboard Trans Carrier ~~in~~across the whole study area. The two datasets ~~are~~were found to be almost identical (Fig. 2b; 3rd row Table 3).

The relationship between TA, SSS and SST is given by Eq. 2 according to:

$$\cancel{TA = 30.84SSS - 4.689SST + 3625.4}\ TA = 32.09SSS - 4.39SST + 1210\text{, } R^2\text{=0.}\cancel{91}\text{90; n=}\cancel{25;}$$

$$\cancel{\text{rms}}\text{23; rmse=13.0 } \mu\text{molkg}^{-1}. \qquad (2)$$

Alkalinity is a semi-conservative parameter and is normally modelled as linear functions of salinity (e.g. Millero et al., 1998; Bellerby et al., 2005; Nondal et al, 2009). However, ~~including SST as~~ using a ~~second fit~~ multi-parameter linear regression with SST and SSS as independent parameters improved the regression ~~staties~~statistics considerably~~.~~ (R^2=0.90; n=23; rmse=13.0 μmolkg^{-1}) compared to a linear regression with only SSS (R^2=0.67; n=23; rmse=24.0 μmolkg^{-1}). This is probably because SST ~~functions~~acts as an indicator of the effect of nutrient cycling on TA in agreement to what has been reported for the open Atlantic Ocean (Lee et al, 2006).

~~In order to assess the error introduced in pH(sst) and Ω_{Ar}(sst) we compared them withvalues based on the cruise and sensor data i.e. pH(sss) or pH~~To estimate a corresponding TA value for each UW fCO_2 observation obtained from MS Trans Carrier, we used salinity values estimated from the UW SST data by using Eq.1. The results (denoted as SSS(sst)) were then inputted into Eq.2 to obtain TA(sst) (see Table 2 for nomenclature). The fact that TA(sst) are based on SSS(sst) rather than measured SSS values introduce an additional error in the estimated pH(sst) and Ω_{Ar}(sst). In order to assess this error we compared pH(sst) and Ω_{Ar}(sst) with values based on the cruise data, i.e. pH(sss) and Ω_{Ar}(sss). First, we computed pH(sss) and Ω_{Ar}(sss) by combining all available measured SSS, estimated TA(sss) from Eq. 2, and co-located UW SST and UW fCO_2. Then we repeated the ~~calculation~~calculations, but this time we replaced the measured SSS with estimated SSS(sst) from Eq. 1 to compute pH(sst) and Ω_{Ar}(sst). The very strong linear relationships between the resulting values in Figs. 2c and 2d (circles) confirms that the estimated pH(sst) and Ω_{Ar}(sst) reproduce ~~very well~~closely the measurement-based values of pH(sss) and Ω_{Ar}(sss) for the whole study area. This is also evident from comparison statistics on rows 1 and 2 in Table 3 which show that measured based values are well correlated ($R^2 \approx 1$, $p<0.001$) with those estimated with rmse values of 0.003 and 0.04 for pH(sss) and Ω_{Ar}(sst), respectively, which are well within the aforementioned maximum target uncertainties developed by the C-CAN (last column in Table 3).

To quantify the total error associated with the pH(sst) and Ω_{Ar}(sst) estimates, we considered two main sources for error. First we computed the residuals (estimated – measurement-based) using the data ~~show~~shown in Figs. 2c and 2d~~.~~ (including the sensor data). The mean difference for the whole study area was 0.~~0018~~002 +/- 0.~~0043~~004 and 0.~~0048~~005 +/- 0.~~0777~~08 for pH and Ω_{Ar}, respectively. Thus, the maximum probable error from this source is 0.~~0061and~~006 and 0.~~083~~09 for pH and Ω_{Ar}, respectively. Additionally, we estimated that the computed and/or measured pH values included an error of 0.007 pH units, which under the current conditions (mean TA, fCO_2, SST, and SSS) would give an error of 0.038 in Ω_{Ar}. These two error estimates were ~~propagated to determine the total error in our estimates, which were found to be ±0.0093 and ±0.091 for pH and Ω_{Ar}, respectively. These error estimates are well within maximum target uncertainties developed by the Global Ocean Acidification Network (GOA-ON) and the California Current Acidification Network (C-CAN) of ±0.2 for Ω_{Ar}, which is indicative for maximum uncertainty of ±0.02 in pH (McLaughlin et al., 2015).~~combined (as the square root of sum of squares) to determine the total error in our estimates, which were found to be ±0.01 and ±0.1 for pH and Ω_{Ar}, respectively. It must be noted that the above total error was derived from all available observational data including the in situ sensor data (shown in Fig. 2c and in described section 2.3), which are the only wintertime measurements used in this study. This is important because the lack of wintertime data in the CS dataset which was used for the identification of AT-SSS/SST relationship (Eq. 2) means that wintertime AT(sst) might be overestimated so that corresponding pH(sst) values would be overestimated. In fact, during the aforementioned comparison between pH(sst) and measured pH we noted that for this particular dataset pH(sst) overestimated the measurements. However, the estimates were consistent with the observations to within the total error of ±0.01 pH units. Thus, by utilizing the above total errors, we also accounted for

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the effect of this possible caveat of Eq. 2 arising from the lack of wintertime TA measurements.

From the above we conclude that we are able to estimate pH(sst) and Ω_{Ar}(sst) across the whole study area and during all seasons with a total errors of ±0.01 and ±0.1 for pH and Ω_{Ar}, respectively.

3.2 Spatiotemporal variations

~~Fig. 2 shows the data collapsed into one virtual year~~ In order to present the mean ~~distribution~~distributions across the different fjords ~~and~~ throughout the annual cycle~~. There~~, we condensed the data into one virtual year by projecting it onto non-equidistant rectangular grids using the “weighted-average gridding” method of the Ocean Data View software (Schlitzer, 2015). As evident from Fig. 3, there is a clear seasonality (for the interannual changes see section 3.3) in both pH(sst) and Ω_{ar} (sst~~) (Fig. 3~~). The former varies between minimum values ~~(≈~~(8.05) around New Year to ~~the~~typical maximum values of around 8.~~2~~25, which occur during the late winter and/or spring (March-April). This increase is due to the reduction of DIC (Fig. 3d), induced by the phytoplankton spring bloom. This clearly counteracts and outweighs the negative effect on pH of warming the water column during this period. However, during April/May, the ~~latter processes~~effect of warming begins to dominate and pH(sst) starts decreasing. By September ~~SSTs~~the SST starts decreasing, while pH continues to drop. This is due to the effect of the fall mixing, which ~~brings up~~enables carbon~~-~~-rich coastal water to reach the surface layer, as mentioned in section 1, and ~~as~~is reflected by ~~the~~ increasing DIC during this period (Fig. 3d).

The mean distribution of Ω_{Ar}(sst) also shows a significant seasonal variation. There are three factors that drive this: (i) reduced concentrations of DIC by the spring bloom ~~drives up~~enriches the concentration of ~~the~~ carbonate ~~ion~~ions, (ii) Ω_{Ar}(sst) increases with rising temperature so that warming during the summer actually reinforces the increase of Ω_{Ar} initiated by biological carbon uptake, and (iii) reduced TA due to ~~runoffs also reinforces the Ω_{Ar}(sst) increase.~~freshwater input from runoff and mixing of deeper carbon-rich water into surface layer reduce Ω_{Ar}(sst) during fall. Thus, Ω_{Ar}(sst) reaches its maximum (>2.5) in July-September, when the spring bloom is over and pH has already started decreasing (Fig. 3a, c). The lowest Ω_{Ar}(sst) values (≈1.3-1.6~~), on the other hand,~~) occur during winter (January-March) when both pH and SST are low, ~~and~~despite TA is high~~.~~ due to high SSS values. The ~~mismatch~~decoupling in the seasonal cycles of pH and Ω_{Ar} clearly supports the case that pH alone is not an adequate measure of ocean acidification, in accordance with the C-CAN recommendation that “measurements should facilitate determination of Ω_{Ar} and a complete description of the carbonate system, including pH and pCO_2” (McLaughlin et al., 2015).

The above described seasonal variations in pH(sst) and Ω_{Ar}(sst) are spatially more or less coherent within the whole study area, except for the slight south-north gradient during May-September, with highest values south of 60°N (see Fig. 3a,c). All in all, during summertime the study area ~~embody~~embodied warm surface water with high Ω_{Ar}(sst) and intermediate pH(sst) values. During winter, the surface water is cold with low Ω_{Ar}(sst) and pH(sst) values.

3.3 Controls of seasonal variability and trends

To investigate the seasonal variability more thoroughly, we ~~arranged the data into~~computed monthly averages of pH(sst), SST, Ω_{Ar} (sst), and nDIC(sst) for one composite year. Then we quantified the effect of DIC, TA, SST and SSS on the monthly changes of pH(sst) and Ω_{Ar} (sst) in order to gain more insight into the processes governing the seasonal variations and their relative importance~~.~~ (Fig. 4).

For pH(sst) we used the decomposition method described in ~~(~~Lauvset et al~~.,~~. (2015) to quantify the importance of different parameters. This method estimates the monthly pH changes expected from corresponding changes observed in SST, SSS, DIC, and TA as well as their sum. The results are shown on Fig. 4 (~~left panels~~a-e) where it can be seen that DIC is the most important driver followed by SST and TA ~~(Fig. 4);~~, whereas SSS had a negligible effect (not shown) on the seasonal pH variations. We also note that the effects of SST and TA combined are nearly equal to, but opposite to that of DIC (Fig. ~~5c~~4c,d,e). As a result, the sum of all effects is <0.06 pH units, and compares well to the observed amplitudes (Fig. ~~5a~~4a), meaning that the decomposition model is able to account for the observed seasonal changes. Note also the TA control is identical to that of SST (Fig. ~~5c~~4c,e). The reason for this is that TA values used here are obtained from SSS(sst) and SST using Eq. 2, which in effect means that they are based on SST. This emphasizes the need for measured SSS and TA values when the objective is to analyze the controls of pH and Ω_{Ar}(sst) variations.

For Ω_{Ar}(sst) we investigated the importance of different ~~drivers by letting one of the drivers~~controls (DIC, TA, SST, SSS) ~~to vary~~by varying them independently over ~~its~~their observed range, while holding all other drivers constant, and re-computing Ω_{Ar}(sst). The magnitude of the standard deviation of the results is indicative ~~for~~of the importance of the

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varying ~~driver~~drivers. The result of this exercise is shown on Fig. ~~4(right panels).~~4f-i. Evidently, the variations of SST and SSS are the least important drivers for Ω_{Ar}(sst) seasonal changes, since varying these parameters ~~induce~~induces changes that are about an order of magnitude less than the observed seasonal amplitude in Ω_{Ar}(sst). On the other hand, changing DIC and TA (Fig. 4h,i) ~~induce~~induces changes that are comparable to the seasonal amplitude observed in Ω_{Ar}(sst) (Fig. 4a). We therefore~~,~~ conclude that seasonal changes in DIC ~~is~~and TA are the most important driver for changes in Ω_{Ar}(sst~~) followed by TA.~~).

From the above we conclude that the main drivers of Ω_{Ar}(sst) are DIC and TA, whereas for pH(sst), SST also ~~have~~has a significant impact~~. In terms of processes, this~~. This means that the formation and destruction of organic matter together with upwelling of carbon~~-~~rich coastal water, seasonal warming and cooling, and runoff inputs, are the processes that govern most of the seasonal variability of OA parameters within the study area. It then follows that interannual variability in the above processes would lead to corresponding variations in pH(sst) and Ω_{Ar}(sst~~-~~). Such interannual changes are evident from the monthly time series (Fig. S1), where the rate of seasonal ~~changes~~change differs between the years, both for SST and DIC normalized to the mean salinity (nDIC~~,~~) according to Friis et al. (2003). Additionally, for SST, the extreme values also change between years. These changes are in turn reflected in the pH(sst) and Ω_{Ar}(sst~~). However, the~~) for which the amplitude of the interannual variability (IAV), calculated as the temporal standard deviation, is presented in Table 4. For pH, IAV was normally much lower than the seasonal changes and ranged between 0.01 and 0.02 although higher changes were observed during the months April (0.04), and July and October (0.03). Similarly, for Ω_{Ar}(sst), the IAV was typically 0.1 which is much lower than the seasonal changes (section 3.2). Higher IAVs were observed for June (0.2) whereas November and December showed the lowest IAVs (<0.05). Quantitatively, the above IAVs are probably lower limits due to the use of constant empirical relationships for the estimation of SSS and AT (Eqs. 1 and 2). That is, there may be interannual changes in the relationship between SST and SSS (Eq. 1) and/or between SSS/SST and AT (Eq. 2). Thus, the use of a constant relationship over the years may have led to underestimation of the resulting IAV. Consequently, a comprehensive analysis of the drivers of the IAV was not carried in this study. However, sensitivity computations we performed showed that year-to-year differences in pH were related to those in fCO_2 rather than SST changes, whereas year-to-year differences in Ω_{Ar}(sst) were more related to those in SST than fCO_2. In any case, the observed year-to-year differences were not systematic, and no multiyear temporal trend was apparent from the 4-year time series analyzed in this study.

3.4 Inference of OA parameters from VOS underway data

Changes in the oceanic CO_2-system variables are related through ratios called Buffer Factors. Specifically, changes in Ω_{Ar} and pH in response to CO_2 variations can be quantified by partial derivatives (~~γ_{DIC}, β_{DIC}, and ω_{DIC}~~ γ_{DIC}, β_{DIC}, and ω_{DIC}), which have been defined by Egleston et al. (2010, their table 1), and the slope of these relationships can be expressed mathematically by:

$$\cancel{\partial \ln \Omega / \partial \ln CO2 = \gamma_{DIC} / \omega_{DIC}} = \frac{DIC - Alk_C^2 / S}{DIC - Alk_C P / HCO_3^-}$$

$$\partial \ln \Omega / \partial \ln CO2 = \gamma_{DIC} / \omega_{DIC} = \frac{DIC - Alk_C^2 / S}{DIC - Alk_C P / HCO_3^-} \quad (3)$$

$$\cancel{\partial \ln H^+ / \partial \ln CO2 = \gamma_{DIC} / \beta_{DIC}} = \frac{(DIC - Alk_C^2)/S}{(DICS - Alk_C^2)/Alk_C}$$

$$\partial \ln H^+ / \partial \ln CO2 = \gamma_{DIC} / \beta_{DIC} = \frac{(DIC - Alk_C^2)/S}{(DICS - Alk_C^2)/Alk_C} \quad (4)$$

where expressions for the carbonate alkalinity Alk_C and the parameters P and S are ~~given~~defined in Egleston et al. (2010~~) .~~). We have evaluated the right hand sides of Eqs. 3 and 4, using the CS cruise data, and the results showed that these quantities change only a few per cents (1.3 and 3.4 %, respectively) due to seasonal changes in the various variables. The ratio ~~γ_{DIC}~~ γ_{DIC} / ~~ω_{DIC}~~ ω_{DIC} changed by 1-6 % and ranged from -1.08 to -0.980, while ~~γ_{DIC}~~ γ_{DIC} / ~~β_{DIC}~~ β_{DIC} changed by 0.5-3 % and ranged from 0.84 to 0.88. This, together with the fact that equations ~~4~~3 and ~~5~~4 can be defined in terms of *ln*(*fCO*$_2$) instead of *ln*(*CO2*) (Egleston et al., 2010; Takahashi et al., 1993), suggests that in situations where underway surface fCO_2 and SST are frequently measured, while the CO_2 system is fully determined only occasionally, an easy way of interpolating the seasonality in pH and Ω_{Ar}, is to predict them from fCO_2. We have implemented this alternative way of estimating pH and Ω_{Ar} using the CS cruise data. For the estimation of Ω_{Ar} we used ~~fCO_{2ts}~~$fCO_{2@meanSST}$, which is fCO_2 adjusted to constant temperature ~~and salinity~~ (i.e. at mean SST~~ and SSS~~), because these ~~normalizations~~normalization improved the regression significantly. Since we were interested in pH and Ω_{Ar} we plotted these parameters directly against *ln*~~-~~(fCO_2) or *ln*(~~fCO_{2ts}~~$fCO_{2t@meanSST}$). The results are shown in Fig. 5 and conform to tight relationships between computed pH and *ln*(fCO_2) values (Fig. 5a), and between computed Ω_{Ar} and *ln*(~~fCO_{2ts}~~$fCO_{2t@meanSST}$) (Fig. 5b). Further, by using linear curve fitting we determined the relationships according to:

$$\cancel{pH = -0.389\ln fCO_{2ts} + 10.354\,;}\; pH = -0.389\ln fCO_2 + 10.354,\ R^2=0.99;\ n=28;$$

$$\cancel{rms}rmse=0.\cancel{0047}005, \qquad (5)$$

$$\cancel{\Omega_{Ar} = \exp(-0.738\ln fCO_{2ts} + 5.010)\,;}\; \Omega_{Ar} = \exp(-0.6741\ln fCO_{2\,\mathrm{at}\,meanSST} + 4.6422),$$

$$R^2=0.\cancel{98}94;\ n=28;\ \cancel{rms}rmse=0.\cancel{059}07, \qquad (6).$$

The magnitude of the residuals (computed – estimated) associated with pH and Ω_{Ar} values obtained from the above relationships were 0.~~0005~~000 +/- 0.~~0049~~005 and 0.~~012~~01 +/- 0.~~061~~06, respectively, which is comparable to the residuals associated with pH(sst) and Ω_{Ar}(sst) (~~section~~Table 3~~.3~~). An advantage of this procedure, however, is that it utilizes much tighter empirical relationships~~ and~~, involves fewer computational steps, and ~~thus~~is based on UW data, which are much more numerous than station data from oceanography cruises. Thus, it minimizes errors introduced by intermediate results such as the TA-SSS/SST regression in Eq. ~~2~~2 and/or seasonal data coverage. Furthermore, a direct comparison revealed that values obtained from Eqs. 5 and 6 were almost identical ~~with~~to those of ~~-~~pH(sst) and Ω_{Ar}(sst) (Fig. S2~~).~~) with values for R^2, p-value, and rmse of 1, 0, and 0.003 for pH; and 1, 0, and 0.02 for Ω_{Ar}. However, it is important to realize that for the above procedure too, a representative full description of the carbonate system is necessary for up-to-date determinations of Eqs. 5 and 6. Further, this calibration data ideally should include high frequency time series observations, since the slopes (i.e. Eqs. 3 and 4) change slightly with the carbonate system variables (e.g. DIC and TA, see Eqs. 3 and 4), which vary on multiple time scales (hours-days-years). Furthermore, the procedure is based on measurements of only one of the four master parameters constituting the carbonate system (i.e. fCO_2). Therefore, it only provides a way to interpolate pH and Ω_{Ar} values, but cannot support the analyses of controls that have been provided in the proceeding section.

From Fig. 5b we note that lowest Ω_{Ar} values are associated with the highest ~~fCO_{2ts}~~$fCO_{2@meanSST}$ values, which occur during late fall and winter. Monitoring of these extreme values are of special interest because: (i) during late fall and early winter the upwelling of carbon~~-~~rich water ~~to the surface~~ occurs ~~so that the~~and surface water also reflects the properties of the deeper water~~ properties~~, and (ii) the rate of change at this point (lowest Ω_{Ar}, highest ~~fCO_{2ts}~~$fCO_{2@meanSST}$) indicates the time when under-saturation of calcium carbonate can be expected in these waters. To estimate this for the current data we used Eq. 5 and the observation that the slope (i.e. Eq. 3) and intercept decreased by about 0.0008 and 0.004 for every 1 µatm increase in mean ~~fCO_{2ts}. We~~$fCO_{2@meanSST}$. We also took into account an uncertainty of ±0.2 in the Ω_{Ar} estimates and found that Ω_{Ar} becomes undersaturated (<1) when mean ~~fCO_{2ts}~~annual $fCO_{2@meanSST}$ is about ~~300~~310±70 µatm higher than its present value~~.~~ (310 µatm). For business as usual emission scenario (RCP 8.5), this is equivalent to about year 2070±10 if we assume that the development in the ocean follows that of the atmosphere (i.e. constant disequilibrium between ocean and atmosphere).

4. Summary and concluding remarks~~:~~

On the basis of four years of weekly underway fCO_2 and SST data combined with ~~less frequent~~sporadic data from research cruises, the ocean acidification parameters pH(sst) and Ω_{Ar}(sst) have been estimated and analyzed for western Norway fjords stretching over more than 60 km from the Korsfjord, through Langenuen strait, to southern parts of the Hardangerfjord. The total errors associated with the estimated values, ±0.~~0093~~01 and ±0.~~090~~1 for pH and Ω_{Ar}, were ~~an order of magnitude less~~about 50% lower than the maximum target uncertainties developed by the Global Ocean Acidification Network.

Strong seasonal variations, more or less spatially coherent over the whole study area, were found for OA parameters in the surface waters of the fjords. These changes were governed mainly by the formation and decay of organic matter, vertical mixing with deeper carbon rich coastal water, and the seasonal changes in SST and SSS. The annual mean pH was 8.13, and this parameter varies typically between minimum values (≈8.05) around January to maximum values of around 8.2, which occur during the spring and/or late winter (March-April) as a consequence of the phytoplankton spring bloom~~, which~~ that reduces DIC~~ levels~~. However, sometime during April/May, the effect of warming starts to dominate, and pH(sst) starts decreasing. Later during fall, deepening of the mixed layer ~~brings up~~allows carbon~~-~~rich coastal water ~~to~~mix into the surface, ~~and reinforces the decrease in pH,~~ which ~~continuous throughout fall~~reduces pH until the low winter values are reached again.

The mean value of Ω_{Ar}(sst) was found to be 2.21, and it reached its maximum (>2.5) in mid to late summer (July to September), when the spring bloom is over and pH has started to

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decrease. The lowest Ω_{Ar}(sst) values (≈1.3-1.6), on the other hand, occurred during winter (January-March), when both pH and SST are low, and DIC is at its highest.

~~Within the study area,~~Strong correlations of pH and Ω_{Ar} ~~have been found to correlate strongly~~ with fCO_2 and ~~fCO_{2ts}~~$fCO_{2@meanSST}$ (fCO_2 adjusted to the mean temperature ~~and salinity~~), respectively~~. These correlations~~ provide an approach to interpolate pH and Ω_{Ar} over large areas in the fjords of western Norway where underway measurements of fCO_2, SST, and SSS are available. However, both the slopes and the intercepts of these correlations vary slightly with DIC and TA. Therefore, the most accurate interpolations will be achieved if the relationships are calibrated with high frequency observations of the complete carbonate system, measured at few strategically placed fixed stations.

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The Ω_{Ar} - ~~fCO_{2ts}~~$fCO_{2@meanSST}$ relationship, and the rate of change of its slope and intercept with DIC, have been used to project the time when under-saturation of calcium carbonate ~~can~~could be expected to occur in the study area. This is expected to occur in the year 2070, if we assume business as usual emission scenario (RCP 8.5), and that oceanic ~~development of fCO_2 follows~~CO_2 concentrations follow that of the atmosphere (i.e. constant disequilibrium between ocean and atmosphere).

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Tables:

Table 1: Details ~~about~~of the CarboSchools (CS) and Raunefjord (RF) cruise datasets. The plus sign denotes the parameters for which sampling/measurement were carried out. For the RF dataset, each data point represents the average of five measurements acquired in the upper five meters.

Datasett; area	Date(m/d/y)	Lon (E)	Lat (N)	Depth (m)	DIC	TA	SST	SSS	Reference/ originator
CarboSchools (CS); Korsfjord/Raunefjord	04/13/2007	5.19	60.34	1	+	+	+	+	I. Skjelvan
	04/13/2007	5.18	60.17	1	+	+	+	+	
	04/25/2007	5.19	60.34	1	+	+	+	+	
	04/25/2007	5.17	60.17	1	+	+	+	+	
	09/04/2008	5.18	60.33	1	+	+	+	+	
	03/12/2009	5.17	60.15	1	+	+	+	+	
	03/12/2009	5.18	60.32	1	+	+	+	+	
	03/12/2009	5.17	60.17	1	+	+	+	+	
	03/12/2009	5.18	60.33	1	+	+	+	+	
	08/25/2009	5.17	60.17	1	+	+	+	+	

	08/24/2009	5.18	60.16	1	+	+	+	+	
	08/24/2009	5.18	60.16	1	+	+	+	+	
	08/24/2009	5.19	60.34	1	+	+	+	+	
	08/25/2009	5.19	60.34	1	+	+	+	+	
	08/25/2009	5.2	60.34	1	+	+	+	+	
	08/25/2009	5.19	60.33	1	+	+	+	+	
	08/27/2009	5.19	60.33	1	+	+	+	+	
	08/27/2009	5.19	60.33	1	+	+	+	+	
	08/27/2009	5.18	60.17	1	+	+	+	+	
	08/27/2009	5.18	60.17	1	+	+	+	+	
	08/27/2009	5.18	60.17	1	+	+	+	+	
	08/27/2009	5.2	60.33	1	+	+	+	+	
	09/08/2010	5.2	60.33	1	+	+	+	+	
2015; Korsfjord	09/29/2015			5	+	+	+	+	I. Skjelvan / A. Omar
2015; Langenuen	09/29/2015			5	+	+	+	+	I. Skjelvan / A. Omar
2015; Hardangerfjord	09/29/2015			5	+	+	+	+	I. Skjelvan / A. Omar

Table 1(~~continue~~continued)

Datasett; area	Date(m/d/y)	Lon_E	Lat_N	Depth (m)	DIC	TA	SST	SSS	Reference/ originator
RF; Raunefjord	01/03/2007			1-5			+	+	S. R. Erga / J. Egge
	01/23/2007			1-5			+	+	
	02/13/2007			1-5			+	+	
	02/27/2007			1-5			+	+	
	03/07/2007			1-5			+	+	
	03/13/2007			1-5			+	+	
	03/27/2007			1-5			+	+	
	04/10/2007			1-5			+	+	
	04/17/2007			1-5			+	+	
	04/23/2007			1-5			+	+	
	05/08/2007			1-5			+	+	
	05/19/2007			1-5			+	+	
	06/05/2007			1-5			+	+	
	06/12/2007			1-5			+	+	
	06/19/2007			1-5			+	+	
	08/31/2007			1-5			+	+	
	09/04/2007			1-5			+	+	
	09/11/2007			1-5			+	+	
	09/18/2007			1-5			+	+	
	09/26/2007			1-5			+	+	

10/02/2007	1-5	+	+
10/09/2007	1-5	+	+
10/18/2007	1-5	+	+
10/31/2007	1-5	+	+
11/27/2007	1-5	+	+
12/11/2007	1-5	+	+
01/02/2008	1-5	+	+
02/05/2008	1-5	+	+
02/21/2008	1-5	+	+
03/05/2008	1-5	+	+
03/11/2008	1-5	+	+
03/25/2008	1-5	+	+
03/31/2008	1-5	+	+
04/08/2008	1-5	+	+
04/22/2008	1-5	+	+
04/29/2008	1-5	+	+
05/06/2008	1-5	+	+
05/13/2008	1-5	+	+
05/20/2008	1-5	+	+
05/27/2008	1-5	+	+
06/04/2008	1-5	+	+
06/11/2008	1-5	+	+
06/17/2008	1-5	+	+
06/24/2008	1-5	+	+
07/01/2008	1-5	+	+
07/08/2008	1-5	+	+
07/16/2008	1-5	+	+
08/12/2008	1-5	+	+
08/19/2008	1-5	+	+
08/26/2008	1-5	+	+
09/02/2008	1-5	+	+
09/09/2008	1-5	+	+
09/16/2008	1-5	+	+
09/23/2008	1-5	+	+
09/30/2008	1-5	+	+
10/07/2008	1-5	+	+
10/14/2008	1-5	+	+
10/21/2008	1-5	+	+
11/04/2008	1-5	+	+
11/20/2008	1-5	+	+
12/19/2008	1-5	+	+

Table ~~3~~2: Overview of the symbols used for quantities estimated and/or derived from the measurement-based variables SSS, SST, TA, pH, DIC, fCO_2, and Ω_{Ar}.

Symbol	**Meaning**
TA(sss)	TA values estimated from measured SSS and SST using Eq. 2.
pH(sss), Ω_{Ar}(sss)	pH, and Ω_{Ar} values estimated by combining TA (sss) and fCO_2.
SSS(sst)	SSS values estimated from SST using Eq. 1.

TA(sst)	TA values determined from estimated SSS(sst) and SST using Eq. 2.
pH(sst), Ω_{Ar}(sst), DIC(sst)	Values of pH, Ω_{Ar} and DIC that have been obtained by combining TA (sst) , fCO_2 and ancillary variables.
fCO_{2t}	fCO_2 at the mean temperature
fCO_{2ts}	fCO_2 at the mean temperature and salinity
nDIC	DIC normalized to the mean salinity

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Table 3: Results of the comparisons between measured-based and estimated values for pH, Ω_{Ar}, SST (°C), and SSS. For the first three parameters, the statistics of the linear relationships depicted on Fig 2b-2d are listed. For SSS, monthly averaged data are compared to estimates obtained with Eq.1 using monthly SST. For SST, the comparison is carried out to verify that measurements from Raunefjord are representative for the whole study area (i.e. UW_SST can be estimated by RF_SST), which is implicitly assumed by the use of Eq.1. R^2 is the coefficient of determination, and “rmse” denotes the root-square-mean error. The latter is compared against benchmarks derived from maximum target uncertainties (Max. uncertainty) developed by Ocean Acidification Networks (section 3.1). The *p-value* is the probability of no linear relation between the estimated and measurement-based values.

Compared variables	Comparison statistics				Benchmarks
	R^2	p-value	# points	rmse	Max. uncertainty
pH_meas/comp. and pH(sst)	1.00	<0.001	106	0.003	±0.02
Ω_{Ar}_computed and Ω_{Ar}(sst)	0.98	<0.001	106	0.04	±0.2
UW_SST and RF_SST	0.95	<0.001	61	0.49	±1.25
SSS and SSS(sst)	0.65	0.002	12	0.3	±1.8

Table 4: Monthly mean values for pH(sst) and Ω_{Ar}(sst) and associated interannual variability (IAV), computed as standard deviations, in the study area for the period 2005-2009.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
pH(sst)	Mean	8.08	8.10	8.16	8.19	8.18	8.15	8.15	8.17	8.14	8.11	8.10	8.08
	IAV	<0.01	0.01	0.04	0.01	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02
Ω_{Ar}(sst)	Mean	1.7	1.7	1.9	2.1	2.3	2.4	2.6	2.7	2.4	2.2	1.9	1.8
	IAV	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	<0.05	<0.05

Figure texts:

Fig. 1: An overview map of western Norway with a detailed map of the study area showing the positions from ~~which~~where cruise and underway data have been acquired. The ~~tick~~thick grey arrow indicates the approximate position of the Norwegian Coastal Current (NCC).

Fig. 2: A) RF SSS as a function of SST (filled symbols) with the regression line described by Eq.1. Sampling month is indicated by the color of the data points. The CS (dots), 2015 (squares), and sensor (stars) datasets are also shown for comparison with the regression line. **B)** Compares RF SST with chronologically co-located UW SST acquired from the whole study area during 2008 (blue) and 2007 (red). **C**) Compares pH(sst) with pH values that have been measured or computed from TA and DIC. Symbols are as in Fig. 1. **D**) Compares Ω_{Ar}(sst) with Ω_{Ar} values that have been computed from measured TA and DIC or from measured pH and UW fCO_2. Symbols are as in Fig. 1.

Fig. 3: A) Estimated pH(sst~~) and~~), B) UW SST, C) estimated Ω_{Ar}(sst~~)~~), and D) estimated DIC which have been normalized to the mean salinity of 30.5 as a function of latitude and time of the year. All data from 2005-2009 have been ~~collapsed~~condensed into one virtual year to resolve the spatial and seasonal variations.

Fig. 4: left panel: Monthly pH changes (ΔpH) as observed (**A**) and expected due to: sum of all derivers (**B**), SST changes (**C**), DIC changes (**D**) and by TA changes (**E**). **right panel:** Standard deviations in monthly mean Ω_{Ar} as a result of variations in all parameters (**F**) or only in SST (**G**) in DIC (H) in TA (**I**).

Fig. 5: A) and B) pH and Ω_{Ar} from CS (dots) and 2015 (red squares) cruises plotted as a function of *ln*(fCO_2) and *ln*(~~$nfCO_{2ts}$~~$fCO_{2@meanSST}$), respectively.

FigS1: Time series of monthly variations in **A**) pH(sst), **B)** SST, **C**) Ω_{Ar}(sst) and **D**) nDIC for the whole study area in 2005-2009.

FigS2: A) compares pH(sst) with pH values obtained from Eq. 5 (y-axis). **B**) Compares Ω_{Ar}(sst) with values obtained from Eq. 6 (y-axis).

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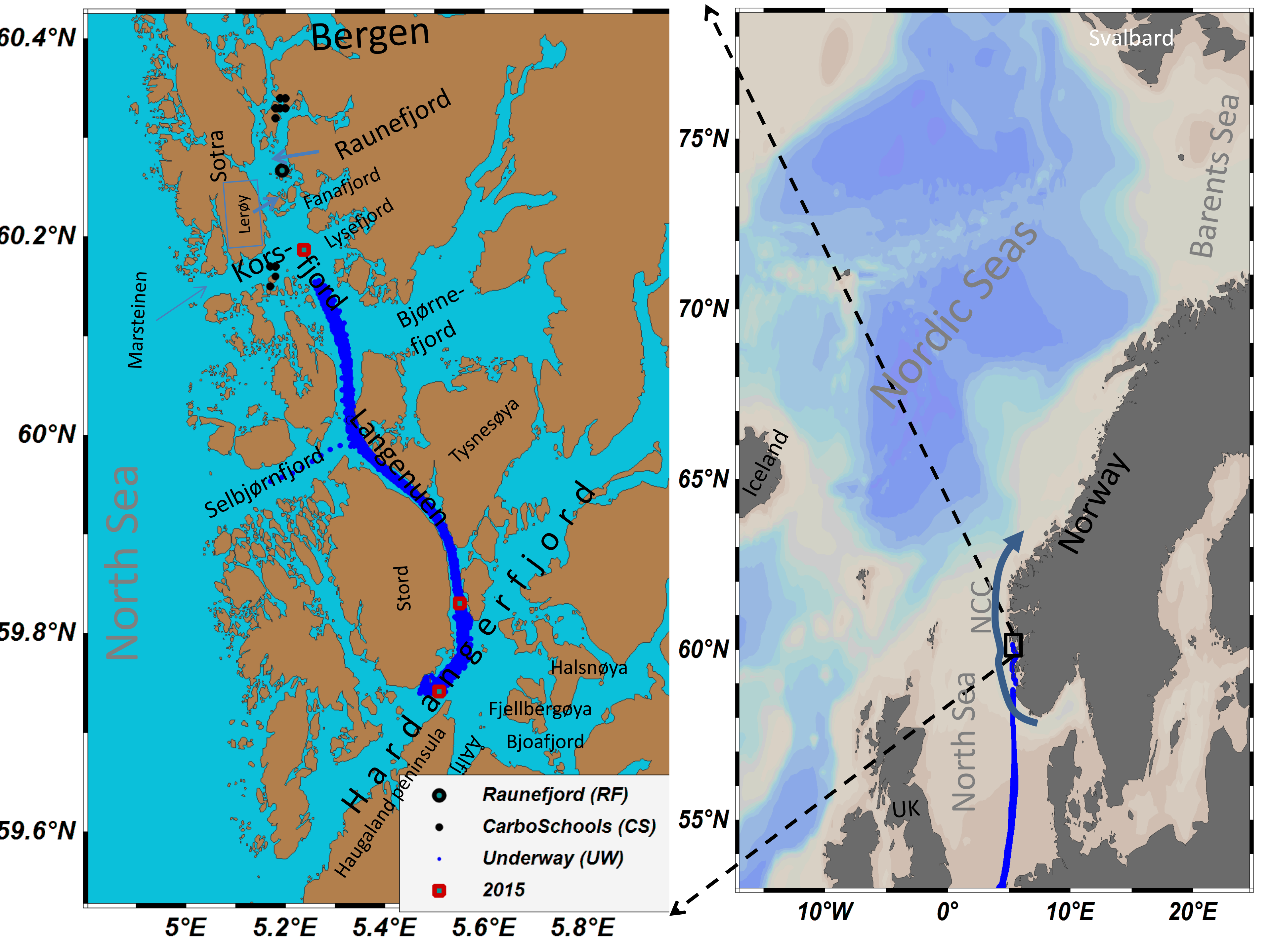
Bergen
Raunefjord
Sotra
Lerøy
Fanafjord
Lysefjord
Korsfjord
Marsteinen
Bjørnefjord
Tysnesøya
Langenuen
Selbjørnfjord
North Sea
Stord
Hardangerfjord
Halsnøya
Fjellbergøya
Bjoafjord
Haugaland peninsula
Raunefjord (RF)
CarboSchools (CS)
Underway (UW)
2015
60.4°N
60.2°N
60°N
59.8°N
59.6°N
5°E
5.2°E
5.4°E
5.6°E
5.8°E
Svalbard
Barents Sea
Nordic Seas
Iceland
Norway
NCC
North Sea
UK
75°N
70°N
65°N
60°N
55°N
10°W
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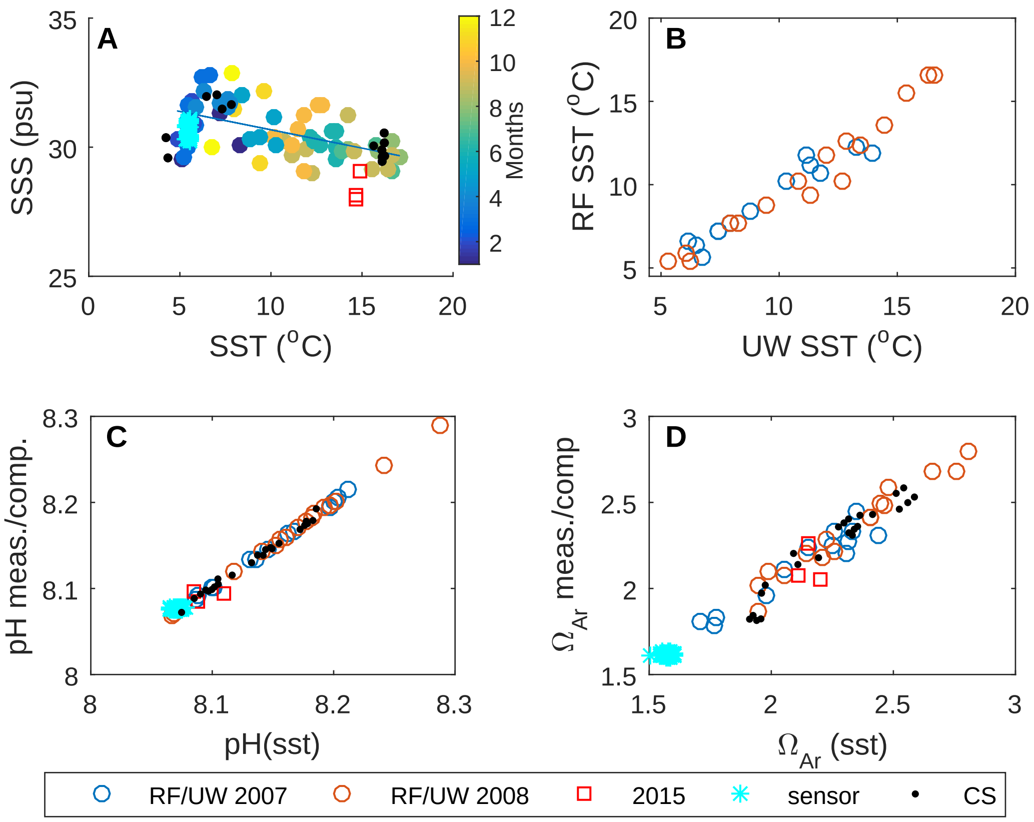
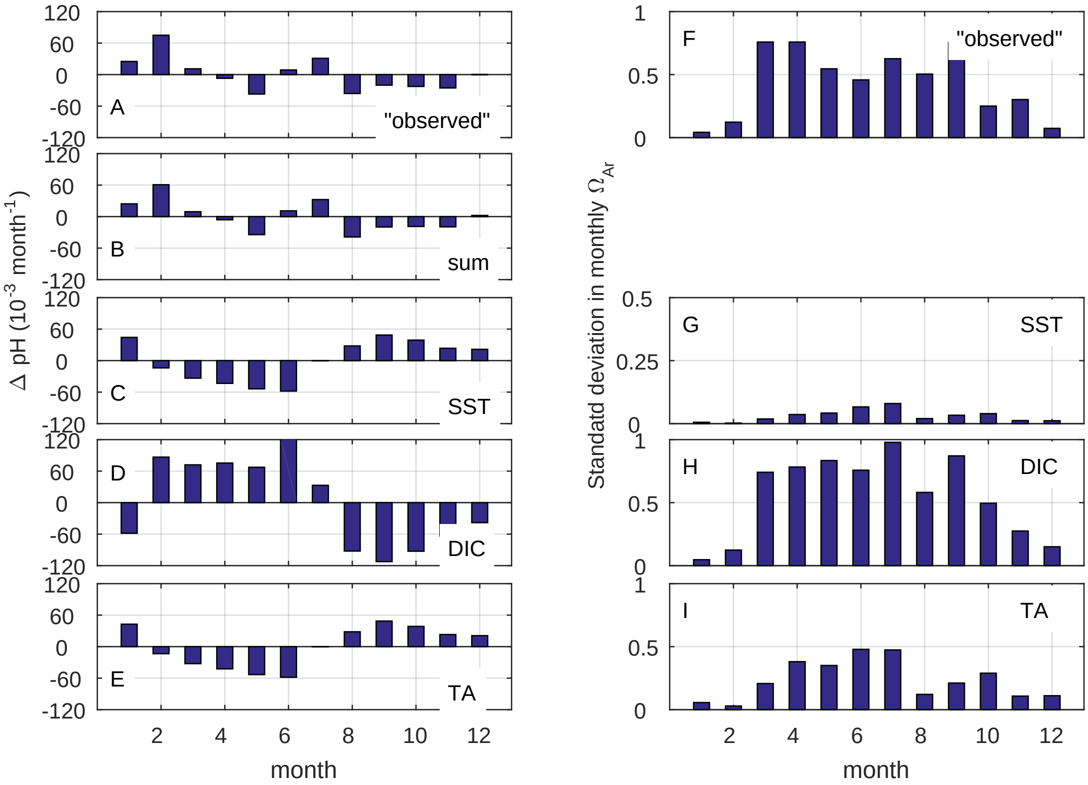
20°E

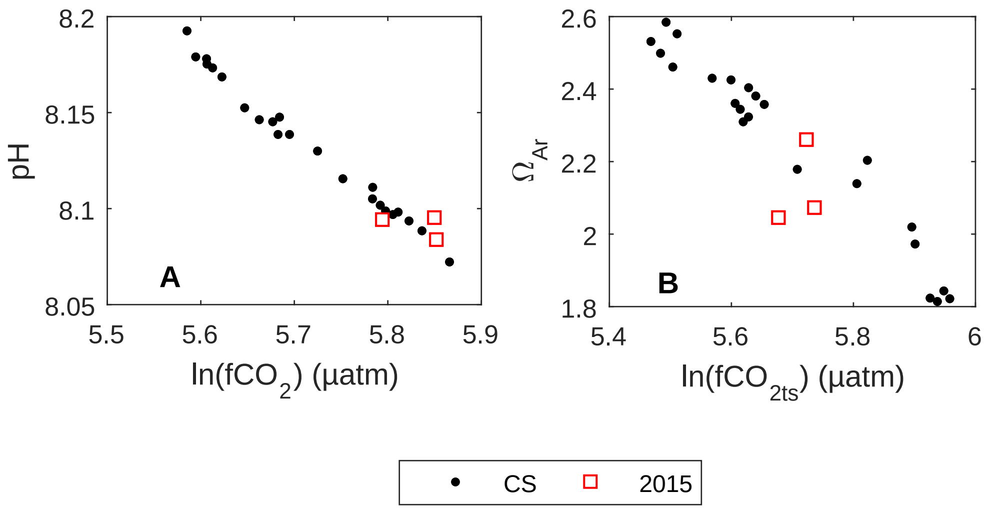


A
SSS (psu)
SST (^oC)
Months
B
RF SST (^oC)
UW SST (^oC)
C
pH meas./comp.
pH(sst)
D
Ω_{Ar} meas./comp
Ω_{Ar} (sst)
RF/UW 2007
RF/UW 2008
2015
sensor
CS

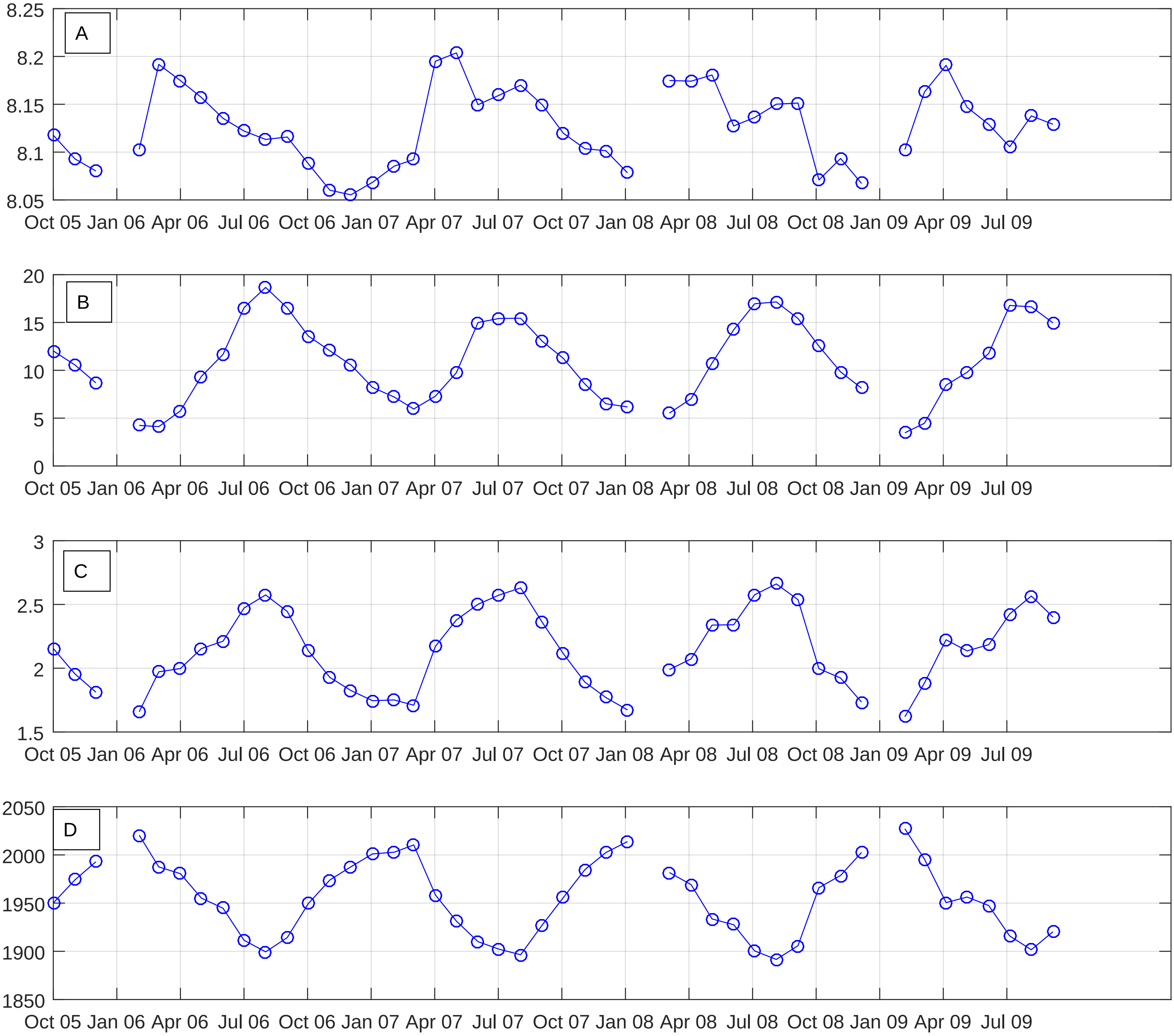

A
B
C
D
60.2°N
60°N
59.8°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
8.35
8.3
8.25
8.2
8.15
8.1
8.05
20
15
10
5
3.5
3
2.5
2
1.5
2050
2000
1950
1900
1850
1800
Ocean Data View

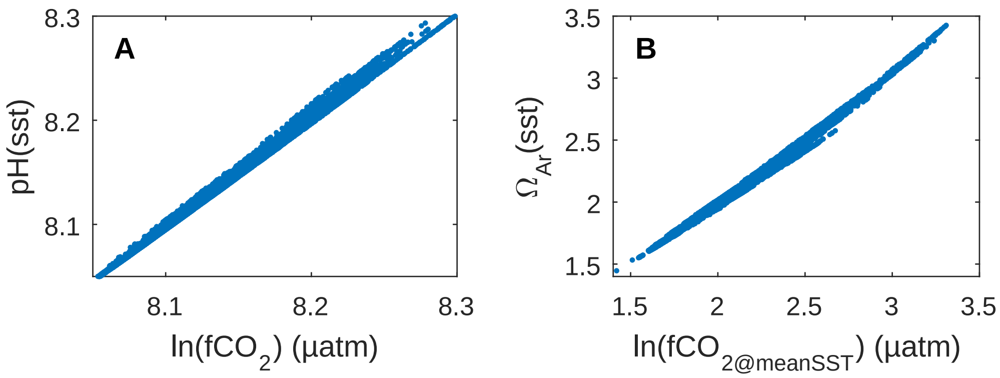


120
60
0
-60
-120
A
"observed"
B
sum
C
SST
D
DIC
E
TA
Δ pH (10^{-3} month^{-1})
2
4
6
8
10
12
month
1
0.5
0
F
"observed"
G
SST
0.25
H
DIC
I
TA
Standatd deviation in monthly Ω_{Ar}



A
pH
8.2
8.15
8.1
8.05
5.5
5.6
5.7
5.8
5.9
$\ln(fCO_2)$ (µatm)
B
Ω_{Ar}
2.6
2.4
2.2
2
1.8
5.4
5.6
5.8
6
$\ln(fCO_{2ts})$ (µatm)
CS
2015


A
B
C
D
8.25
8.2
8.15
8.1
8.05
20
15
10
5
0
3
2.5
2
1.5
2050
2000
1950
1900
1850
Oct 05 Jan 06 Apr 06 Jul 06 Oct 06 Jan 07 Apr 07 Jul 07 Oct 07 Jan 08 Apr 08 Jul 08 Oct 08 Jan 09 Apr 09 Jul 09


A
8.3
8.2
8.1
pH(sst)
8.1
8.2
8.3
ln(fCO2) (µatm)
B
3.5
3
2.5
2
1.5
ΩAr(sst)
1.5
2
2.5
3
3.5
ln(fCO2@meanSST) (µatm)