

## **Biogeosciences manuscript bg-2020-70**

“A regional hindcast model simulating ecosystem dynamics, inorganic carbon chemistry and ocean acidification in the Gulf of Alaska” by Hauri et al.

Dear Dr. Landschützer,

We would like to thank you for your time reading our manuscript and responses to the reviewers. We appreciate your concerns regarding our colorbars, but would like to take this opportunity to explain why it is important to us to use the red-yellow-blue colorbars for this data, rather than applying a monotone sequential colorbar as suggested by you and one of the reviewers. In contrary to what you stated in your comment, perceptual research shows that the human eye is more sensitive to differences in luminance (dark to light to dark) than to hue and no difference in luminance (dark to light; Zeller and Rogers, 2020 and citations therein). Patterns are therefore more visible in the red-yellow-blue figure than the yellow-green figure. In Zeller and Rogers (2020) it is also mentioned that “The same colormap applied to a diverse array of data gets monotonous and confusing”. As such, the authors argue that colormaps should be individually tailored to each dataset to present the features discussed in the article. Using adequate colormaps is an important form of communication of the science, which should be left to the scientist who knows the dataset best. We have used this colormap in multiple presentations and papers, including one published in this journal (Hauri et al., Biogeosciences, 2013, or e.g. Gruber et al., Science, 2012; Hauri et al., Nature Climate Change, 2016) and have received a surprising amount of positive feedback from the ocean acidification and inorganic carbon community about the clarity of our colormaps and presentation of the data.

Keeping this in mind, we would like to ask you to accept the current version of the figures with the red-yellow-blue colorbars.

Best regards,  
Claudine Hauri and co-authors

### References:

Zeller, S., and D. Rogers (2020), Visualizing science: How color determines what we see, *Eos*, 101, <https://doi.org/10.1029/2020EO144330>.

### **Point-by-point response to the reviews**

We thank the reviewers for assessing our manuscript and constructive comments, which have further improved our work. The reviewer comments are given in black and our reply in blue.

#### Detailed response to reviewer’s comments: Referee #1

##### General Comments:

This manuscript evaluates the performance of a new implementation of the ROMS model for the Gulf of Alaska region that includes ocean biogeochemistry and a high resolution

terrestrial hydrological model. The article is well organized and the writing is clear. The authors evaluate model biogeochemical performance against a suite of observed parameters and dataset types. I have only minor comments for the authors to consider as well as a few technical corrections.

We thank the referee for this positive comment.

Specific Comments:

Is the model run time period (1980-2013?) noted explicitly anywhere?

We added this information to the abstract p.1 l. 9: “To improve our conceptual understanding of the system we conducted a hindcast simulation from 1980 to 2013.”

And also to the main text P.6 L.10 : “After a model spin-up of 10 years, the hindcast simulation (1980 to 2013) was forced at the surface with three-hourly winds, surface air temperature..”

Page 6, Line 6: Does this mean that you do not correct tracer values for dilution effects caused by precipitation?

Yes, correct. To clarify we added “...does not change any volume or dilute any other tracers, such as DIC and TA.”

This is also a new discussion point:

p. 24, l. 35: Precipitation is only counted as negative salt flux and does not change the volume or dilute any other parameters in this current GOA-COBALT model version. While the decrease in salinity increases  $\Omega_{arag}$  and pH, and decrease  $pCO_2$  (Figure 14), our model does not account for the diluting effect of low TA and DIC rainwater. Annual mean riverine input into our model domain is 1.5 times higher than annual mean precipitation across the first 100 km along the coast and up to 7 times higher across the first 10 km along the coast. Model cells in vicinity of large rivers, such as the Copper River, receive up to three orders of magnitude more freshwater from rivers than from precipitation. Furthermore, the modeled surface salinity pattern closely reflects the influence of riverine input (Figure 13), whereas the precipitation pattern is not mirrored (not shown). Therefore, the diluting effect of precipitation on TA and DIC therefore seems to be negligible compared to the large volumes of water coming in from the thousands of streams and rivers along the coast. However, this hypothesis still needs to be tested especially because rain may increase in the future as a result of climate change (Mcafee et al., 2014).”

Figure 11: The TA/DIC colorbar seems to oppose intuition (high = red, low = blue).

We chose red for low because that means there is more DIC and less TA in the system, leading to lower aragonite saturation state, which corresponds with the colorbars used in figures 4 – 9.

Page 17, Line 9: The April pH range is 0.02 (8.08 to 8.10) while the August pH range is 0.09 (8.07 to 8.16). These values are not similar. The latter represents a 77% larger  $[H^+]$  range, which agrees well with the 74% larger omega range in August than

in April. As written, the manuscript text is not incorrect; however, it also does not precisely describe the differing chemical conditions (ranges) between months. This is a good point. The increase of range from April to August is just as large in pH as in omega. We adjusted the text accordingly:

Now p. 20 l. 8 “Surface  $\Omega_{\text{arag}}$  ranges between 1.14 and 2.5, pH between 8.07 and 8.16, and pCO<sub>2</sub> between 205 uatm and 333 uatm, reflecting the influence of freshwater in fall...”

Section 5: This section is not very clear. I would avoid using “positive effect” and “negative effect” and instead state whether decreases in salinity lead to decreases or increases in the parameter of interest.

We followed this advice as much as possible, however, using “positive and negative effect” could not always be avoided.

p.21 l. 1ff: “The linear Taylor decomposition indicates that decreasing salinity increases both,  $\Omega_{\text{arag}}$  and pH, while mixing with low TA and DIC freshwater end members decreases  $\Omega_{\text{arag}}$  and pH ... The increase in pH due to decreasing salinity is much stronger than for  $\Omega_{\text{arag}}$ , thereby cancelling or even counteracting, depending on the freshwater end member, the decrease in pH due to mixing... In contrast,  $\Omega_{\text{arag}}$  is more strongly affected by mixing than by salinity, resulting in a decrease of  $\Omega_{\text{arag}}$  by about 1 unit. In contrast to  $\Omega_{\text{arag}}$  and pH, decreasing salinity strongly decreases pCO<sub>2</sub>, which is also supported by, but to a lesser extent, a decrease of pCO<sub>2</sub> due to mixing with low TA and DIC end members... .

Additionally, on Page 17, Line 12, you could summarize your finding to assist in clarifying the point: “Thus, the influence of salinity on pH works to counteract the influence of low TA/DIC freshwater input on pH such that the observed pH exhibits no correlation with the observed salinity.”

Thank you for this suggestion! On p.21 l.5 we added: “Thus, the influence of salinity on pH works to counteract the influence of low TA and DIC freshwater end members on pH such that the observed pH exhibits no correlation with the observed salinity.”

Figure 12: August is a productive time period along the coastline based on Figure 3. Why then does “Biogeochemistry” in Figure 12 cause pCO<sub>2</sub> to be higher nearshore than offshore?

pCO<sub>2</sub> is higher offshore than nearshore – we reversed the colormap to clarify (now Figure 14. Biogeochemistry causes a relative increase in pCO<sub>2</sub> and decrease in pH and Omega because of net respiration during this time of the year. Strong phytoplankton blooms occur in April through June. In August, Chl-a levels are generally lower, with just a few exceptions in the very nearshore. This transition leads to an increase in DIC and therefore an increasing effect in pCO<sub>2</sub>.

Also, wouldn't “Mixing” with low TA/DIC freshwaters cause pCO<sub>2</sub> to increase relative to the offshore domain rather than decrease? Yes! Thanks for catching this as it was wrong in the text:

We changed it to (p.21 l.7): “In contrast to  $\Omega_{\text{arag}}$  and pH, decreasing salinity strongly decreases pCO<sub>2</sub>, which is counteracted to some degree by an increase of pCO<sub>2</sub> due to mixing with low TA and DIC end members and net respiration .... Deviations from the

shaded areas in Figure 13d are mainly driven by biogeochemistry, which decreases  $\Omega_{\text{arag}}$  and pH, and increases pCO<sub>2</sub> as a result of net respiration in August.

Page 21, Line 1: This should be altered to something like: “The observed seasonal relationships between omega, pH, and pCO<sub>2</sub> in freshwater influenced coastal waters off of Alaska are different from those found in other regions, such as the open ocean.” The actual relationships in your domain are the same fundamental thermodynamic relationships that apply everywhere. The unique drivers in your domain lead to less commonly observed variations in these parameters, however.  
We accepted the proposed change (p.24 l.11).

Page 21, Line 4: You might consider adding a sentence similar to this one (“This decoupling: : :”) to section 5.  
On p21, l.10 we added:” The additive effects of salinity and mixing with low TA and DIC freshwater lead to a decoupling of  $\Omega_{\text{arag}}$ , pH, and pCO<sub>2</sub>.”

Page 22, Line 2: Wouldn't this be “omega sensitive” organisms?  
We changed it to “some organisms”

Page 22, Line 4: Can you provide a reference for the pteropod comment?  
Done.

Technical Corrections:

Page 1, Line 17: Remove “simultaneously” or “also”.  
Done.

Figure 1: Text on the map is too small. Should there be blue regions on land?  
We replaced the text with roman numbers and added the legend in the figure caption. The turquoise regions on land are glaciated regions as indicated in the figure caption.

Page 4, Line 24: This text indicates that the southeast model domain extends to the Canadian-US border but this is not shown in Figure 1. Southeast does not need to be capitalized.  
We changed the text to be more precise (p.5 l.9): “The grid covers a large coastal area from the southern tip of Prince of Wales Island in the southeast to west of Sandpoint in the middle of the Aleutian Islands ...”

Table 1: There seems to be an issue with the symbols. It was not immediately clear what the small text below the table had to do with the table. Perhaps if the scalars were listed just below (closer to) the Table, or different symbols were used, it would be more obvious.  
We moved the symbols to the figure caption.

Table 2: Does “very small number” mean the magnitude of number or the number of observations constraining the model?  
“very small number” refers to the magnitude of number. We clarified in the table caption:



“The values of all other variables were initialized to a very small number ( $< 0.0001$ ).”

Figure 2: Does it make more sense to compare the observations in this figure to the same years of model output rather than the full model climatology (1980-2013)?

We are not comparing the full model climatology to the observations. Instead, we are comparing 2008-2012 observed and modeled climatologies with each other. This period was chosen because the data for this period is publically available. With these figures we are trying to evaluate whether the model is capable of reproducing the general patterns typical for May and September. Since it is a highly variable system we think that comparing climatologies is the most appropriate strategy to reach this goal.

Page 17, Line 12: In contrast, rather than in contrary.

Done

Page 18, Line 1: In contrast, rather than in contrary.

Done

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#### Detailed response to reviewer’s comments: Referee #2

##### 1 General Comments

Hauri et al. introduces a new ROMS configuration of the Gulf of Alaska (GOA-COBALT) that improves upon previous efforts by introducing variable riverine and glacial freshwater fluxes to the modeled region. This is a solid overview paper with extensive evaluation of the simulation.

However, I believe there are issues with vagueness/clarity on some key methods and statistics (e.g., end-member analysis, linear Taylor decomposition, and correlations). I've also suggested some significant changes to the figures, which lack important information (bias between model and observations) and also use inappropriate colormaps which hinder interpretability. Lastly, I have pointed out a number of technical errors and suggestions that should be addressed prior to publication. That being said, I believe GOA-COABALT will make an immediate impact on the community. Congratulations on a great model release!

We thank the reviewer for the great suggestions and positive comment!

##### 2 Specific Comments

1. I would recommend adding an additional sentence to the abstract to highlight the addition of variable freshwater forcing to this model. I know it's mentioned in L7-8, but it seems to be a substantial addition to regional modeling of the GOA and should be mentioned as such.

We added the following sentence (p.1 l.9): “The model was explicitly forced with temporally- and spatially-varying coastal freshwater discharges from a high-resolution terrestrial hydrological model, thereby affecting salinity, alkalinity, dissolved inorganic

carbon and nutrient concentrations, which represents a substantial improvement over previous GOA modelling attempts.”

2. It would be nice to include the model mesh in Fig. 1 to make clear the horizontal resolution of GOA-COBALT relative to the features of the GOA, especially given this paper is associated with the public release of the model. Also to make clear it's not e.g., telescopic. If 4.5 km is too fine to see in Fig. 1, you could have an inset where you zoom in on a sub-region and show the mesh.

We added an inset with the model mesh.

3. L19-23, p4: Can you give some approximation of what this vertical resolution is? E.g., N meters per grid cell in the nearshore and offshore.

We adjusted the text to clarify (p.5 l.5):

“The vertical discretization is based on a terrain-following coordinate system (50 depth levels), with increased resolution towards the surface and the bottom of the ocean. Due to shallower bathymetry, the shelf and coastal areas have higher vertical resolution. For example, in the shallowest areas (depth = 0.5 m), the vertical spacing is 0.01 m, while in the deepest water, the vertical spacing is 5 m in surface waters, expanding smoothly to over 300 m near the bottom.”

4. L6-7, pg. 6: Does this mean that precipitation does not affect DIC or TA through dilution?

Yes. We clarified (p.6, l.14): “Precipitation is solely counted as a negative salt flux and does not change any volume or dilute any other tracers, such as DIC and TA.”

This is typically standard in Earth System Models, while freshwater dilution from river inputs is less standard. Are there estimates for the impact of precipitation dilution vs. riverine/glacial dilution in the GOA? I.e., is it a negligible term relative to rivers and runoff? This should be clarified in the text.

We clarified in the discussion (p.24, l.35):

“Precipitation is only counted as negative salt flux and does not change the water volume or dilute any other parameters in this current GOA-COBALT model version. While the decrease in salinity increases  $\Omega_{arag}$  and pH, and decrease pCO<sub>2</sub> (Figure 14), our model does not account for the diluting effect of low TA and DIC rainwater. Modelled precipitation can be as high as 3 to 5 m<sup>3</sup> s<sup>-1</sup> near Yakutat. Mean riverine input is an order of magnitude higher and maximum riverine input can be as high as 8000 to 16000 m<sup>3</sup>/sec. The diluting effect of precipitation on TA and DIC therefore seems to be negligible compared to the large volumes of water coming in from the thousands of streams and rivers along the coast. However, this hypothesis still needs to be tested especially because rain may increase in the future as a result of climate change (Mcafee et al., 2014).”

5. L16-17, pg. 6: Could you expand further on how DIC was normalized using the anthropogenic CO<sub>2</sub> estimates?

We clarified in the text (p.7, l.1): “GLODAP DIC data, which was referenced to 2002, was normalized to 1980 using the anthropogenic CO<sub>2</sub> estimates for the GOA by (Carter

et al., 2017). Carter et al., (2017) suggest two different rates of depth-dependent increase of anthropogenic CO<sub>2</sub> per year for the period 1980 - 1999 and for 2000 - present. The anthropogenic CO<sub>2</sub> increase for the corresponding time period was added (or subtracted) in monthly increments from the reference year.”

6. L22-23, pg. 6: Could you briefly describe this simulation that initialized the other variables in the text? E.g. what model it was, what time the output spanned. Was this a climatology initialization, a restart file?

p.7, l. 9: All other variables were initialized based on a climatology from a Common Ocean-Ice Reference Experiment (CORE-II) forced GFDL-COBALT simulation (1988-2007) described in Stock et al., (2013).

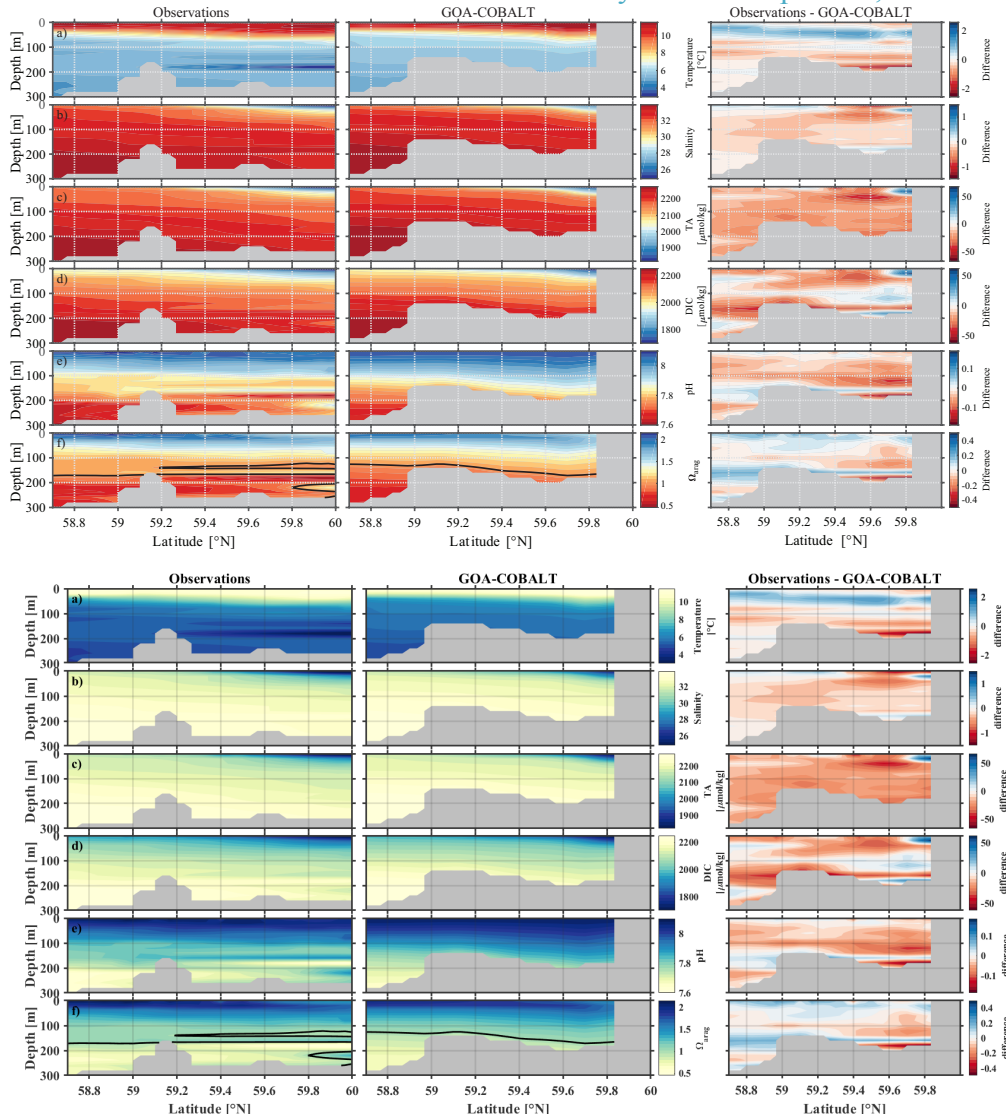
7. L30-31, pg. 6: I assume this sentence through the end of Section 3.1 is describing the land hydrography model reviewed in Danielson et al. If this is the case, could you make it slightly more clear that the remainder of this section is summarizing Danielson et. al? I was confused by the correlation and p-value reported here, thinking it was referring to GOA-COBALT. If that is what's actually happening here, it should be more clear whether this is a pattern correlation, temporal correlation, over what domain, etc.

We clarified by adding the bold sentence (p.7, l.19): “Our approach of using a hindcast simulation from a highly resolved land hydrography model (Beamer et al., 2016) to force the freshwater input was recently evaluated through comparison to salinity, temperature, velocity, and dynamic height observations (Danielson et al., in review). **The findings by Danielson et al., (in review) are summarized in the following paragraph.**”

8. I would suggest changing the colormaps for the majority of figures in this text. Thyng et al. [2016] provides a good overview of colormap selection in “How to select an honest, effective, colormap.” Every colormap used here is a red-to-blue diverging map, whereas most of this data is sequential and would be much more honestly portrayed on a sequential colormap. Some great colormaps available in python, Matlab, etc. are cmocean and Fabio Crameri's color maps. The main issue is that the red-to-blue colormaps diverge at an arbitrary value in this manuscript, causing a large visual distinction between red and blue regions that is not meaningful physically. The red-to-blue can be used for aragonite and in the case of anomalies, but should be centered around 1 for , since that is a critical threshold for that variable, and around zero for the anomalies. I imagine this sounds tedious, but I think it will drastically improve the visual presentation and interpretability of the output. More meaningful features will be apparent in the cross sections, e.g. in Figure 4, which will help the reader compare the model to observations. Below I compared a CESM hindcast run to ERSST observations as a demonstration. In the \_rst example I use a red-to-blue diverging colormap. In the second, I use a perceptually uniform sequential colormap. I think the advantages will be more clear in the cross-section maps, but this still shows the di\_ifferences and draws the eye away from the arbitrary divergent point at 15C

We thank the reviewer for this suggestion and we have given this point a lot of thought. We redid the figures using one of the suggested colormaps. However, we came to the

conclusion that more features are visible with the previously used red-yellow-blue colorbar and therefore decided to stick to this style. For comparison, see below.



- On a similar note, I am surprised that there is no third column in Figs. 2, 3, 4, 5, etc. showing the difference between the model and observations. Effort was made to interpolate the model and observations to the same grid, so it should be relatively straightforward to display the bias in the model by subtracting the two. I think showing this is crucial for the reader to see the regional expression and the magnitude of the bias. Currently, the reader relies on the author's highlighting of certain subregions of these biases in the text. For Figure 2 in particular, it's very hard to compare these by eye. On another note, in Figure 4, it looks like nearshore surface pH could be 0.2 units too acidic in the model, which would represent a 60% bias in the hydrogen ion concentration. Many of the quantitative arguments in the text about "overestimation" and "underestimation" will be made significantly more clear with the addition of a difference column (either raw or in percent bias)

We thank the reviewer for this suggestion and added a difference column to Figures 2, 3, 4, 5, 7, and 8.

10. Figs. 7 and 8: Is the white here due to missing data? If so, that should be made clear via something like gray or hatching since it could be misidentified as the value at the center of the colorbar. Although this would be alleviated in addressing (8).

We changed the white areas to grey areas to better indicate the missing data. This is now also described in the figure captions: "Grey areas show missing data."

11. L10, p14: Can you clarify in the text what these correlation coefficients represent? Is this the pattern correlation between the climatologies in the left and right columns of Figs. 4 and 5? Is this a temporal correlation of the transect average time series? What is the p-value for this correlation? I would suggest having a statistical analysis section of the methods that mentions your use of Pearson correlations, whether they are pattern or temporal correlations, and how you assess statistical significance. (See \_nal speci\_c comment as well regarding methods)

We clarified in the text (p. 13, 1.8): "Overall, the model does a reasonable job in simulating the spatial patterns of salinity, temperature, TA, DIC, pH, and  $\Omega_{arag}$  in spring and in fall, with statistically significant (p-value < 0.05) Pearson correlation coefficients between 0.75 and 0.95 (Figures 6a and b). The Pearson correlation coefficients and their corresponding p-values were calculated based on the climatologies presented in Figures 4 and 5."

12. L3-4, p15: Can you quantify this through, e.g. RMSE or a correlation of interannual variability? This section investigates selected case studies of years and variables but doesn't do a bulk quantification to assess model skill.

To better quantify the model's skill to reproduce observed interannual variability we added Figures 9 and 10, showing Hovmoeller and x-y plots of monthly anomalies. Table 3 also summarizes corresponding RMSE, Pearson correlation coefficients, p-values. We also rewrote section 3.4 to reflect these new figures and statistics.

13. L13-15, p15: Perhaps I am misreading this, but both photosynthesis and freshwater dilution should reduce DIC, and thus raise pH to more basic levels. So why is it surprising that pH is high, "despite the freshwater influence and its diluting character"? Or did you mean acidic by "high" here? Please clarify.

The sentence is correct. Freshwater dilutes DIC and TA, leading to decrease of pH and aragonite saturation state. This result depends on the DIC and TA endmembers and their TA/DIC ratio, which again depends on the geology of the watershed. In our case, the TA/DIC ratio of the freshwater is low, thus decreases pH and aragonite saturation state. However, because of primary productivity, DIC is decreased more relative to TA, which leads to a net increase in pH and aragonite.

14. I found Section 5 very hard to interpret, and suggest that it is re-written and the

methodologies here made more clear. Firstly, the end member analysis methodology should be made more clear. Admittedly I do not have a background in end member analysis, so perhaps it is clear to the informed reader what is happening here. As someone with a modeling background, I first thought “end member” implied that multiple simulations were run and one at the edge of the distribution of riverine boundary conditions was selected for analysis. It's unclear what “non-zero” DIC means when all of the DIC range in Table 2 is non-zero. In general, it needs to be spelled out that this is an end member mixing analysis (I assume), and more care should be taken explaining the methodology here. Secondly, the linear Taylor decomposition should also be spelled out. I don't think every step of Rheuban et al. (2019) needs to be replicated here, but it would be helpful to the reader to have some of the key equations and assumptions. Particularly that the sensitivity terms aren't explicitly calculated, how anomalies are generated, etc. I would suggest an additional section to the methods summarizing the end member analysis and linear Taylor decomposition.

We added more methodological detail (see below). However, since we followed the step-by-step methods published in Rheuban et al., 2019, we don't think it is necessary to repeat any of their equations (p.18, 1.13):

“Glacial freshwater is the most important driver of the near-shore inorganic carbon dynamics of the GOA in summer and fall. We further investigate the influence of coastal dilution from the rather acidic TA and DIC freshwater end member (Table 2) on surface  $\Omega_{\text{arag}}$ , pH, and pCO<sub>2</sub>. Following the step by step description in Rheuban et al., (2019) we used a linear Taylor decomposition to separate and analyze the controlling factors of the variability in surface  $\Omega_{\text{arag}}$ , pH, and pCO<sub>2</sub>. Offshore mixing endmembers of  $\Omega_{\text{arag}}$ , pH, and pCO<sub>2</sub> were determined from offshore DIC and TA in April and August with CO<sub>2</sub>sys.m (Lewis and Wallace, 1998; vanHeuven and Wallace, 2011) and were used as reference values. Anomalies from the reference value were calculated for each grid cell using a linear Taylor series decomposition, adding up the thermodynamic effects of temperature and salinity, the perturbations due to biogeochemistry, and conservative mixing with freshwater DIC and TA endmembers. For a more detailed description of the methodology the reader is referred to (Rheuban et al., 2019).”

### 3 Technical Comments

1. I find the first sentence of the abstract awkward: “The coastal ecosystem of the Gulf of Alaska (GOA) is especially vulnerable to the effects of ocean acidification and climate change that can only be understood within the context of the natural variability of physical and chemical conditions.” Is it the coastal ecosystem or the effects of OA/climate change that can only be understood within the context of natural variability? I wouldn't say that natural variability is a key topic addressed in this paper either. I would suggest revising this sentence to change its content or to make it more clear.

We rephrased the first few sentences to (p.1, 1.1): “The coastal ecosystem of the Gulf of Alaska (GOA) is especially vulnerable to the effects of ocean acidification and climate change. Detection of these long-term trends requires a good understanding of the system's natural state. The GOA is a highly dynamic system that exhibits large



inorganic carbon variability from subseasonal to interannual timescales. This variability is poorly understood due to the lack of observations in this expansive and remote region.”

The main reasons why we developed this model are to better understand the natural variability and long-term trends. This article focuses on introducing the formulation of the model as well as the simulated geographic patterns and seasonal dynamics; simulated long-term trends will be the focus of our next publication.

2. L3, pg1: iron enriched" should be iron-enriched" (and in other places in the manuscript).

Done

3. L7, pg1: “high resolution" should be “high-resolution." I think this is used four times more in the text with changing usage of \high resolution" vs. “high-resolution."

Done

4. L14, pg1: I would suggest dropping \As such,"

Done

5. L16, pg1: “CO2 sensitive" should be “CO2-sensitive" and elsewhere in the manuscript.

Done

6. Table 1: Is “alpha" supposed to be  $\alpha$ ? The formatting of this table is a bit difficult to interpret. E.g. the italicized sub-header, and it's not clear immediately that the a and b below explain the table values. Maybe this will be fixed on typesetting. We left alpha written out as it is in the model code. To be more consistent with the original model nomenclature we changed the headers to the following: “Parameter” to “Name” and “Symbol” to “Parameter”. We restructured the table a little and moved “a” and “b” into the figure caption.

7. L7-8, pg2: I think this would be cleaner with something like “... high physical, biological, and chemical spatiotemporal variability across the GOA continental shelf."

Done

8. L11, pg2: What is “its" referring to here? Grammatically it could relate to “this region" or “climate change and ocean acidification," among other interpretations. I would break L9-12 up into 2-3 sentences for clarity.

We changed it to (p.2 l.12): “The large natural variability and the lack of data for this region make it challenging to understand the inorganic carbon, nutrient, and ecosystem dynamics and predict the potential impacts of the regional manifestation of climate change and ocean acidification on fisheries, economies, and communities (Mathis et al., 2014). Therefore, expansion of the current observational and modelling efforts needs to be made a priority.”



9. L14, pg2: It might be helpful to spell out why a seasonal increase in vertical mixing would lead to reduced carbonate concentrations here, since this is early in the introduction. Also what does seasonal "increase" refer to? Does it increase from winter to summer, summer to winter? Is the seasonality of mixing increasing with time?

We changed it to (p.2, l.19): " This high latitude region is naturally low in  $\text{CO}_3^{2-}$  due to the increased solubility of  $\text{CO}_2$  at low temperatures, increased vertical mixing of  $\text{CO}_2$ -enriched deep water into the upper water column in winter, riverine and glacial inputs in summer and fall, and inner shelf dynamics that tend to retain coastal discharges close to shore ..."

10. L18, pg2: I find the use of "endowed" awkward here and elsewhere. I think it would be more simple to just say "contains low TA" or "is characterized by low TA" for example.

Done.

11. L20-21, pg2: I would split the last clause off to its own sentence. "exacerbating" should be "exacerbates."

Done.

12. L24-25, pg2: I would revise to something like the following for ease on the reader: "These two limiting nutrients lead to a phytoplankton community composition dominated by diatoms in the dFe-rich near-shore area and by small phytoplankton in the dFe-poor off-shelf area."

Done.

13. L4, p3: "impede" should be "impedes" in the current way its written. If you were to drop "coverage" it should be "impede."

Done.

L9, p3: I think "of the system" should be added to the end here. Or to expand more, mentioning that this is because the frequency of available observations causes aliasing issues or isn't sampled enough to cover the spatial and temporal decorrelation scales of the region.

Changed to (p.4, l.3): "These draw an incomplete picture of the spatial and temporal variability of the system because the low frequency of available observations causes aliasing issues."

L12, pg3: I would drop "successfully" here. How does one know that they are successful at representing the future?

Done.

16. L1, p4: Drop the comma following Ekman pumping.

Done.

17. L3-4, p4: I think this could be refined to “However, neither of these models simulate the influence of freshwater input along the coast, which exhibits high spatiotemporal variability.” This puts the emphasis on the fact that they don't simulate freshwater input, rather than mentioning the variability first.

Done.

18. L9, p4: Should read “long-term anthropogenic trend.”

Done.

19. L12-14, p4: This sentence is quite grammatically confusing as it stands. I suggest it is rewritten entirely.

We deleted this sentence and rephrased it at the end of the section (see answer to your next comment.)

20. L14-17, p4: I would end this summary with a sentence explaining how this expands on past modeling efforts for the GOA.

We added (p.4, l.28): “We expand on previous regional modelling efforts by using spatially and temporally variable freshwater forcing, parameterizing freshwater DIC, TA, and nutrients based on available seasonal observations, and conducting a multidecadal hindcast simulation. “

21. L23, p4: Should be “eddy-resolving.”

Done.

22. L23, p4: It might be worth explicitly mentioning that this resolves coastal upwelling scales in this region.

Changed to (p.5, l.8):” The horizontal resolution is eddy-resolving at 4.5 km, which resolves regional coastal upwelling scales.”

23. L27, p4: What does “the model” refer to here? Multiple experiments with the Coyle et al. model, or multiple experiments with multiple GOA models?

We rewrote the paragraph to clarify (p.5, l.11):

The current model configuration is based on Danielson et al., (2016), although with a larger grid extent and a lower horizontal resolution to accommodate the computationally intense ecosystem model. Our GOA-COBALT domain is based on Coyle et al., 2012, however including the Alexander Archipelago. Experiments with the Coyle et al., (2012) model have shown that the model had insufficient near-surface vertical mixing, leading to overly fresh water at the surface which is challenging to mix down. In order to improve on our surface mixing, we added the parameterization of Li and Fox-Kemper (2017).

24. L33, p4: Is there supposed to be a comma following “energy-balance” in \energy-balance snow ice/melt,”? Also I don't think there's supposed to be a hyphen in energy balance.

We removed the sentence about the hydrological model here because it was repeated

in section “Initial Conditions, Boundary Conditions and Forcing”. The errors pointed out were corrected there accordingly.

25. L4, p5: Earth should be capitalized.

Done.

26. L17, p5: Water column shouldn't have a hyphen, as earlier in this line.

Done.

27. Section 2.2: Check past vs. present tense here. It varies in the first few lines.

Done.

28. L10-12, p6: This is an exact copy of the sentence in L33, p4. I'd suggest deleting the earlier case of it.

Done – and corrected here.

29. L13-14, p6: I might just spell out “DIC concentrations are higher than TA” instead of using “DIC > TA” which is difficult to read at first.

Done.

30. L3, p9: I would change “To sum up” to “In summary,”

Done

31. L7, p12: “draw-down” should be “drawdown.”

Done

32. Section 3.3: Figure 5 is never cited here and should be in L7, pg13. Only Figure 4 is referenced once in this whole section. I would suggest adding more Figure references for clarity to the reader.

We added more citations for Figures 4 and 5 throughout the section.

33. L10, p14: correlation coefficient should not be capitalized.

Done

34. Figs. 7 and 8: Can the stations be translated to latitude for clarity as in the other Seward Line plots? Or at least designate which direction is offshore vs. nearshore?

We translated the station locations to latitude and also realized that the previous plots had a few stations from Prince William Sound included, which we no longer include in this analysis. Furthermore, we also realized that there were a few errors with the station naming, which is no longer an issue, since we are using latitude in the final version of the figure.

35. L27-30, pg 14: Is this in reference to May or September? This would be made more clear by citing one or both figures here.

This is in reference to May. We added figure citations throughout this section to clarify.

36. L7-8, p15: "Lowest surface temperatures of < 3C are found nearshore in February and March" Should probably put (not shown) here since it directly follows the introduction of Fig. 9 and these months aren't included.

Done.

37. L8, p15: Should be "surface waters slowly warm"

Done.

38. L9, p15: Is "Smax" necessary here? I don't think this symbol is used elsewhere.

It is used below.

39. L27, p15: "In the following" should be dropped. Or turned into "In the following section,"

Done.

40. L9, p18: There should be no hyphen following "moderately" (an adverb).

Done.

41. L18-19, p18: Drop "interestingly" and "however" here.

Done.

42. If allowed by Biogeosciences, I would reference the relevant figures in the summary/conclusion as you work through the points.

We added figure references throughout.

43. L30, p18: "time-series" should be "time series" and/or standardized throughout. Both "time-series" and "time-series" is used in the manuscript.

Changed to "time series" throughout.

44. L9, p21: "endmembers" should be "end members" or standardized to "end-members".

Changed to "end member" throughout.

#### References

Kristen M Thyng, Chad A Greene, Robert D Hetland, Heather M Zimmerle, and Steven F DiMarco. True colors of oceanography: Guidelines for effective and accurate colormap selection. *Oceanography*, 29(3):9-13, 2016.

#####

#### Detailed response to reviewer's comments: Referee #3

#### General comments:

The manuscript by Hauri et al. evaluates a new regional marine biogeochemistry model COBALT-GOA. The study is well motivated, clearly structured and very readable. The

key strength of this new modelling study is the coupling of the regional model to a hydrological model that is forced by reanalysis climate. Therefore freshwater influx is driven by internal variability. The authors discuss the consequences of freshwater influx on biogeochemistry, in particular the aragonite saturation. The model is helpful to learn more about biogeochemical seasonal cycle in a region with sparse data.

We thank the reviewer for his positive comments and helpful suggestions.

My largest comment concerns the presentation of the modelling results. How long was the model run? I have expected to see a 30 years + timeseries, especially as you state that you want to analyse the effects of inter-annual variability apart from the climate change signal. The comparison presented only covers 5 years. Why did you focus on these particular years? Why not longer, why not more recent? Did you do some spin-up before 1980?

The hindcast model simulation covers the period from 1980 to 2013. We added this information to the abstract p.1 l. 9: “To improve our conceptual understanding of the system we conducted a hindcast simulation from 1980 to 2013.”

And also to the main text P.6 L.10 : “After a model spin-up of 10 years, the hindcast simulation (1980 to 2013) was forced at the surface with three-hourly winds, surface air temperature..”

With this publication we intend to introduce the new model set up, present a detailed model evaluation, and use the model to learn about present day seasonal variability and drivers of the inorganic carbon system, with a focus on the influence of freshwater on pH, aragonite saturation state, and pCO<sub>2</sub>. We are currently working on a follow up paper with a focus on long-term trends and interannual variability.

Currently, inorganic carbon data is only publicly available for 2008 – 2012, thus the focus on those years.

Specific comments:

p1L10: try avoiding “perhaps”

Done.

p2L10: “make this region a challenge”. What is the challenge in this region?

We changed it to (p.2 l.12): “The large natural variability and the lack of data for this region make it challenging to understand the inorganic carbon, nutrient, and ecosystem dynamics and predict the potential impacts of the regional manifestation of climate change and ocean acidification on fisheries, economies, and communities (Mathis et al., 2014). Therefore, expansion of the current observational and modelling efforts needs to be made a priority.”

p4L9: “we need : : : 5) multiple phytoplankton groups”. Why is this specifically needed here? It has been in the model already before I guess and also one bulk phytoplankton can

produce high-nutrient low-chlorophyll regions

We chose to use 3PS-COBALT because of its capability to reproduce better the high productivity in nearshore areas (see van Oostende et al., 2018 – full reference is in paper). We conducted a simulation with the regular COBALT using the same parameters as listed in the paper. The Chla concentration was considerably lower in the nearshore.

p5L1: what's the resolution of the reanalysis? Do you need to 0?

The resolution of the reanalysis data is 0.2 degrees. At 60 degrees latitude, this resolution works out to a resolution of 22 km (north-south) by 11 km (east-west). The reanalysis data are first distributed to the 1km model grid using MicroMet (Liston and Elder, 2006).

This is now described in the text as following (p.6 l.19):

“The reanalysis data was regridded from its 0.2 degree resolution to the 1km hydrological model grid using MicroMet...”

p6L5: why do you use a different reanalysis for the climate forcing than compared to the hydrological model?

The hydrological hindcast simulation was conducted separately as part of a different project. We started collaborating with the scientists after they already conducted the simulation.

p6L6: “precip does not dilute any other tracer”. Is this a standard procedure? Can you justify why this is legitimate? Can you cite other studies using this?

The only other GoA regional modeling study (Siedlecki et al., 2017) uses the same procedure.

We clarified in the discussion (p.24, l.35):

“Precipitation is only counted as negative salt flux and does not change the water volume or dilute any other parameters in this current GOA-COBALT model version. While the decrease in salinity increases  $\Omega_{arag}$  and pH, and decrease pCO<sub>2</sub> (Figure 14), our model does not account for the diluting effect of low TA and DIC rainwater. Modelled precipitation can be as high as 3 to 5 m<sup>3</sup> s<sup>-1</sup> near Yakutat. Mean riverine input is an order of magnitude higher and maximum riverine input can be as high as 8000 to 16000 m<sup>3</sup>/sec. The diluting effect of precipitation on TA and DIC therefore seems to be negligible compared to the large volumes of water coming in from the thousands of streams and rivers along the coast. However, this hypothesis still needs to be tested especially because rain may increase in the future as a result of climate change (Mcafee et al., 2014).”

p6L23: I am surprised that you use the Mauna Loa seasonal cycle. At more northern latitudes the seasonal amplitude is much larger than in moderate latitudes. See Keppel-Aleks, Gretchen, James T. Randerson, Keith Lindsay, Britton B. Stephens, J. Keith Moore, Scott C. Doney, Peter E. Thornton, et al. “Atmospheric Carbon Dioxide Variability in the Community Earth System Model: Evaluation and Transient Dynamics during the Twentieth and Twenty-First Centuries.” *Journal of Climate* 26, no. 13 (January 14, 2013): 4447–75. <https://doi.org/10/f439zf>. Table4. Please explain why this is OK for

your study.

This is a good point. As you mentioned, there is a difference in seasonal amplitude between Mauna Loa (9.4 +/-1.9 ppm) and the Gulf of Alaska (14.0 +/- 2.9 ppm, Keppel-Aleks et al., 2013). Sea surface pCO<sub>2</sub> observations from the coastal Gulf of Alaska (<https://www.pmel.noaa.gov/co2/story/GAKOA>) and daily model output suggest an amplitude of over 200 ppm. Due to the relatively larger seasonal amplitude in sea surface pCO<sub>2</sub> compared to the seasonal amplitude of atmospheric pCO<sub>2</sub>, we think it is okay to have used the Mauna Loa timeseries for our simulation. However, we will use regional atmospheric pCO<sub>2</sub> values for our next simulation.

p7Table2: confused by the ordering of values: min,mean,max is easier to grasp for me  
We changed it to min, mean, max.

p7L3: “reproduce”. Please indicate [not shown]  
Done.

p11Fig5: add explanation black line in f)  
We added the following sentence the Figure caption 4 and 5: The black line in panel f) indicates  $\Omega_{\text{arag}} = 1$ .

p12L6: “insignificant”: by what means insignificant? Some p-value analysis? Low compared to internal variability or seasonal cycle.  
We rephrased: The bias of surface pH vanishes with distance from the coast, whereas  $\Omega_{\text{arag}}$  is overestimated by 0.07 at the offshore end of the transect.

p13L4: “model’s bathymetric is too shallow”: How come the model’s bathymetry is too shallow? Cannot you change the model bathymetry?  
The bathymetry of the Gulf of Alaska is highly complex and has only recently been mapped out. There are still many uncertainties regarding the bathymetry and the available products differ, especially in the coastal region. Also, since the grid resolution is 4.5 km and the bathymetry is highly complex, it is likely that the bathymetry observed during the CTD casts does not correspond with the bathymetry at the corresponding location in the model. We clarified in the text (p.12, l.7): “However, because the model's bathymetry is shallower than the observed depth at this particular location....”

p17Fig10: I was wondering whether you also analysed salinity-normalised DIC (sDIC as in Gruber & Sarmiento 2006)? How much of this seasonal cycle in DIC comes from salinity and how much from other factors?  
Yes, we looked at salinity normalized DIC, but realized that using salinity normalized DIC is only appropriate if the freshwater end-member has a zero DIC value. Otherwise salinity-normalized DIC is not conservative with mixing.

p21L9: What do you mean by “endmembers”?  
We rephrased (p.24, l.19): “The strong influence of freshwater on the inorganic carbon system emphasizes the importance of choosing the right DIC and TA concentrations in freshwater in order to correctly model the inorganic carbon dynamics in this area.”



p21L10f: you may cite this new study about biogeochemical composition of freshwater  
<https://www.biogeosciences.net/17/55/2020/>

Thank you for pointing this publication out to us!

Technical comments:

I could not find a repository containing scripts to produce the figures shown. This would be helpful for reproducibility, i.e. understand how the plots were generated.

[https://publications.copernicus.org/services/data\\_policy.html](https://publications.copernicus.org/services/data_policy.html) other underlying materials: software and scripts availability.

We chose not to make the matlab scripts publicly available, however, model code and model output are available. Interested readers can contact us directly and we will be happy to share matlab scripts.

# A regional hindcast model simulating ecosystem dynamics, inorganic carbon chemistry and ocean acidification in the Gulf of Alaska

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**Abstract.** The coastal ecosystem of the Gulf of Alaska (GOA) is especially vulnerable to the effects of ocean acidification and climate change ~~that can only be understood within the context of the natural variability of physical and chemical conditions. Controlled by its complex bathymetry, iron-enriched freshwater discharge, and wind and solar radiation, the~~. Detection of these long-term trends requires a good understanding of the system's natural state. The GOA is a highly dynamic system that exhibits large inorganic carbon variability from subseasonal to interannual timescales. This variability is poorly understood due to the lack of observations in this expansive and remote region. ~~To improve our conceptual understanding of the system, we~~ We developed a new model set-up for the GOA that couples the three-dimensional Regional Oceanic Model System (ROMS) ~~and the Carbon, Ocean Biogeochemistry and Lower Trophic (COBALT) ecosystem model, and a high-resolution.~~ To improve our conceptual understanding of the system we conducted a hindcast simulation from 1980 to 2013. The model was explicitly forced with temporally- and spatially-varying coastal freshwater discharges from a high-resolution terrestrial hydrological model ~~-, thereby affecting salinity, alkalinity, dissolved inorganic carbon and nutrient concentrations. This represents a substantial improvement over previous GOA modelling attempts.~~ Here, we evaluate the model on seasonal to interannual timescales using the best available inorganic carbon observations. The model was particularly successful in reproducing observed aragonite oversaturation and undersaturation of near-bottom water in May and September, respectively. The largest deficiency of the model is ~~perhaps~~ its inability to adequately simulate spring time surface inorganic carbon chemistry, as it overestimates surface dissolved inorganic carbon, which translates into an underestimation of the surface aragonite saturation state at this time. We also use the model to describe the seasonal cycle and drivers of inorganic carbon parameters along the Seward Line transect in under-sampled months. ~~As such, model~~ Model output suggests that a majority of the near-bottom water along the Seward Line is seasonally ~~under-saturated-undersaturated~~ with regard to aragonite between June and January, as a result of upwelling and remineralization. Such an extensive period of reoccurring aragonite undersaturation may be harmful to ~~CO<sub>2</sub>-sensitive~~ ocean acidification-sensitive organisms. Furthermore, the influence of freshwater not only decreases arag-

onite saturation state in coastal surface waters in summer and fall, but simultaneously ~~also~~ decreases surface  $p\text{CO}_2$ , thereby decoupling the aragonite saturation state from  $p\text{CO}_2$ . The full seasonal cycle and geographic extent of the GOA region is undersampled, and our model results give new and important insights for months of the year and areas that lack *in situ* inorganic carbon observations.

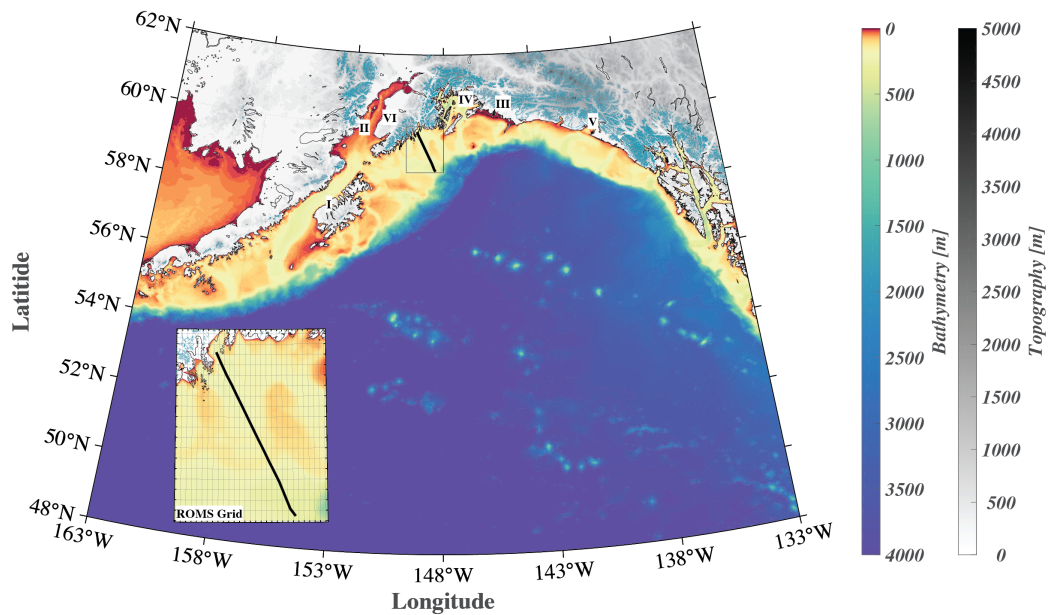
5 *Copyright statement.* TEXT

## 1 Introduction

The Gulf of Alaska Large Marine Ecosystem (GOA-LME) is home to highly productive commercial and subsistence fisheries including salmon, pollock, crab, Pacific cod, halibut, mollusks and other shellfish (Mundy, 2005). The dynamics of these fisheries and their susceptibility to climate change and ocean acidification remains poorly understood. Large glaciated mountains (Figure 1), complex bathymetry, seasonally varying cycles of winds, ~~iron-enriched~~ iron-enriched freshwater discharge, and solar radiation (Stabeno et al., 2004; Weingartner et al., 2005; Janout et al., 2010) set the stage for high ~~temporal and spatial~~ physical, chemical, and biological spatiotemporal variability across the GOA continental shelf. At the same time, the GOA-LME is sparsely sampled due to its large spatial extent, harsh environmental conditions, and remote geography. The ~~societal importance of the ecosystem, the~~ large natural variability ~~;~~ and the lack of data ~~make this region a challenge and a priority for understanding ecosystem dynamics, inorganic carbon chemistry, the~~ for this region make it challenging to understand the inorganic carbon, nutrient, and ecosystem dynamics and predict the potential impacts of the regional manifestation of climate change and ocean acidification ~~;~~ and its potential impact on the nation's on fisheries, economies, and communities (Mathis et al., 2014). Therefore, expansion of the current observational and modelling efforts needs to be made a priority.

The GOA-LME is especially susceptible to the effects of climate change and ocean acidification. This high latitude region is naturally low in  $[\text{CO}_3^{2-}]$  due to the increased solubility of  $\text{CO}_2$  at low temperatures, ~~seasonal increase in vertical mixing~~ increased vertical mixing of  $\text{CO}_2$ -enriched deep water into the upper water column in winter, riverine and glacial inputs in summer and fall, and inner shelf dynamics that tend to retain coastal discharges close to shore (Feely and Chen, 1982; Feely et al., 1988; Byrne et al., 2010; Weingartner et al., 2005). The freshwater fluxes into the coastal zone are increasing (Neal et al., 2010; Hill et al., 2015; Hood et al., 2015; Beamer et al., 2016) as this sub-polar region continues to warm and deglaciate (Arendt et al., 2002; Larsen et al., 2007; O'Neel et al., 2005). Because glacial meltwater in this region is ~~endowed with~~ characterized by low total alkalinity (TA) relative to dissolved inorganic carbon (DIC) (Stackpoole et al., 2016, 2017), increasing freshwater discharge pushes the system further towards undersaturation with respect to aragonite, ~~and thereby likely exacerbating.~~ This process likely exacerbates the effects of ocean acidification (Evans et al., 2014).

The GOA-LME is characterized by high concentrations of biologically available dissolved iron (dFe) and low nitrate ( $\text{NO}_3$ ) concentrations on the shelf, and low dFe and high  $\text{NO}_3$  concentrations off-shelf (Aguilar-Islas et al., 2015; Wu et al., 2009; Lippitt et al., 2010; Martin et al., 1989). These two limiting nutrients lead to a ~~diatom-dominated~~ phytoplankton community



**Figure 1.** Map of the "GOA-COBALT" model domain showing depth [m] of the ocean in color and altitude of the mountains [m] in grey. Glaciated areas are indicated by turquoise coloring of the mountains. The Seward Line is shown by the black line. PWS-The inset shows the model mesh and its horizontal resolution of 4.5 km. I = Kodiak Island, II = Cook Inlet, III = Copper River, IV = Prince William Sound, V = Yakutat Bay, VI = Kenai Peninsula.

composition dominated by diatoms in the dFe-rich near-shore and area and by small phytoplankton in the dFe-poor off-shelf areas-area (Strom et al., 2007). Limited inorganic carbon observations suggest that along with primary productivity and remineralization, physical processes such as downwelling, on-shelf intrusions of deep water, tidal mixing, freshwater discharge, and eddies, are important drivers of the inorganic carbon system dynamics. High biological productivity in spring depresses  $p\text{CO}_2$  in the water column, resulting in shelf waters supersaturated with respect to aragonite, and supporting large fluxes of atmospheric  $\text{CO}_2$  into the ocean (Fabry et al., 2009; Evans and Mathis, 2013). In September, bottom waters along the shelf are undersaturated with respect to aragonite. This large-scale pattern of aragonite undersaturation has been speculated to be a-is a suggested result of on-shelf intrusion of DIC-rich Pacific basin water near the seafloor, and remineralization of large quantities of organic matter produced during spring blooms (Fabry et al., 2009; Evans et al., 2014). Recent inorganic carbon surveys near marine tidewater glaciers in Glacier Bay, Alaska and Prince William Sound also suggest that glacial melt water, which is endowed with naturally low total alkalinity (TA), induces seasonal aragonite undersaturation in surface waters (Evans et al., 2014; Reisdorph and Mathis, 2014) and forms corrosive mode water that may subsequently be advected and potentially subducted to distant shelf regions (Evans et al., 2013, 2014).

Insufficient inorganic carbon data coverage impede-impedes our ability to understand the interplay between drivers in different seasons and to determine the relative importance of the various controls of the inorganic carbon system at different locations.

Ongoing and historic inorganic carbon system observations in the GOA consist of a limited set of shipboard oceanographic observations, underway measurements from research vessels and scientific sampling systems installed on ferries, and a small number of sensors deployed at fixed nearshore coastal locations (Fabry et al., 2009; Evans and Mathis, 2013; Evans et al., 2014, 2015; Reisdorph and Mathis, 2014; Miller et al., 2018). These draw an incomplete picture of the spatial and temporal variability of the system because the low frequency of available observations causes aliasing issues. Also, because variability is large from seasonal to decadal scales in these waters, the timeseries from deployed sensors at fixed nearshore locations are not long enough yet to detect an anthropogenic trend in seawater  $p\text{CO}_2$  and pH (Sutton et al., 2018).

In other shelf systems, regional biogeochemical models have ~~successfully~~ been used to better understand past, present, and future inorganic carbon dynamics and impacts of climate change and ocean acidification on these ecosystems (Hauri et al., 2013; Turi et al., 2016; Gruber et al., 2012; Franco et al., 2018). Previous regional GOA-LME modeling studies focused on refining large scale and mesoscale circulation features (Dobbins et al., 2009; Xiu et al., 2012), iron limitation (Fiechter and Moore, 2009), and the influence of Ekman pumping (Fiechter et al., 2009) and eddies (Coyle et al., 2012) on the timing and magnitude of the spring bloom. There are only two regional models that simulate the oceanic carbon cycle in the GOA (Siedlecki et al., 2017; Xiu and Chai, 2014). However, neither of these models simulate the influence of ~~spatially and temporally highly variable~~ freshwater input along the coast, which exhibits high spatiotemporal variability. Siedlecki et al. (2017) used the monthly riverine input climatology by Royer (1982) and applied it equally to the top most vertical cell along the land mask, whereas Xiu and Chai (2014) did not include riverine input at all. Therefore, to fill gaps in the understanding of the inorganic carbon cycle in the GOA we need a moderately ~~high-resolution~~ high-resolution model that includes 1) important physical processes such as downwelling, eddies, and cross-shelf fluxes, 2) the carbon cycle, 3) the large spatial and temporal variability of freshwater input, 4) historical simulation long enough to be able to distinguish natural variability from the ~~anthropogenic long-term~~ long-term anthropogenic trend, 5) multiple phytoplankton groups, and 6) iron limitation to reproduce the highly productive nearshore and high-nutrient low-chlorophyll offshore regions.

Here, we introduce a new GOA model that includes a three-dimensional regional ocean circulation model, a complex ecosystem model, and a moderately high-resolution terrestrial hydrological model. ~~This model system will allow us to better simulate the influence of variations in past freshwater runoff, full suite of atmospheric forcing and physical air-sea fluxes of heat, water vapor and momentum, and atmospheric  $\text{CO}_2$  on the physical, chemical, and biological oceanography. We make~~ We present a thorough model evaluation to test the model's capability of simulating seasonal and interannual inorganic carbon patterns, and use it to study the seasonal variability and drivers of the inorganic carbon system along the historic Seward Line (Figure 1). We expand on previous regional modelling efforts by using spatially and temporally variable freshwater forcing, parameterizing freshwater DIC, TA, and nutrients based on available seasonal observations, and conducting a multidecadal hindcast simulation.

## 2 Methods

### 2.1 Model set-up

We used a GOA configuration of the three-dimensional physical Regional Oceanic Model System (ROMS, Shchepetkin and McWilliams (2005)). ROMS is a free-surface, hydrostatic primitive equation and finite volume (Arakawa C-grid) ocean circulation model. The vertical discretization is based on a terrain-following coordinate system (50 depth levels), with increased resolution towards the surface and the bottom of the ocean. Due to shallower bathymetry, the shelf and coastal areas have higher vertical resolution. For example, In the shallowest areas (depth = 0.5 m), the vertical spacing is 0.01 m, while in the deepest water, the vertical spacing is 5 m in surface waters, expanding smoothly to over 300 m near the bottom. The horizontal resolution is ~~eddy-resolving~~ eddy-resolving at 4.5 km, which resolves regional coastal upwelling scales. The grid covers a large coastal area from the ~~Canadian – US border in the Southeast~~ southern tip of Prince of Wales Island in the southeast to west of Sandpoint in the middle of the Aleutian Islands (Figure 1). The current model configuration is based on Danielson et al. (2016), although with a larger grid extent, and a lower horizontal resolution to accommodate the computationally intense ecosystem model. ~~We attempt to improve on the GOA domain used by Coyle et al. (2012) in that we include~~ Our GOA-COBALT domain is based on Coyle et al. (2012), however including the Alexander Archipelago. ~~Prior experiments in the GOA Experiments with the Coyle et al. (2012) model~~ have shown that the model had insufficient near-surface vertical mixing, leading to overly fresh water at the surface, which is challenging to mix down. In order to improve on our surface mixing, we added the parameterization of Li and Fox-Kemper (2017). They looked to Large-eddy simulations (LESs) to study the effects of unresolved Stokes drift driven by surface waves and the resulting Langmuir circulation on the vertical mixing in a variety of stratification regimes. Their parameterization is now being routinely used in global climate simulations (e.g. Adcroft et al. (2019)).

The ~~hydrological model is based on a suite of weather, energy-balance snow ice/melt, soil water balance, and runoff routing models forced with Climate Forecast System Reanalysis data products (Saha et al., 2010).~~ The biogeochemical model used for this study is a modified version of the Carbon, Ocean Biogeochemistry and Lower Trophic (COBALT) marine ecosystem model, which has been applied on a global scale in conjunction with the Geophysical Fluid Dynamics Laboratory's (GFDL's) ~~earth~~ Earth system model (Stock et al., 2014). Only recently, COBALT was coupled to ROMS and modified with an additional coastal chain-forming diatom to better represent biogeochemical processes and properties in highly productive coastal regions (3PS-COBALT, Van Oostende et al. (2018)). 3PS-COBALT resolves the cycles of nitrogen, carbon, phosphate, silicate, iron, calcium carbonate, oxygen, and lithogenic material with 36 state variables. The model contains small phytoplankton that are grazed by microzooplankton, a medium phytoplankton that can be consumed by small copepods and a larger, chain forming diatom, which can only be grazed by large copepods and krill. Light, temperature, the most limiting nutrient and metabolic costs are used to calculate primary productivity for each phytoplankton group. The chlorophyll-to-carbon ratio is dynamic and based on light (Manizza et al., 2005) and nutrient limitations. Iron limitation depends on an internal cell quota and nitrate/phosphate limitations are simply dependent on their ambient concentrations in the seawater. The currency of biomass and productivity in the model is nitrogen. Organic nitrogen is converted into organic carbon following the Redfield Ratio of 106:16 (Redfield et al., 1963). ~~Dissolved inorganic carbon (DIC)~~ DIC and TA are state variables and dictate the inorganic carbon

**Table 1.** Summary of the definitions, abbreviations, values and units of the model parameters adjusted from Van Oostende et al. (2018) to better represent the ecosystem in higher northern latitudes (Strom et al., 2010).  $a = 365.25 * 24 * 3600$ ,  $b = 4.5998$ .

Parameter	Symbol-Name	Value	Units
<u>alpha fescav</u>	Iron scavenging coefficient onto sinking detritus <i>Chl-a specific initial slope of the photosynthesis-light curve</i>	<del>alpha fescav</del> $10/a$	$\text{sec}^{-1}$
<u>alpha Lg</u>	Large chain-forming phytoplankton	<del>alpha Lg</del> $3.0e-6 * b$	$(\text{g C}) (\text{g Chl}^{-1}) (\text{W m}^{-2})^{-1}$
<del>Medium Phytoplankton</del> alpha Md	<u>Medium Phytoplankton</u>	$3.33e-6 * b$	$(\text{g C}) (\text{g Chl}^{-1}) (\text{W m}^{-2})^{-1}$
<del>Small Phytoplankton</del> alpha Sm	<u>Small Phytoplankton</u>	$6.0e-6 * b$	$(\text{g C}) (\text{g Chl}^{-1}) (\text{W m}^{-2})^{-1}$

system. Like all other tracer concentrations in the model, these two variables are affected by diffusion, horizontal and vertical advection, and sources minus sink terms that include net primary production,  $\text{CaCO}_3$  formation and dissolution both in the water column and sediments, detritus remineralization in the ~~water-column~~ water column and sediments, zooplankton respiration, and atmosphere-ocean  $\text{CO}_2$  fluxes. The Chl-*a* specific initial slope of the photosynthesis-light curve and iron scavenging coefficient onto sinking detritus were both adjusted to better represent the GOA biogeochemistry and ecosystem (Table 1). All other constants are based on Van Oostende et al. (2018).

## 2.2 Initial Conditions, Boundary Conditions and Forcing

Physical initial and boundary conditions for currents, ocean temperature, salinity, and sea surface height were taken from the Simple Ocean Data Assimilation ocean/sea ice reanalysis 3.3.1 [SODA, Carton et al. (2018), available as five-day averages].

~~The model~~ After a model spin-up of 10 years, the hindcast simulation (1980 to 2013) was forced at the surface with three-hourly winds, surface air temperature, pressure, humidity, precipitation and radiation from the Japanese 55-year Reanalysis (JRA55-do) 1.3 project (Tsujino et al., 2018). The atmospheric fields ~~are~~ were used to compute surface stresses and fluxes using a bulk flux algorithm (Large and Yeager, 2008). Precipitation ~~is~~ was solely counted as a negative salt flux and ~~does~~ did not change any volume or dilute any other tracers, such as DIC and TA. Along its coastal boundary, freshwater was brought in from numerous rivers and tidewater glaciers. This was done with a point-source river input through exchange of mass, momentum and tracers through the coastal wall at all depths (Danielson et al., in review). A hydrological model provided riverine input at a 1 km resolution and at a daily timestep (Beamer et al., 2016). The hydrological model ~~is~~ was based on a suite of weather, ~~energy-balance~~ energy balance, ~~snow/ice~~ snow/ice melt, soil water balance, and runoff routing models forced with Climate Forecast system Reanalysis data (Saha et al., 2010). The reanalysis data was regridded from its 0.2 degree resolution to the 1km hydrological model grid using MicroMet (Liston and Elder, 2006). Nutrient, DIC, and TA concentrations in the freshwater ~~are~~ were based on available observations and are summarized in (Table 2). As found in other freshwater data (Rheuban et al., 2019), DIC concentrations were higher than TA showing that the freshwater discharging into the GOA is quite acidic (Stackpoole et al., 2016, 2017).

DIC and TA initial conditions for the hindcast simulation were extracted from the mapped version 2 of the Global Ocean Data



**Table 2.** Table listing riverine dissolved inorganic carbon, total alkalinity, nitrate, dissolved iron, dissolved oxygen, and temperature values. When seasonal observations were available, the variables followed a seasonal cycle. These variables are listed with their minimum, mean, ~~maximum~~, and ~~minimum-maximum~~ levels. ~~All~~ The values of all other variables were initialized ~~with to~~ a very small number ( $< 0.0001$ ).

Parameter	Value	Units	Reference
Dissolved inorganic carbon	<u>365</u> , 397, 446, <del>365</del>	$\mu\text{mol kg}^{-1}$	Kenai river (Stackpoole et al., 2016, 2017)
Total alkalinity	<u>333</u> , 366, 410, <del>333</del>	$\mu\text{mol kg}^{-1}$	Kenai river (Stackpoole et al., 2016, 2017)
Iron	30	$\text{nmol kg}^{-1}$	(Aguilar-Islas et al., 2015)*
Nitrate	<u>1.5</u> , 4.86, 8.91, <del>1.5</del>	$\mu\text{mol kg}^{-1}$	Herbert River (Hood and Berner, 2009)
Temperature	<u>0.16</u> , 5.06, 11.88, <del>0.16</del>	$^{\circ}\text{C}$	Danielson, personal communication
Dissolved oxygen	<u>355.1</u> , 386.5, 405.2, <del>355.1</del>	$\mu\text{mol kg}^{-1}$	Cowee Creek (Fellman et al., 2015)

\*Aguilar-Islas et al. (2015) observed a maximum of  $10 \text{ nmol kg}^{-1}$  dFe in nearshore waters with a salinity of 25. In order to model high nearshore dFe values (see Figure 2), riverine dFe was set to  $30 \text{ nmol kg}^{-1}$ .

Analysis Project dataset (GLODAPv2.2016b, Lauvset et al. (2016)). GLODAP DIC data, which ~~is was~~ referenced to 2002, was normalized to 1980 using the anthropogenic  $\text{CO}_2$  estimates for the GOA by Carter et al. (2017). Carter et al. (2017) suggest two different rates of depth-dependent increase of anthropogenic  $\text{CO}_2$  per year for the period 1980 - 1999 and for 2000 - present. The anthropogenic  $\text{CO}_2$  increase for the corresponding time period was added (or subtracted) in monthly increments from the reference year. A seasonal cycle was added to the surface based on Takahashi et al. (2014). Following Hauri et al. (2013), DIC and TA ~~are were~~ assumed to vary throughout the upper 200 m of the water column, but ~~are were~~ attenuated proportional to the seasonal variations of temperature across depth. Each year, DIC boundary conditions ~~increase increased~~ as a result of anthropogenic  $\text{CO}_2$  increase, following estimates for the region made by Carter et al. (2017). Nitrate, phosphate, oxygen, and silicate initial conditions were taken from the World Ocean Atlas 2013 (Garcia et al., 2013). All other variables were initialized based on ~~output from a global model simulation (Stock et al., 2014)~~ a climatology from a Common Ocean-Ice Reference Experiment (CORE-II) forced GFDL-COBALT simulation (1988-2007) described in Stock et al. (2014). Atmospheric  $p\text{CO}_2$  was forced with monthly means derived from the Mauna Loa  $\text{CO}_2$  record (<https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html>).

### 3 Model Evaluation

#### 3.1 Physics

15 The model domain is strongly influenced by freshwater coming from hundreds of glacier-fed rivers and tidewater glaciers that ring the GOA. Our approach of using a hindcast simulation from a highly resolved land hydrography model (Beamer et al., 2016) to force the freshwater input was recently evaluated through comparison to salinity, temperature, velocity, and dynamic height observations (Danielson et al., in review). The findings by Danielson et al. (in review) are summarized in the following paragraph. The influence of the springtime freshet is well reproduced by the model, with low salinities ( $\sim 26$  PSU)

in the nearshore upper 10 to 20 m of the water column ( $r \sim 0.5$  ~~-0.6~~ -0.6,  $p \sim 0.05$ ). While the correlation between salinity observations and model output is only slightly weaker in summertime, the model has difficulty in reproducing small-amplitude salinity variations between October and March, when riverine input is lowest and the signal to noise ratio of salinity is small. Temperature is particularly well modelled in the first half of the year, with highest correlations ( $r \sim 0.9$ ,  $p < 0.001$  0.05) in the middle of the water column. The model is also able to skilfully reproduce monthly dynamic height anomalies in summer, fall, and winter (not shown). Overall, freshwater fluxes used in this study are more realistic than in previous studies because they are derived from a temporally and spatially highly resolved hindcast simulation forced with meteorological reanalysis data sets. Compared to previous studies (Royer, 1982; Wang et al., 2004; Hill et al., 2015; Siedlecki et al., 2017), this current model configuration is better able to reproduce low salinity levels in coastal areas across the GOA and can thereby more adequately reproduce the Alaska Coastal Current (Danielson et al., in review).

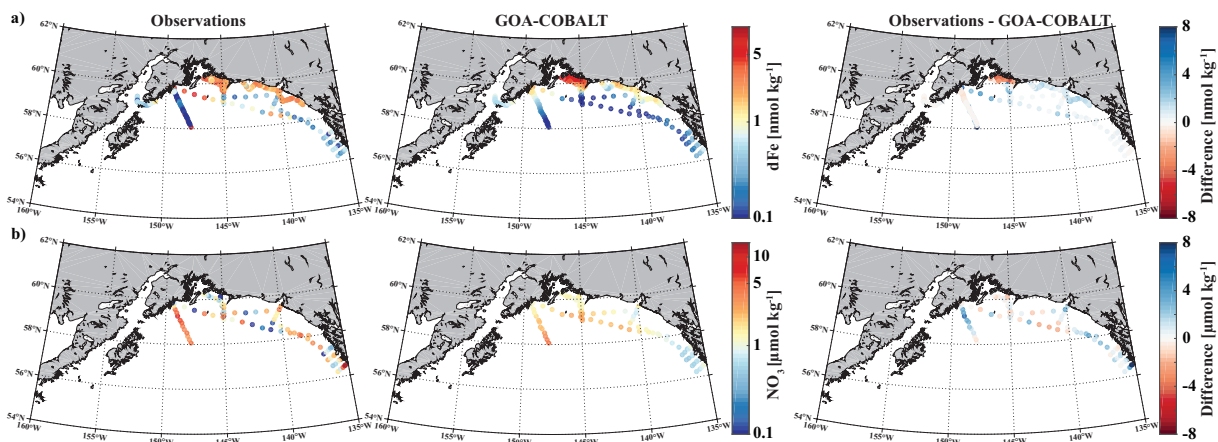
### 3.2 Nutrients and Chl- $\alpha$

High concentrations of biologically available dFe prevail across the inner to mid GOA shelf due to the dFe-rich input of glacially fed rivers (Aguilar-Islas et al., 2015; Wu et al., 2009; Lippiatt et al., 2010). While these shelf areas are low in  $\text{NO}_3$ , they border the  $\text{NO}_3$ -rich and dFe-poor waters off-shelf (Martin et al., 1989). The spatial variability of these two limiting nutrients orchestrate the phytoplankton community composition, with diatom-dominated areas in the dFe-rich near-shore environment and small phytoplankton in ~~iron-depleted~~ dFe-depleted offshore areas (Strom et al., 2010). Here, we first evaluate the modelled spatial variability of surface dFe,  $\text{NO}_3$ , and Chl- $\alpha$  by comparing it to *in situ* and satellite observations (Aguilar-Islas et al., 2015; Lippiatt et al., 2010; Crusius et al., 2017; MODIS-Aqua Ocean Color Data; NASA Goddard Space Flight Center, 2014, Accessed 08/17/2019).

dFe observations along a transect near the Copper River estuary suggest that coastal surface concentrations can reach up to 9.4  $\text{nmol kg}^{-1}$  in mid to late summer west of Prince William Sound (Figure 2a), when glacial melt and riverine input are highest. These surface concentrations decrease rapidly with distance from shore, with levels of  $<1 \text{ nmol kg}^{-1}$  near the shelf break and beyond. The horizontal surface dFe gradient across the shelf, with high dFe concentrations in coastal areas and dFe levels near depletion off-shore, was simulated well by the model. For example, the model shows dFe values of up to 8  $\text{nmol kg}^{-1}$  (Figure 2a) in some coastal areas and low concentrations ( $< 0.5 \text{ nmol kg}^{-1}$ ) at the shelf break. ~~On average~~ Overall, the model ~~underestimates summertime surface iron concentrations by  $\sim 2 \text{ nmol kg}^{-1}$~~  slightly underestimates dFe along the coast, except for the area surrounding Copper River and near the shelf break, despite the relatively high dFe riverine boundary condition (Table 2).

The low observed surface summertime values of  $\text{NO}_3$  in coastal areas are simulated well by the model. Observed  $\text{NO}_3$  values range up to 5.4  $\mu\text{mol kg}^{-1}$  (with exception of a few outliers in southeast Alaska) and modelled surface  $\text{NO}_3$  concentrations ~~also only~~ reach a maximum of 4.3  $\mu\text{mol kg}^{-1}$  (Figure 2b).

The modelled spring phytoplankton bloom starts in April and ~~therefore~~ coarsely matches with the timing of the satellite observed spring bloom (Figure 3). Then, simulated surface Chl- $\alpha$  ranges between 3 to 4  $\mu\text{g kg}^{-1}$  across the entire shelf, with

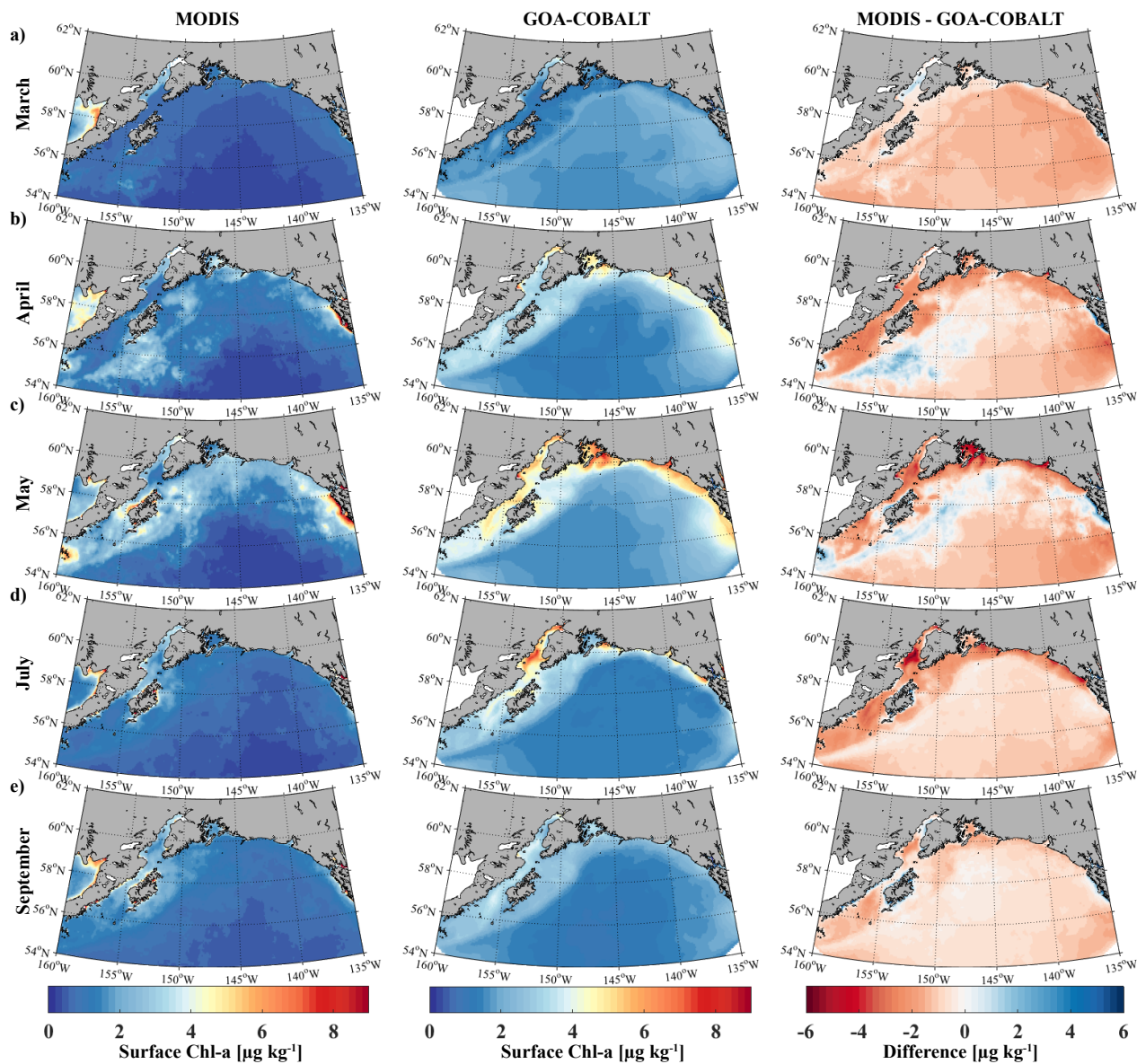


**Figure 2.** Observed (left) and ~~modeled~~ GOA-COBALT simulated (right/middle) surface dissolved iron (a,  $dFe$  [ $nmol\ kg^{-1}$ ]) and nitrate (b,  $NO_3$  [ $\mu mol\ kg^{-1}$ ]) concentrations. The right panel shows the difference between observed and modelled a)  $dFe$  and b)  $NO_3$ . The observations were taken in July, August, and September (Aguilar-Islas et al., 2015; Lippiatt et al., 2010; Crusius et al., 2017). The model output is based on a mean of modelled July, August, and September values from a 1980 to 2013 climatology. ~~Dissolved iron  $dFe$~~  and ~~nitrate  $NO_3$~~  are plotted on a log scale.

some nearshore areas reaching surface  $Chl-\alpha$  levels of  $5\ \mu g\ kg^{-1}$ . However, satellite images suggest that in April,  $Chl-\alpha$  concentrations are more patchy than shown by the model, with lower concentrations across the shelf ( $1-2\ \mu g\ kg^{-1}$ ). While peak observed  $Chl-\alpha$  concentrations between  $7$  and  $9\ \mu g\ kg^{-1}$  are localized in southeast Alaska in May, simulated  $Chl-\alpha$  levels of  $5\ \mu g\ kg^{-1}$  are more wide spread along the coast, with peak concentrations of  $6$  to  $7\ \mu g\ kg^{-1}$  in some select areas. In July through August, simulated  $Chl-\alpha$  levels slowly taper off, though some nearshore areas still reach peak concentrations of  $6\ \mu g\ kg^{-1}$ . In September, on-shelf modelled  $Chl-\alpha$  are  $< 3\ \mu g\ kg^{-1}$ . To sum upIn summary, observed  $Chl-\alpha$  concentrations are lower than suggested by the model across the shelf and the domain throughout the summer. With exception of November through February, when modelled  $Chl-\alpha$  concentrations are  $< 1\ \mu g\ kg^{-1}$ , standing stock  $Chl-\alpha$  concentrations are also overestimated by a factor of two by the model throughout the year.

### 10 3.3 Model skill to simulate spring and fall oceanographic conditions

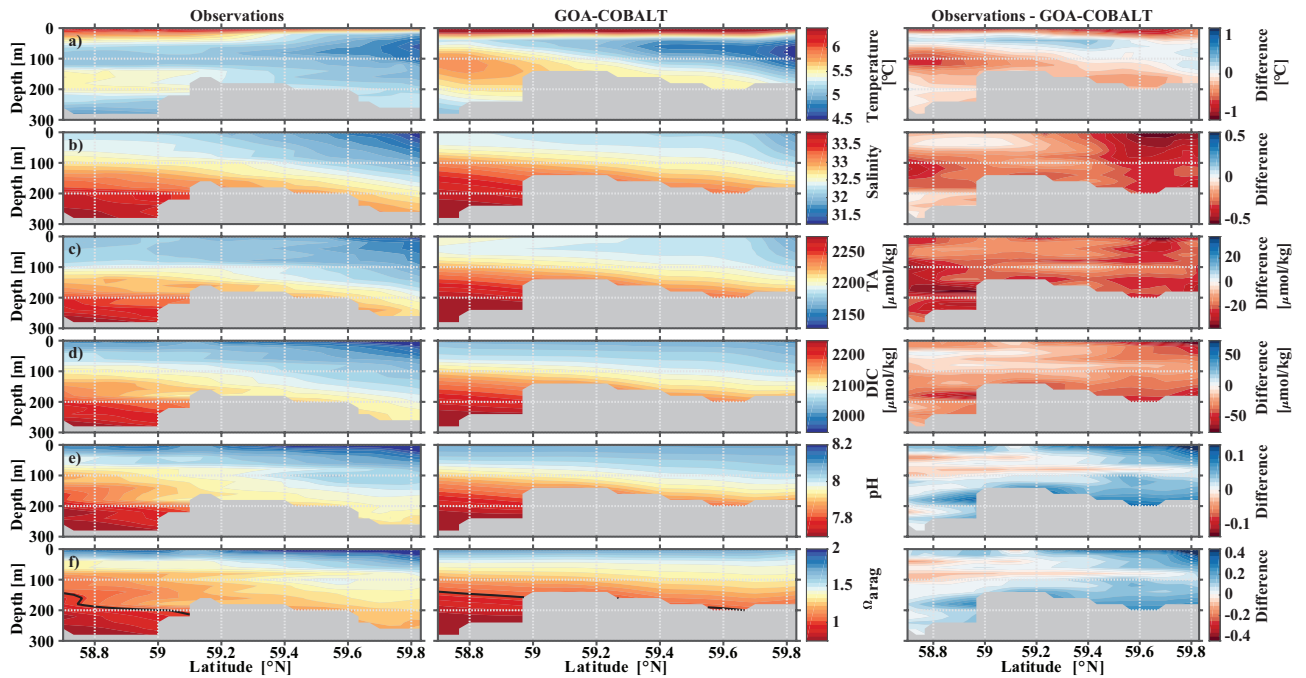
Inorganic carbon observations in the GOA have been collected every spring and fall along the historic Seward Line since 2008 (Evans et al., 2013). Here, we compare May and September monthly means of our 2008 - 2012 model output to the publicly available ship board observations taken in May and September of the corresponding years. To do so, the model output was sampled at the closest grid point to every Seward Line station. The model output and observations were then interpolated onto



**Figure 3.** Monthly climatology (1980 - 2013) for satellite based (left, MODIS) and [GOA-COBALT](#) simulated (right/middle) surface Chl- $\alpha$  concentrations for (a) March, (b) April, (c) May, (d) July, and (e) September. [The right panel shows the difference between MODIS and GOA-COBALT surface Chl- \$\alpha\$  concentrations.](#) Source for MODIS data: (MODIS-Aqua Ocean Color Data; NASA Goddard Space Flight Center, 2014, Accessed 08/17/2019)

the same grid and averaged across all years for May and September.

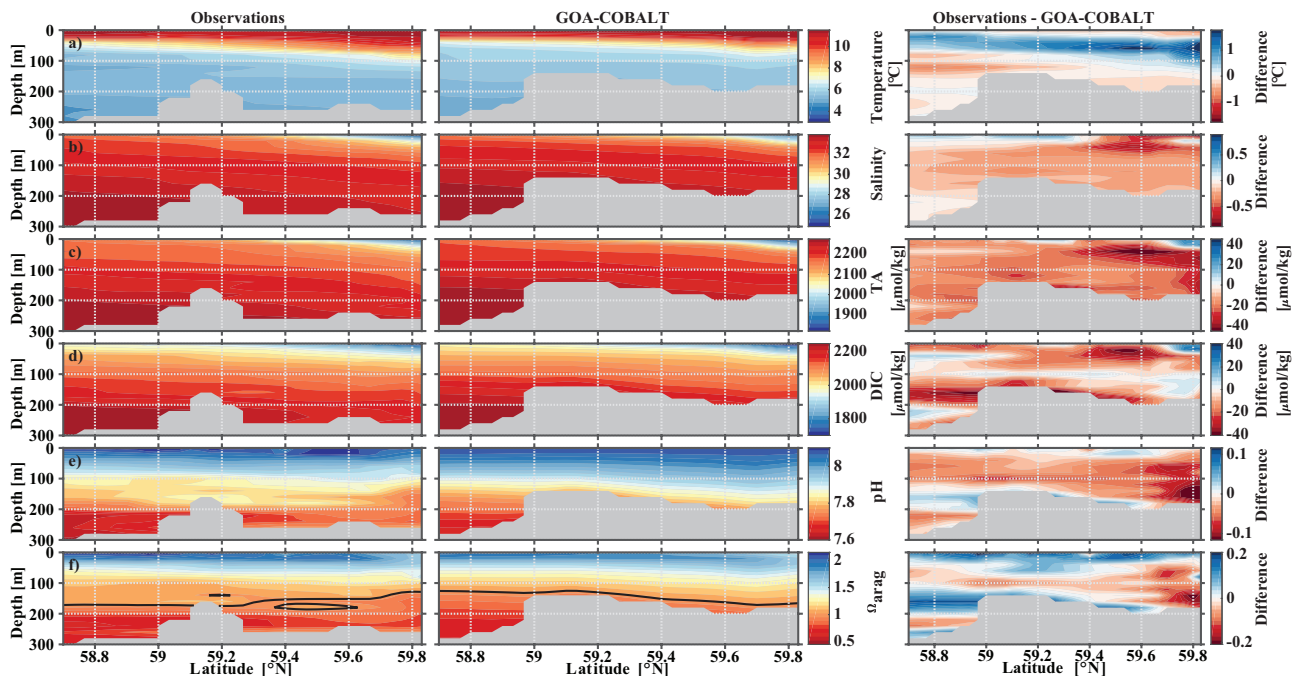
In May, observations and model output clearly show the influence of freshwater on the coastal water properties, including inorganic carbon chemistry (Figure 4). In nearshore surface areas, waters are cold, fresh, and low in TA and DIC concentrations.



**Figure 4.** Visual comparison of vertical sections of (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ), (e) pH, and (f) aragonite saturation state ( $\Omega_{arag}$ ) of climatologies (2008 - 2012) of observations taken along the Seward Line in May (left, Evans et al. (2013)) and corresponding monthly model output (middle), and the difference between observed and GOA-COBALT simulated variables (right). The model output was sampled at locations where observations were taken. Observations and model points were then vertically and horizontally interpolated onto the same grid and averaged across years 2008 - 2012. The white-grey area depicts observed sampling depth in the left panel and seafloor or coast in the model output. The black line in panel f indicates  $\Omega_{arag} = 1$ .

The influence of freshwater is visible throughout the transect, but with slowly increasing values of salinity, DIC, and TA with distance from the coast. The model generally reproduces these patterns well, although with slightly higher values for all three parameters across the transect. For example, observed surface salinity ranges between 31.4 at  $59.8^{\circ}\text{N}$  and 32.2 at the end of the transect (Figure 4b). TA varies between  $2143 \mu\text{mol kg}^{-1}$  and  $2170 \mu\text{mol kg}^{-1}$ , and DIC between  $1965 \mu\text{mol kg}^{-1}$  and  $2017 \mu\text{mol kg}^{-1}$  (Figures 4c and d). Simulated ranges of these parameters are similar (salinity: 31.7 - 32.4, TA: 2163 - 2203  $\mu\text{mol kg}^{-1}$ , DIC: 2009 - 2038  $\mu\text{mol kg}^{-1}$ ). The largest bias in salinity ( $S_{bias} = 0.6$ ), alkalinity ( $TA_{bias} = 35 \mu\text{mol kg}^{-1}$ ), and DIC ( $DIC_{bias} = 46 \mu\text{mol kg}^{-1}$ ) are found around  $59.6^{\circ}\text{N}$ . The overestimation of salinity suggests that the freshwater influence is overly weak, leading to the modelled overestimation of TA and DIC. However, the bias in DIC relative to the bias in TA is largest in the grid cell closest to the coast, which leads to an underestimation of modelled pH and  $\Omega_{arag}$  of up to 0.09 and 0.29, respectively (Figures 4e and f). The bias of surface pH and  $\Omega_{arag}$  vanishes with distance from the coast. At the offshore end of the transect, the model overestimates  $\Omega_{arag}$  by 0.07 (pH overestimation is insignificant). The larger difference



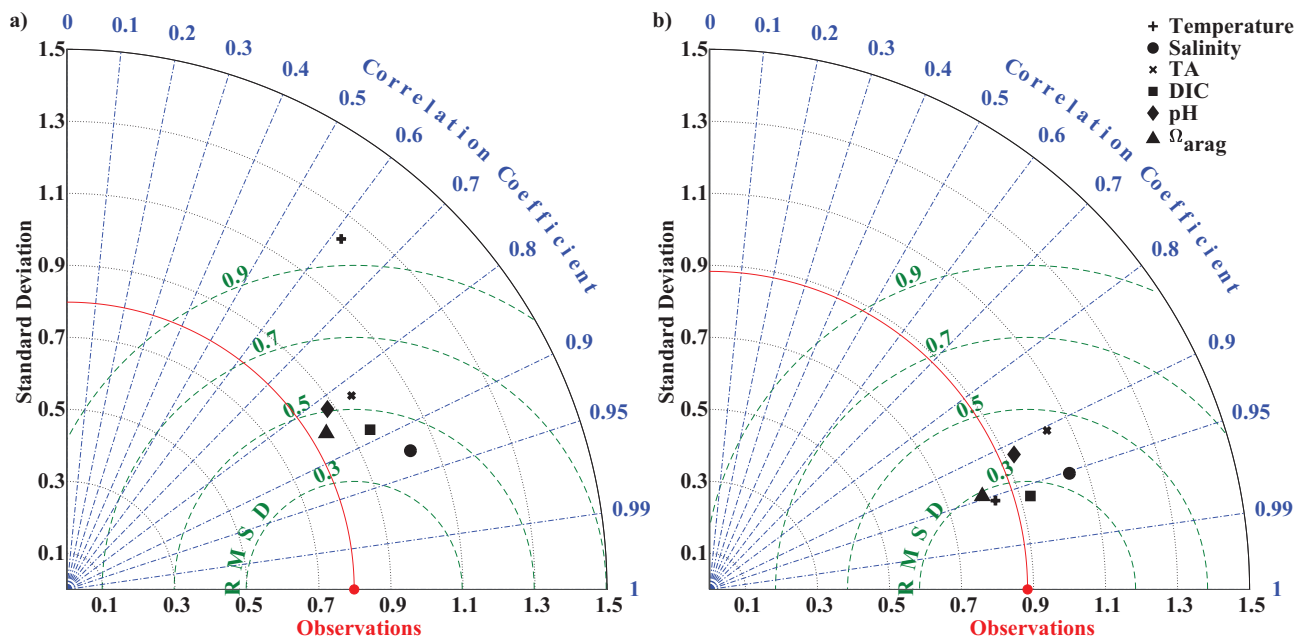


**Figure 5.** Visual comparison of vertical sections of (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ), (e) pH, and (f) aragonite saturation state ( $\Omega_{arag}$ ) of climatologies (2008 - 2012) of observations taken along the Seward Line in September (left, Evans et al. (2013)) and corresponding monthly model output (middle), and the difference between observed and GOA-COBALT simulated variables (right). The model output was sampled at locations where observations were taken. Observations and model points were then vertically and horizontally interpolated onto the same grid and averaged across years 2008 - 2012. The white-grey area depicts observed sampling depth in the left panel and seafloor or coast in the model output. The black line in panel f indicates  $\Omega_{arag} = 1$ .

in DIC relative to TA near the coast is likely due to an underestimation of biological carbon draw-down, leading to the underestimation of pH and  $\Omega_{arag}$  in nearshore surface waters.

At depth farther offshore, salinity, DIC and TA enriched waters are visible on the shelf. As a result, the springtime *in situ* aragonite saturation horizon (depth where  $\Omega_{arag} = 1$ ) is shallower offshore than nearshore (Figure 4f). Observations suggest that with a depth of the aragonite saturation horizon of about 200 m, the seafloor on the shelf up to  $59.1^{\circ}\text{N}$  is undersaturated with regard to aragonite. The model underestimates the aragonite saturation horizon depth slightly. However, because the model's bathymetry is too shallow (white shallower than the observed depth at this particular location (grey areas in Figure 4)), modelled bottom water masses across the shelf are not understaturated with regard to  $\Omega_{arag}$  north of  $59^{\circ}\text{N}$ .

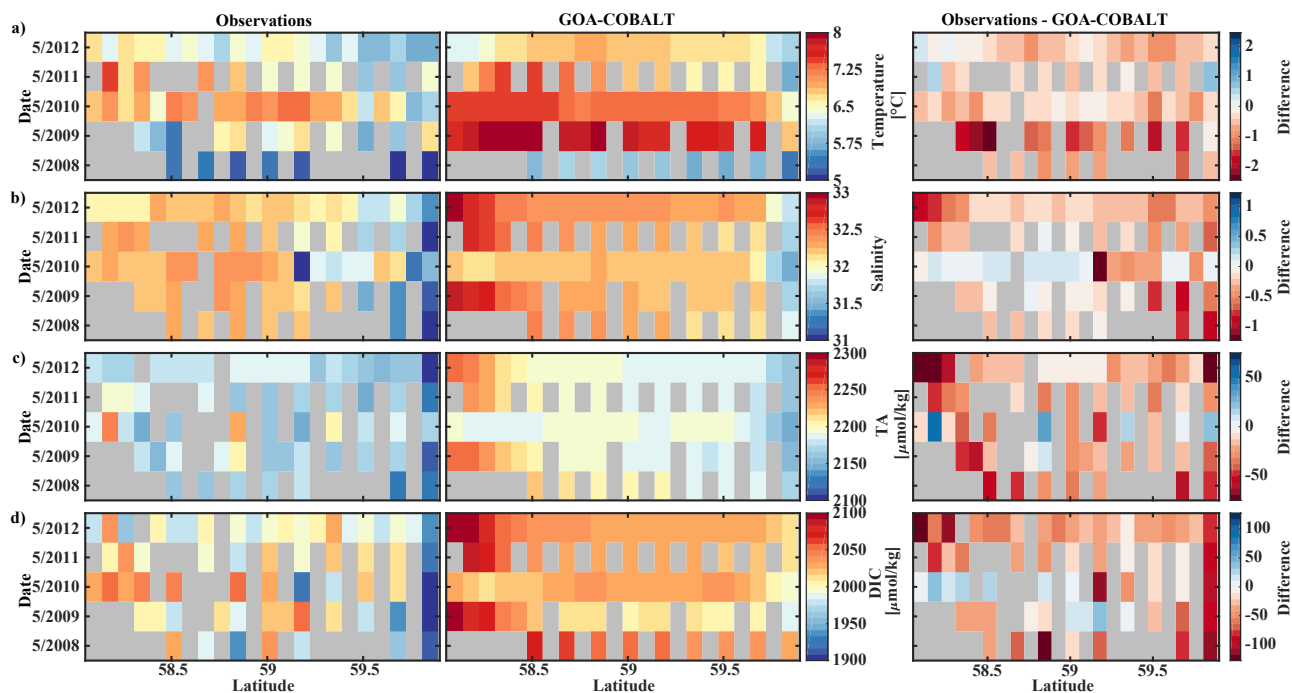
In September, nearshore surface waters are warm ( $\sim 11^{\circ}\text{C}$ ) and much fresher than in spring (Figures 5a and b). Observed surface salinity is as low as 27.6 at  $59.8^{\circ}\text{N}$  and increases to 32 salinity units at the end of the transect. Modelled surface salinity ranges between 26.3 and 31.8. It is important to note that observed surface salinity at the station closest to the coast is



**Figure 6.** Taylor diagrams (Taylor, 2001) of model simulated temperature, salinity, total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ), pH, and aragonite saturation state ( $\Omega_{arag}$ ) compared to observations taken along the Seward Line in a) May and b) September [across the upper 300 m \(Figures 4 and 5\)](#). [Averaged Climatologies of averaged](#) modelled monthly means of May and September are compared to [data collected climatologies of observed conditions](#) during spring and fall cruises in years 2008 through 2012. The distance from the origin is the normalized standard deviation of the modeled parameters. The azimuth angle shows the correlation between the observations and the modelled output, whereas the distance between the model point and the red observation point shows the normalized root mean square misfit between modeled and observed data.

also as low as 26.8, but is masked out in this point by point comparison. As a result of this bias in salinity, modelled [nearshore TA and DIC in the upper 30 m](#) are underestimated by [160 and 60-30 and 20  \$\mu\text{mol kg}^{-1}\$  at 59.8°N \(Figures 5c and d\)](#). Because the model is likely underestimating the magnitude of late season phytoplankton blooms, the bias in DIC is [not as large as slightly smaller than](#) in TA. Modelled [surface- \$\Omega\_{arag}\$  is 1.48 at the coast and thereby](#) underestimates observations by [0.27 < 0.2 in this area \(Figure 5f\)](#). At depth, model output aligns well with observations. Both observations and model output suggest that bottom waters across the Seward Line transect are undersaturated with regard to aragonite in fall. Observations also show an intermediate maximum in DIC at about 150 m depth, which leads to an even shallower aragonite saturation horizon ([Figure 5d](#)). This small scale feature may be due to remineralization at mid depth and is not simulated by the model. Overall, the model does a reasonable job [in simulating salinity, temperature, simulating the spatial patterns of salinity](#), TA, DIC, pH, and  $\Omega_{arag}$  in spring and in fall, with [Pearson Correlation Coefficients between 0.75 and 0.95, statistically significant \(p-value < 0.05\) Pearson correlation coefficients between 0.82 and 0.97 \(Figures 6a and b\)](#). The model overestimates springtime temperature along the surface and around 100 m offshore, which is reflected in a slightly lower Pearson correlation coefficient of 0.62. The Pearson



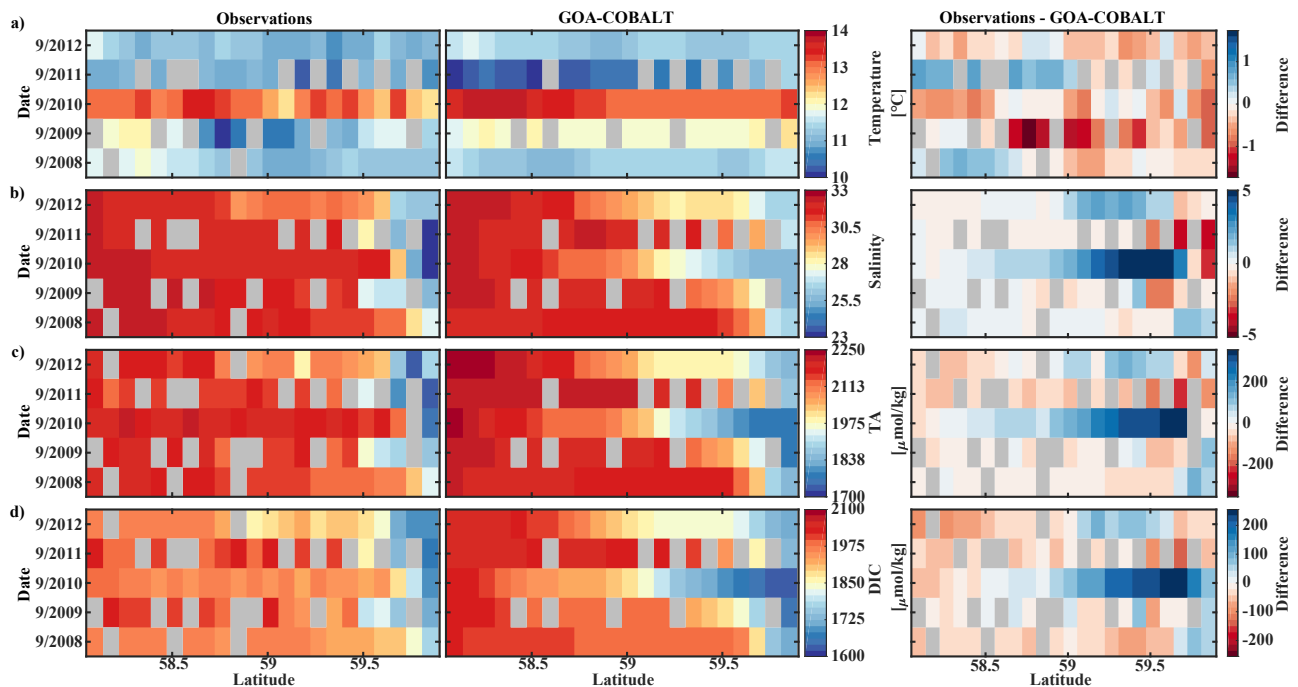


**Figure 7.** Hovmoeller plots showing observed (left) and modelled [monthly mean](#) (right) ~~monthly mean~~ surface (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ) in May along the Seward Line between 2008 - 2012. [Grey areas show missing data.](#)

[correlation coefficients and their corresponding p-values were calculated based on the climatologies presented in Figures 4 and 5.](#) All standard deviations and ~~Correlation Coefficients~~ [correlation coefficients](#) between observed and modelled variables are summarized in Taylor Diagrams in Figure 6.

### 3.4 Model skill to simulate interannual variability

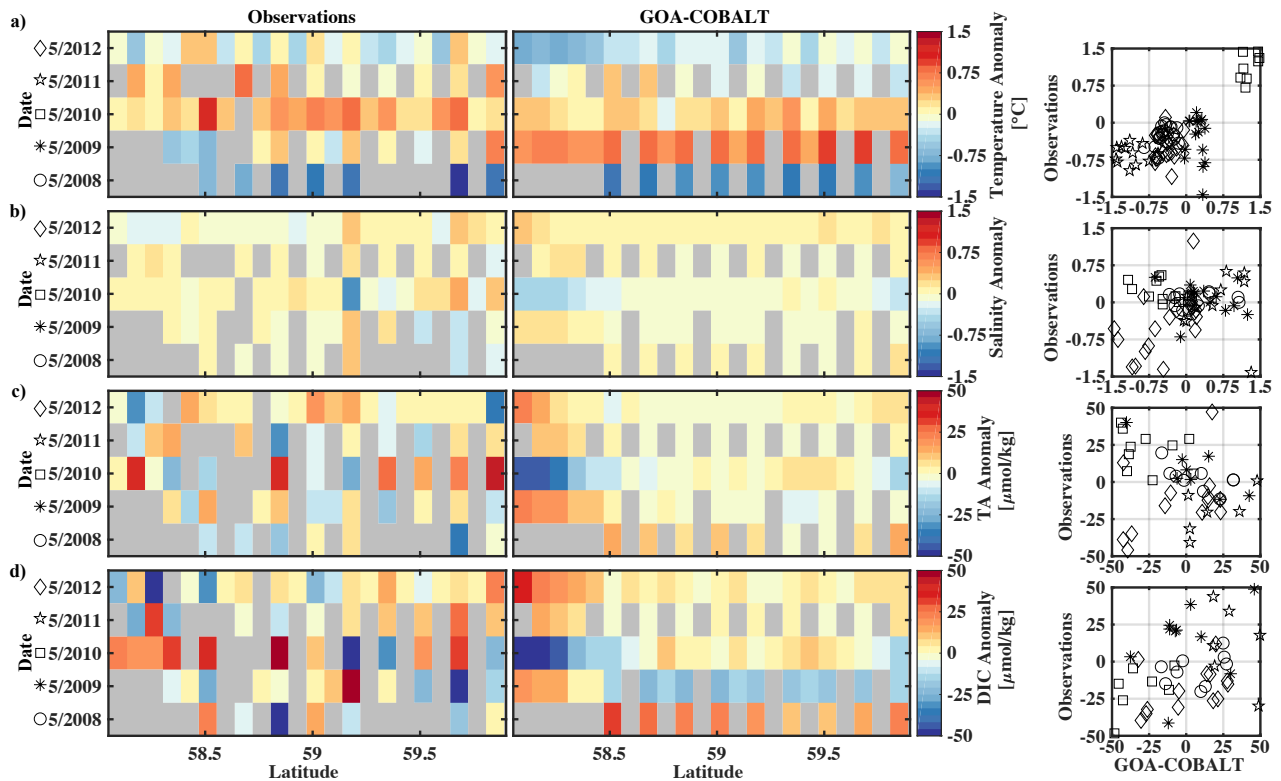
- 5 The GOA oceanography undergoes large interannual to decadal variability as a result of the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) and other climate modes of variability that drive changes in freshwater flux, water temperature and winds (Whitney and Freeland, 1999; Hare and Mantua, 2000). These physical changes are likely translated into the inorganic carbon chemistry. ~~As a first approach, we use Hovmoeller plots to~~ [Here, we](#) investigate the model's skill to simulate interannual features, [comparing Hovmoeller plots of observations taken in May and September between 2008 and 2012 and modelled monthly means of the corresponding time and location for temperature, salinity, TA, and DIC](#) (Figures 7 and 8). [We also calculated monthly observed and modelled anomalies for May and September, based on the observed and modelled five year monthly mean of each variable](#) (Figures 9 and 10). In the following, we will describe observations of years that stand out within this five year record and determine whether these features were captured by the model.
- 10



**Figure 8.** Hovmoeller plots showing observed (left) and modelled monthly mean (right) ~~monthly mean~~ surface (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ) in September along the Seward Line between 2008 - 2012. Grey areas show missing data.

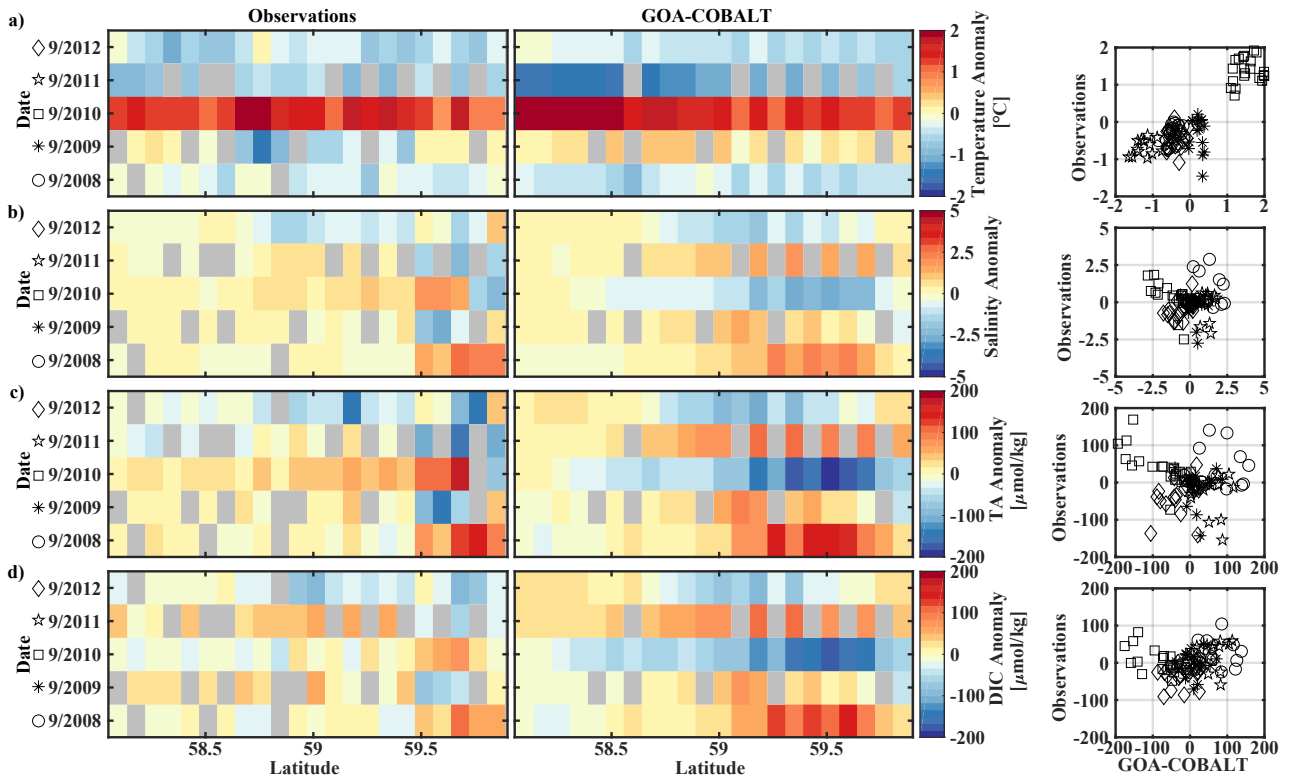
Observed and modelled springtime surface temperature show large interannual variability (Figure 7a and 9a). Within the 5 year long record, 2008 was a particularly cold spring, with surface temperatures around  $5^{\circ}\text{C}$ . The model also simulated May 2008 as the coldest spring ~~within this five year period, however, it~~ but overestimated the temperature by ~~about~~ approximately  $1^{\circ}\text{C}$ . In May 2010, observed sea surface temperatures were particularly high ( $> 6^{\circ}\text{C}$ ) across the shelf, which was well reflected by the model. While the model also suggests high temperatures in the previous spring, the observations do not show a particularly warm spring in 2009. ~~In May 2012, colder surface temperatures ( $< 6^{\circ}\text{C}$ ) prevailed near the coast and through station 15 in both the observed and modelled data.~~ The modelled and observed interannual variability of surface temperature in May are statistically significantly correlated with a Pcc of 0.54 (Table 3). The interannual variability in salinity is visible by how far the freshwater penetrates into the open ocean. For example, observations ~~and model output~~ suggest that freshwater penetrated farther offshore in ~~years 2008, 2009, and 2011.~~ ~~A similar pattern is visible in observed and modelled TA, with low TA values ( $< 2170 \mu\text{mol kg}^{-1}$ ) advecting across the shelf and beyond in 2009 and 2010.~~ As already described in Section 3.3, the model persistently overestimates DIC in spring and summer. While the influence of low salinity on DIC becomes visible in 2009 and 2010, the observed low DIC in 2012 was not reproduced than in other years (Figure 7b), which was not reflected by the model; likely because it was driven by strong biological carbon drawdown rather than freshwater.

15 The anomalous warm sea surface temperatures observed in spring 2010 remained persistent into fall, with temperatures around



**Figure 9.** Hovmoeller plots showing observed (left) and modelled (center) monthly anomalies from the 5-year mean (2008–2012) of surface (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ) in May along the Seward Line. Grey areas show missing data. The right column shows plots of observed versus modelled monthly anomalies for the corresponding parameter. Different marker types are used to indicate different years. Marker legend is given in the left column. Root mean square error (RMSE), Pearson correlation coefficient (Pcc), and p-value for the observed and modelled interannual monthly anomalies are listed in Table 3.

13  $^{\circ}\text{C}$  across the whole transect (Figure 8 Figures 8a and 10a). This anomalously warm fall was well simulated by the model. Overall, modelled interannual variability of fall surface temperatures correlated well with the observations (Pcc = 0.87,  $p < 0.05$ ). Interestingly, in the same-year anomalously warm fall of 2010, observations suggest anomalously high salinities penetrating closer to the nearshore than in other years, which was not reflected by the model (Figures 8b and 10b). However, observed lower salinities mid transect in 2009 and 2011–2012 were also simulated by the model, which directly translated into TA and DIC (Figures 8c and d). Overall, fall DIC levels were better simulated by the model than spring conditions there was no clear interannual pattern in observed or simulated salinity, TA, and DIC between 2008–2012 (Figures 7–10b-d), and no statistically significant correlation between the observed and modelled spring and fall anomalies (Table 3).



**Figure 10.** Hovmoeller plots showing observed (left) and modelled (center) monthly anomalies from the 5-year mean (2008 -2012) of surface (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), and (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ) in September along the Seward Line. Grey areas show missing data. The right column shows plots of observed versus modelled monthly anomalies for the corresponding parameter. Different marker types are used to indicate different years. Marker legend is given in the left column. Root mean square error (RMSE), Pearson correlation coefficient (Pcc), and p-value for the observed and modelled interannual monthly anomalies are listed in Table 3.

#### 4 Seasonal inorganic carbon variability along the Seward Line

The historic Seward Line timeseries gives insights into the inorganic carbon dynamics in May and September. Here, we use our model output to explore other months of the year that are not covered by inorganic carbon observations (Figure 11). Lowest surface temperatures of  $< 3^{\circ}\text{C}$  are found nearshore in February and March (not shown). In spring, surface ~~water-waters~~ slowly warm, reaching an annual maximum in July/August, when surface temperatures are  $> 13^{\circ}\text{C}$ . Highest nearshore surface salinities ( $S^{max}=31$ ) are observed in late winter, which decrease to 24 salinity units between August and October, when the influence of freshwater is strongest. The freshwater also decreases surface TA and DIC to their lowest levels of  $1625 \mu\text{mol kg}^{-1}$  and  $1500 \mu\text{mol kg}^{-1}$ , respectively, in August. The additional biologically driven decrease of DIC between April and June, when surface Chl- $\alpha$  concentrations (up to  $7 \mu\text{g kg}^{-1}$ ) are highest, leads to relatively high pH (8.13) and  $\Omega_{arag}$  (2.05),

**Table 3.** Table listing root mean square error (RMSE), Pearson correlation coefficient (Pcc), and p-value between observed and modelled interannual variability at the surface. RMSE, Pcc, and corresponding p-value were based on observed and modelled monthly anomalies from a temporal mean of May (2008 - 2012) along the Seaward line transect. Statistically significant Pccs and the p-values are indicated in bold. The anomalies are shown in Figures 9 and 10.

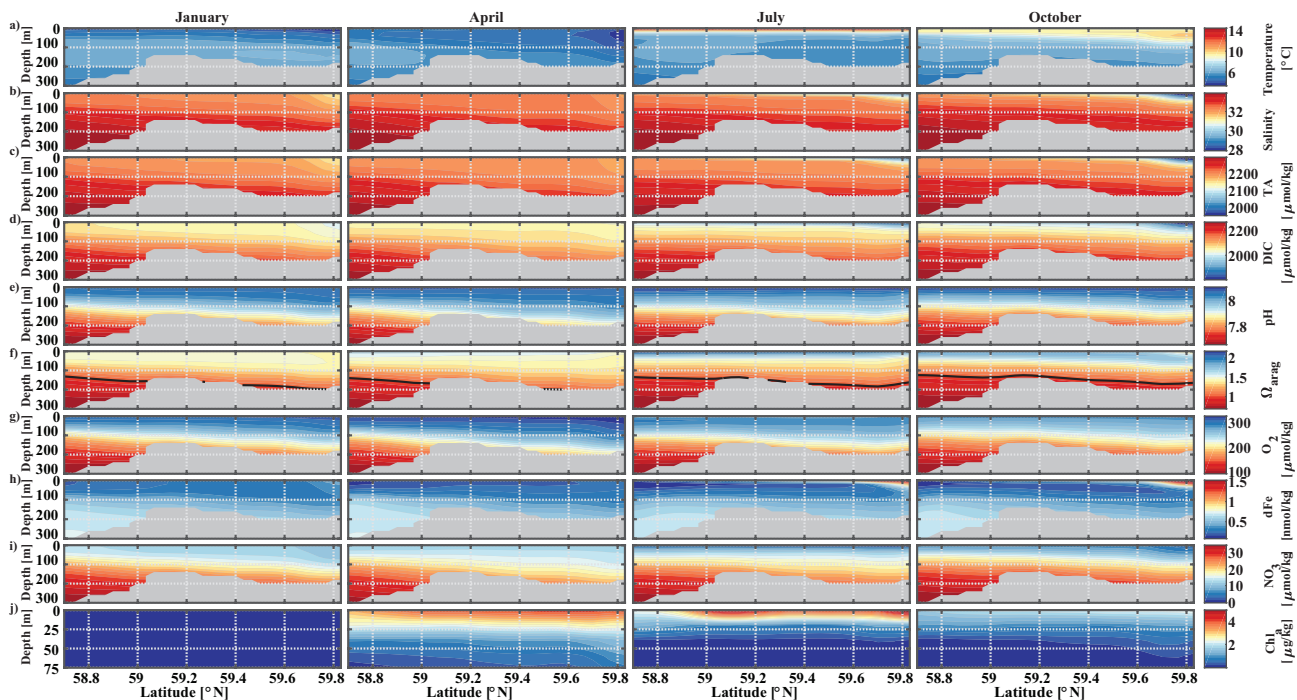
Parameter	Month	RMSE	Pcc	p-value
Temperature	May	0.50	<b>0.54</b>	<b>&lt;0.05</b>
	September	0.48	<b>0.87</b>	<b>&lt;0.05</b>
Salinity	May	0.24	-0.08	0.48
	September	1.42	-0.03	0.80
TA	May	21.6	-0.22	0.09
	September	98.5	-0.19	0.08
DIC	May	32.6	-0.23	0.07
	September	69.1	0.18	0.10

despite the freshwater influence and its diluting character. Once phytoplankton blooms begin to taper off in July and August, DIC slowly increases relative to TA, leading to a decrease in  $\Omega_{arag}$  to a low of 1.21 and pH of 8.05 in October.  $\Omega_{arag}$  remains  $< 1.5$  across the whole water column between January and March. In April, the incoming light and nutrient concentrations are sufficient again to trigger phytoplankton blooms that slowly decrease DIC and thereby increase  $\Omega_{arag}$  and pH.

- 5 Starting in May, downwelling relaxes and more saline and DIC rich waters intrude onto the shelf, leading to maximum bottom salinities and DIC of  $S^{max}=33.6$  and  $DIC^{max}=2186 \mu\text{mol kg}^{-1}$ , respectively, on the shelf. Relaxation of downwelling results in aragonite undersaturation of bottom waters across the transect between June and January. Destruction of organic matter and remineralization additionally increase DIC between June and September and thereby further enhance aragonite undersaturation (Figure 12 b). ~~Only nearshore areas north of 59.8°N remain oversaturated throughout the year.~~ The onset of downwelling in
- 10 September typically starts the annual decrease of near-bottom shelf salinity and DIC ( $\Omega_{arag}$  and pH) levels, which reach their respective minimums in late winter or spring.

### 5 Influence of glacial freshwater on surface $\Omega_{arag}$ , pH, and $p\text{CO}_2$

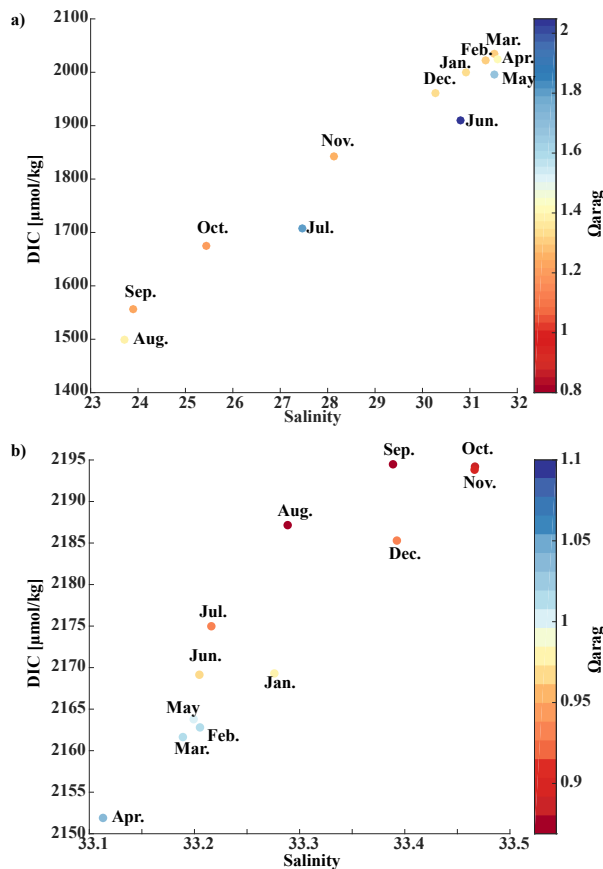
Glacial freshwater is the most important driver of the near-shore inorganic carbon dynamics of the GOA in summer and fall. ~~In the following, we~~ We further investigate the influence of coastal dilution from the ~~non-zero DIC and TA and rather~~ ~~acidic freshwater end-member (Table 2)~~ rather acidic TA and DIC freshwater end member (Table 2) on surface  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$  (Figure 13a). ~~To do so, we used mixing.~~ Following the step by step description in Rheuban et al. (2019) we used a linear Taylor decomposition to separate and analyze the controlling factors of the variability in surface  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$ . Offshore mixing endmembers of  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$  were determined from offshore DIC and TA in April and August with CO2sys.m



**Figure 11.** Seward Line transect of modelled (a) temperature ( $^{\circ}\text{C}$ ), (b) salinity, (c) total alkalinity (TA,  $\mu\text{mol kg}^{-1}$ ), (d) dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ), (e) pH, (f) aragonite saturation state ( $\Omega_{arag}$ ), (g) dissolved oxygen (DO,  $\mu\text{mol kg}^{-1}$ ), (h) dissolved iron (FE,  $\text{nmol kg}^{-1}$ ), (i) nitrate ( $\text{NO}_3$   $\mu\text{mol kg}^{-1}$ ), and (j) Chl- $\alpha$  ( $\mu\text{g kg}^{-1}$ ) in January, April, July, and October (averaged across 2008 - 2012). Note that Chl- $\alpha$  is only plotted across the upper 75 m of the water column. The black solid line in row f indicates  $\Omega_{arag} = 1$ . [The grey areas indicate seafloor.](#)

(Lewis and Wallace, 1998; van Heuven and Wallace, 2011) and were used as reference values. All calculations are based on the dissociation constants of Lueker et al. (2000) and the  $\text{KHSO}_4$  and Total Boron-Salinity formulations of Dickson (1990) and Dickson (1974), respectively. Anomalies from the reference value were calculated for each grid cell using a linear Taylor series decomposition, adding up the thermodynamic effects of temperature and salinity, the perturbations due to biogeochemistry, and conservative mixing with freshwater DIC and TA endmembers. For a more detailed description of the methodology the reader is referred to Rheuban et al. (2019). We focus our analysis on April and August because these two months are, respectively, the least and most affected by freshwater. Figure 13 shows mixing diagrams of surface  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$  versus salinity from an area starting at the Kenai Peninsula to south of Yakutat Bay. Note that the plots show the effects of salinity changes, and biogeochemistry on surface  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$ , as well as seasonal differences in temperature and in the off-shore and freshwater end-members DIC and TA. Following Rheuban et al. (2019), we used a linear Taylor decomposition to evaluate the importance of these different drivers in controlling the variations in surface  $\Omega_{arag}$ , pH, and  $p\text{CO}_2$  (Figure 14). The shaded areas in Figures 13c and d show the additive effect-effects of salinity and dilution with seasonally varying DIC and TA freshwater end-members as calculated with the linear Taylor expansion. The grey area in Figure 13c





**Figure 12.** Salinity-Modelled salinity versus dissolved inorganic carbon (DIC,  $\mu\text{mol kg}^{-1}$ ) as a function of  $\Omega_{arag}$  and month a) at the surface and grid cell closest to the coast and b) on the seafloor at 59.2 °N along the Seward Line. Note that colorbars and axis are on different scales.

accounts for variability in DIC and TA between January and April and in Figure 13c for DIC and TA variability between April and August. Deviations from the shaded area are driven by biogeochemistry and temperature. ~~We focus our analysis on April and August because these two months are, respectively, the least and most affected by freshwater.~~

In April, surface salinity is  $> 30$ , with exception of a few near-shore spots in Prince William Sound and Yakutat Bay, where surface salinity can decrease to 28 salinity units (Figure 13 a). Surface  $\Omega_{arag}$  ranges between 1.5 and 1.85, pH varies between 8.08 and 8.10, and  $p\text{CO}_2$  between 280  $\mu\text{atm}$  and 340  $\mu\text{atm}$  (Figures 13 b and c).

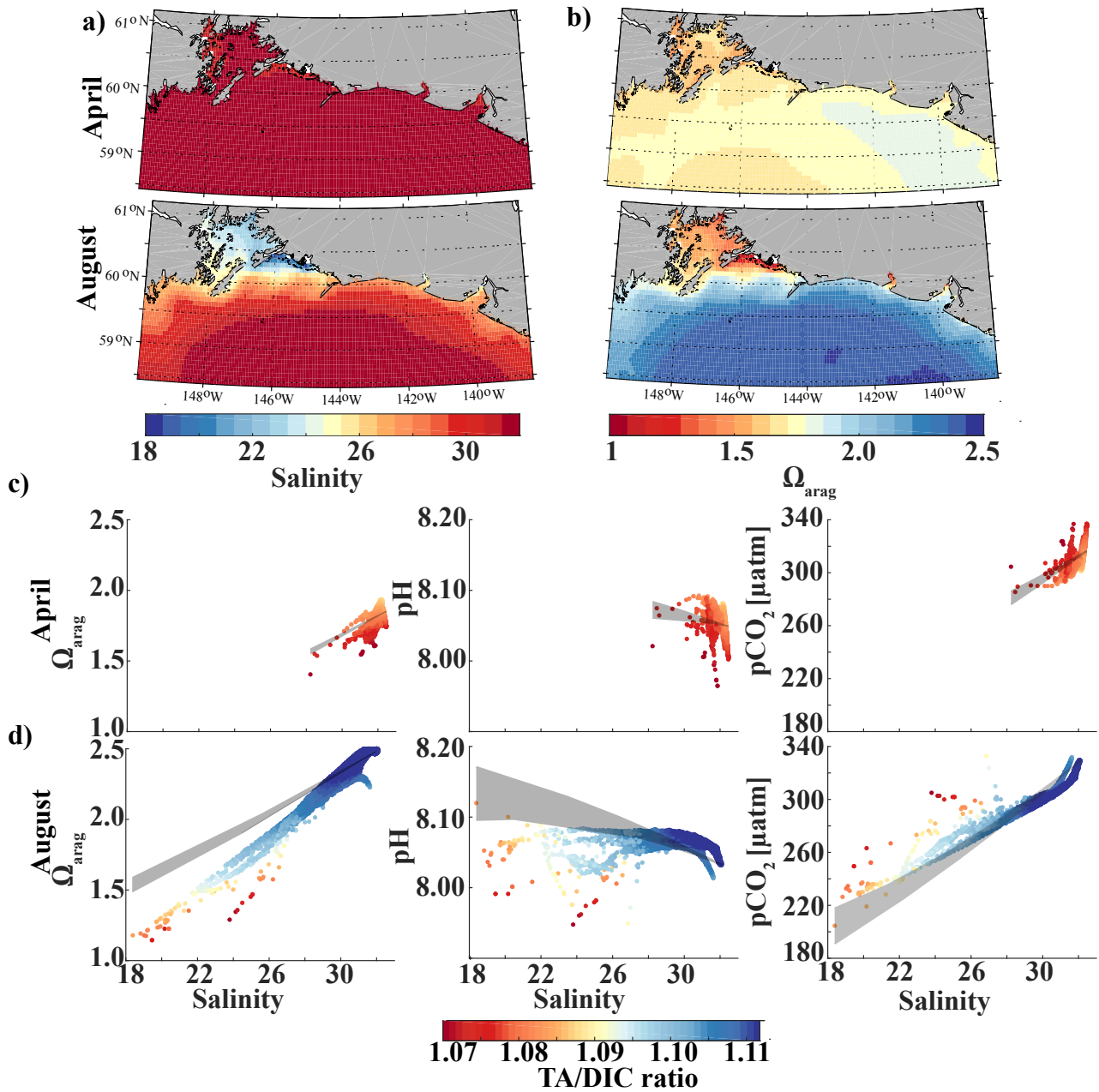
In August, surface salinity can be as low as 18 in Prince William Sound and near Copper River, with a strong salinity gradient increasing towards offshore, reaching salinities  $> 32$  there (Figure 13a). Surface  $\Omega_{arag}$  ranges between 1.14 and 2.5 ~~and~~, pH between 8.07 and 8.16, and  $p\text{CO}_2$  between 205  $\mu\text{atm}$  and 333  $\mu\text{atm}$ , both reflecting the strong reflecting the influence of freshwater. ~~In contrast, the range of pH in August is similar to the one in April (8.07 to 8.16), suggesting that freshwater affects pH to a much smaller degree than  $\Omega_{arag}$  and  $p\text{CO}_2$ . Decreasing salinity exerts a positive effect on~~ in fall (Figure 13d).

The linear Taylor decomposition indicates that decreasing salinity increases both,  $\Omega_{arag}$  and pH, while mixing with low TA and DIC freshwater end-members has a negative effect. For pH, the positive effect of end members decreases  $\Omega_{arag}$  and pH (Figures 14a and b). The increase in pH due to decreasing salinity is much stronger than for  $\Omega_{arag}$ , thereby cancelling or even counteracting, depending on the freshwater end-member, the negative effect of mixing. In contrary, end member, the decrease in pH due to mixing. Thus, the influence of salinity on pH works to counteract the influence of low TA and DIC freshwater end members on pH such that the observed pH exhibits no correlation with the observed salinity.  $\Omega_{arag}$  is more strongly affected by mixing than by salinity, resulting in a decrease of  $\Omega_{arag}$  by about 1 unit (Figures 14a and b). In contrary, In contrast to  $\Omega_{arag}$  and pH, decreasing salinity exerts a strong negative effect on strongly decreases  $pCO_2$ , which is also supported by, but to a lesser extent, a negative effect of counteracted to some degree by an increase of  $pCO_2$  due to mixing with low TA and DIC end-members end members and respiration (Figure 14c). The additive effects of salinity and mixing with low TA and DIC freshwater therefore lead to a decoupling of  $\Omega_{arag}$ , pH, and  $pCO_2$ . Deviations from the shaded areas in Figure 13d are mainly driven by biogeochemistry, decreasing which decreases  $\Omega_{arag}$  and pH, and increasing increases  $pCO_2$  as a result of net respiration during August. Temperature effects are small for  $\Omega_{arag}$  and pH, whereas for  $pCO_2$ , the negative effect of decreasing temperature is similar to the negative effect of mixing with low TA and DIC freshwater end-members end members, enhancing a decrease in  $pCO_2$ .

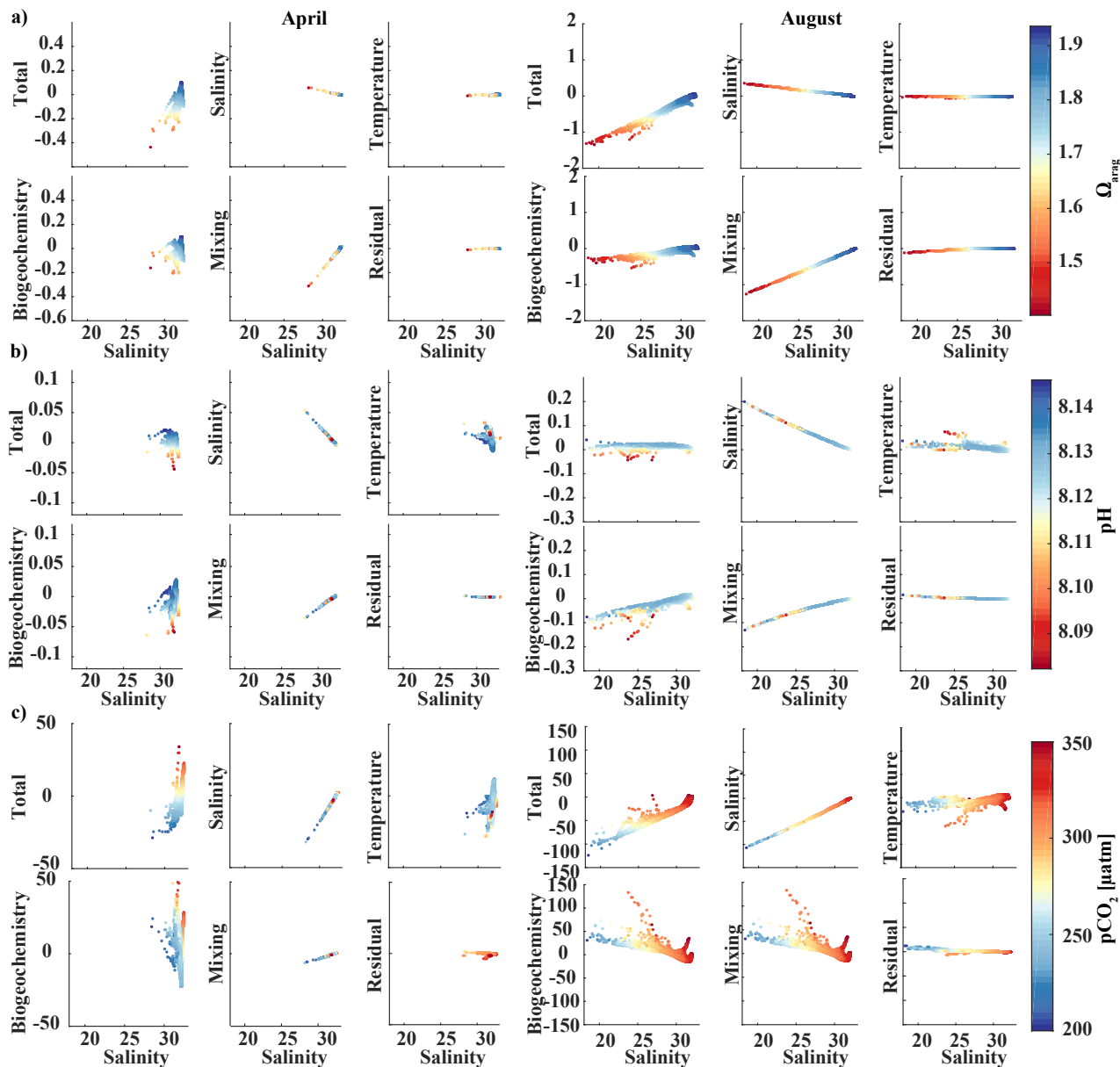
## 6 Summary and Conclusions

Here, we introduced a new regional biogeochemical model GOA-COBALT and evaluated the model's skill in simulating seasonal and interannual inorganic carbon patterns. Our model set-up is unique because it includes a moderately-high-resolution moderately high-resolution, three-dimensional regional ocean circulation model, a complex ecosystem model with an ocean carbon cycle, a high-resolution terrestrial hydrological model, and is forced with reanalysis products to simulate interannual variability and long term changes over the past 30+ years. In addition, we used available TA and DIC observations to parameterize seasonal concentrations of DIC and TA in the freshwater forcing.

Comparison with a limited amount of *in situ* inorganic carbon observations showed that the model is able to reproduce the general hydrographic and inorganic carbon patterns along the Sewardline in spring and fall. The GOA-COBALT was particularly successful in reproducing the depth of the aragonite saturation horizon, showing oversaturated conditions across large parts of the shelf in May and undersaturation across the shelf in September. The largest deficiency of (Figures 4 and 5). GOA-COBALT may be that it generally overestimates generally overestimates peak Chl- $\alpha$  concentrations and that the Chl- $\alpha$  peak is simulated in June rather than in May. Interestingly throughout spring and summer (Figure 3). However, results of the inorganic carbon data - model analysis suggest, however, that DIC is not drawn down enough by spring biological production (Figure 4). This contradiction may be due to an underestimation of modelled C:Chl- $\alpha$  ratios, which are dependent on light and nutrient limitation (Geider et al., 1997; Stock et al., 2014). Modelled C:Chl- $\alpha$  of large and small phytoplankton on the shelf are < 30 g/g and < 40 g/g respectively. Measurements of C:Chl- $\alpha$  of small phytoplankton in the GOA suggest a median C:Chl- $\alpha$  of 41 g/g during intense and early blooms and 76 g/g in low Chl- $\alpha$  conditions (Strom et al., 2016). Equivalent data for large



**Figure 13.** Map of climatological mean (1980 -2013) of a) surface salinity and b) surface  $\Omega_{arag}$  in April (top) and August (bottom). Plots of surface  $\Omega_{arag}$  (left), pH (middle), and  $pCO_2$  [ $\mu\text{atm}$ ](right) vs. salinity as a function of TA/DIC ratio in c) April and d) August. The shaded area indicates the range of  $\Omega_{arag}$ , pH, and  $pCO_2$ , respectively, if changes of the respective variable would only arise from variations in salinity and from the dilution effect of freshwater on DIC and TA.



**Figure 14.** Component distributions of the linear Taylor decomposition of surface a)  $\Omega_{arag}$ , b) pH, and c)  $pCO_2$  versus salinity in April (left) and August (right). Following Rheuban et al. (2019) components are total perturbation from the oceanic ~~end-member~~ end member (Salinity > 32), perturbations due to salinity, temperature, biogeochemistry, freshwater mixing, and an estimated residual term.

phytoplankton does not exist.

GOA-COBALT is more successful in reproducing surface inorganic carbon patterns in September, when freshwater is the dominant driver of the system. ~~In addition to its capacity of resolving prominent seasonal inorganic carbon variability, the~~

~~model also resolved some of the observed interannual differences present in the publicly available five-year-long inorganic carbon Seward Line record.~~ However, the GOA-LME is largely undersampled despite its large spatial and temporal variability. ~~The~~ limited amount of inorganic carbon observations that cover one transect in May and September, and include a few newer nearshore ~~time-series~~ time series are not sufficient to properly evaluate the model. More observations are needed to test the model's skills in areas other than the Seward Line and during other times of the year. While some of the year to year differences seen in Figures 7 and 8 may be a result of aliasing the spatial and temporal variability that exists during the cruises, the most prominent anomalies reproduced by the model have been described in the past. For example, as a result of anomalies in coastal runoff, winter cooling, stratification, and winds, sea surface temperature was by 1.5 °C colder in spring 2006, 2007, and 2008 than average spring temperatures, and the lowest since early 1970 (Janout et al., 2010). In contrast, as a result of warm air temperatures, GOA sea surface temperatures in 2009-2010 were anomalously high (Danielson et al., 2019).

The ~~relationship~~ observed seasonal relationships between  $\Omega_{arag}$ , pH, and  $pCO_2$  in freshwater influenced coastal waters ~~is different than what is found elsewhere~~ off of Alaska are different from those found in other regions, such as the open ocean (Figure 13). Similarly to what Evans et al. (2014) observed *in situ* near a tidewater glacier in Prince William Sound, our freshwater-inorganic carbon analysis showed that low  $\Omega_{arag}$  values are not always accompanied by low pH and high  $pCO_2$  values in this glacially influenced environment. This decoupling of the three inorganic carbon parameters is driven by the additive effects of salinity and mixing with low TA and DIC ~~end-members~~ end members. Whether the freshwater induced low surface  $pCO_2$  caused enhanced  $CO_2$  uptake in coastal areas, as speculated by Evans et al. (2014), could not be confirmed here and will need additional investigation.

The strong influence of freshwater on the inorganic carbon system emphasizes the importance of choosing the right DIC and TA ~~freshwater endmembers~~ concentrations in freshwater in order to correctly model the inorganic carbon dynamics in this area. However, there is a lack of biogeochemical data that describes the composition of different freshwater sources on seasonal timescales. The biogeochemical composition of freshwater is influenced by its exposure to basal rock and therefore by the pathways and duration it takes, and processes it undergoes until it is introduced to the ocean (Lacroix et al., 2020). Current sources of freshwater in the GOA are tidewater glaciers, proglacial streams, and non-glacial streams, each exposing the water to basal rock, soils and the atmosphere differently. As this region continues to rapidly deglaciate (Arendt et al., 2002; Larsen et al., 2007; O'Neel et al., 2005), not only the amount of freshwater discharge will increase (Beamer et al., 2017), but most of the glaciers surrounding the GOA will recede away from the ocean and into higher elevations (Huss and Hock, 2015), resulting in a change of the biogeochemical composition of freshwater. This and previous studies have shown that freshwater discharge is the largest driver of the nearshore inorganic carbon dynamics in summer and fall, and is known to exacerbate the effects of ocean acidification (Evans et al., 2014; Siedlecki et al., 2017; Pilcher et al., 2018). Understanding the composition of freshwater sources is, therefore, particularly important for the study of long-term trends of ocean acidification in the GOA-LME. As a first best approach, we used seasonal observations of DIC and TA from Kenai River (proglacial river) and applied it to every freshwater point source across the domain, however this approach is likely masking out large differences in the biogeochemical composition of freshwater input that could have implications on the coastal inorganic carbon system.

Precipitation is only counted as negative salt flux and does not change the volume or dilute any other parameters in this current

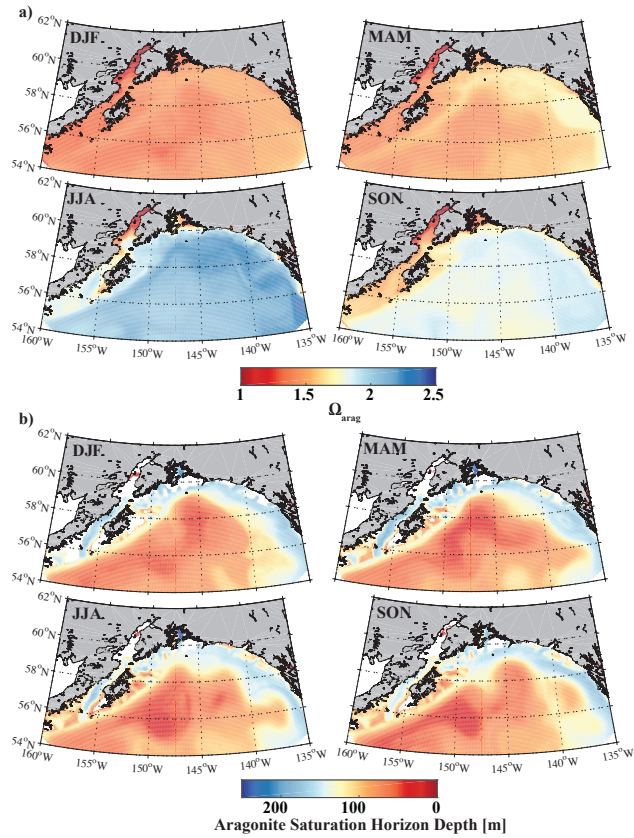
GOA-COBALT model version. While the decrease in salinity increases  $\Omega_{arag}$  and pH, and decreases  $pCO_2$  (Figure 14), our model does not account for the diluting effect of low TA and DIC rainwater. Annual mean riverine input into our model domain is 1.5 times higher than annual mean precipitation across the first 100 km along the coast and up to 7 times higher across the first 10 km along the coast. Model cells in vicinity of large rivers, such as the Copper River, receive up to three orders of magnitude more freshwater from rivers than from precipitation. Furthermore, the modeled surface salinity pattern closely reflects the influence of riverine input (Figure 13), whereas the precipitation pattern is not mirrored (not shown). The diluting effect of precipitation on TA and DIC therefore seems to be negligible compared to the large volumes of water coming in from the thousands of streams and rivers along the coast. However, this hypothesis still needs to be tested, especially because rain may increase in the future as a result of climate change (McAfee et al., 2014).

The only other regional biogeochemical model with an oceanic carbon cycle (Siedlecki et al., 2017; Pilcher et al., 2018) used Royer (1982)'s monthly riverine input ~~time-series~~ [time series](#) and applied it equally to the top cell along the coast, masking out the large spatial and interannual variability of freshwater input along the GOA coast. Furthermore, Siedlecki et al. (2017) simulated year 2009, with only one year of spinup and with DIC and TA boundary conditions based on salinity relationships. Their static freshwater TA concentration to represent a tidewater glacier was  $650 \mu\text{mol kg}^{-1}$ , while freshwater runoff did not affect coastal DIC at all. In comparison, our GOA-COBALT model and the Siedlecki et al. (2017) both simulate the lowest surface  $\Omega_{arag}$  in winter and highest in summer (Figure 15). Similarly, the aragonite saturation horizon is shallowest in summer and fall in both models. In our model, the aragonite saturation horizon is shallower throughout the year, thereby causing aragonite undersaturation across wider areas on the shelf. A thorough model inter-comparison study would need to be done to understand how the new features of our model set-up have affected and potentially improved the modeling results over Siedlecki et al. (2017) and Pilcher et al. (2018).

Our simulation results give new and important insights for months of the year that lack *in situ* inorganic carbon observations. For example, the majority of the near-bottom water along the Seward Line is seasonally ~~under-saturated~~ [undersaturated](#) with regard to aragonite between June and January. Such long and reoccurring aragonite undersaturation events may be harmful to  ~~$CO_2$ -sensitive~~ [some](#) organisms. Furthermore, between January and March, conditions are unfavorable for pteropods across the entire water column with aragonite saturation state  $< 1.5$  ([Bednaršek et al., 2019](#)). This study also made it apparent that more observations across the shelf and different times of the year are needed in order to improve the model and evaluate its skills in areas other than near Seward.

Future work will focus on the progression of ocean acidification and climate change and impacts on the inorganic carbon chemistry. We also anticipate this simulation to be a useful tool for the study of the duration and intensity of extreme events and climate-ocean teleconnections. With increased confidence in the model, another logical next step would be to guide the future expansion, diversification, and optimization of OA observing systems in the GOA-LME.





**Figure 15.** Climatological mean of a) surface aragonite saturation state ( $\Omega_{arag}$ ) and b) aragonite saturation horizon (m) for December, January, and February (DJF), March, April, and May (MAM), June, July, and August (JJA), and September, October, and November (SON).

*Code and data availability.* The code and forcing files are available on zenodo.org under DOI's 10.5281/zenodo.3647663, 10.5281/zenodo.3661518, and 10.5281/zenodo.3647609. The model output is publicly available (<https://doi.org/10.24431/rw1k43t>) and can be visualized with a user-friendly web interface. This is a product of our collaboration with Axiom Data Science.

*Author contributions.* K.H., C.H., S.D., and C.S. developed and tuned the model system for the GOA. C.H. and B.I. prepared the model output. C.H., C.S., B.I., and S.C.D. analyzed the model output. R.D. ported the COBALT code into ROMS. All authors commented on the manuscript.

*Competing interests.* We declare that no competing interests are present.

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