nature portfolio

Peer Review File

Upper ocean warming and sea ice reduction in the East Greenland Current from 2003 to 2019.

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

1st Mar 23

Dear Dr de Steur,

Please allow me to apologise for the delay in sending a decision on your manuscript titled "Ocean heat increase and sea ice reduction in the Fram Strait conveys Arctic Ocean change". It has now been seen by 2 reviewers, and I include their comments at the end of this message. They find your work, and in particular your data, of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. For publication in Communications Earth & Environment to be appropriate, we will need you to develop the narrative of your manuscript to clarify the advance your paper represents over the existing literature, for example, along the lines suggested by the reviewers. We encourage you to discuss the background literature in more detail, and also work on a more comprehensive discussion of implications of your findings. Title and abstract should reflect the insights that you add to the published literature.

Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Heike Langenberg, PhD

Chief Editor

Communications Earth & Environment

On Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements (Download the link to your computer as a PDF.)

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:

Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

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In particular, the Data availability statement should include:

- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)

- Accession codes where appropriate

- If applicable, a statement regarding data available with restrictions

- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in

the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper reports important observations of changes in the oceanographic properties in Fram Strait over the last 20 years. In particular, the temperature of the upper East Greenland Current (EGC) has increased significantly. On the continental shelf, the Polar Water (PW) has warmed in summer (Fig 2), which is linked to reduced sea ice upstream one month earlier and greater ocean heat content (Fig. 3). On the slope, warm Atlantic Water (AW) now occurs year-round, not just in summer (Fig. 4). The change is linked to warm sea-surface temperatures in the central Fram Strait one month earlier (Fig. 5). The change occurred as a step-like regime shift in summer 2015 (Fig. 6). Collectively, the Fram Strait temperature increases are linked to sea ice reductions downstream in subsequent months (Figs 7, 8).

The datasets are valuable to Arctic oceanographers and climate scientists. The reported temperature changes, and their prior and subsequent effects, are important. These are significant changes to a region that is sensitive to anthropogenic climate change. These changes may have important downstream and subsequent consequences for ocean properties and ocean circulation.

The paper is well written and carefully reasoned. The figures are clear. There are a few minor issues, mostly to do with clarity, and some typos etc. There are no major weaknesses. However, I have a couple of comments that are more significant. Overall, I think a minor revision is needed then the paper should be accepted.

Major Comments

1. Some statements depend implicitly on the reference temperature used to compute the heat flux or heat content. For example, line 28 says “a near doubling of heat content in the Beaufort Gyre halocline”. Another example is at line 141, which says “PW in the upper 55 m contained ten times more heat”. The “doubling” and “ten times” statements depend on the arbitrary reference temperature. Therefore, they don’t have robust physical significance because of the sensitivity to reference temperature. The statements should be revised to avoid this ambiguity.

2. The paper shows in-situ measurements of temperature, salinity and ice draft. I presume the moorings carried current meters as well. What about these velocity measurements? Velocity measurements provide important context for the temperature changes. Specifically, what current changes (if any) are associated with the temperature changes? Does the 2015 regime change reflect a change in current (e.g., its direction or variability)? The answers to these questions may illuminate the speculation on line 114 about eddies.

Minor Comments

Lines 11–12: State the season for the upper ocean temperature increase? (summer on the shelf from Fig 2 and year-round in the eastern EGC from Fig 4). Or connect the sentences starting “We show that” and “While Polar Water”. The novice reader might not grasp that Polar Water and Atlantic Water refer to the upper EGC.

Lines 99–102: It says about Fig 2e, f: “These profiles demonstrate that anomalously high temperatures in the upper 55 m toward the surface are related with a thicker layer of fresh upper halocline water, while subsurface temperature maxima are associated with saline halocline water.” I don’t see this in Fig 2e, f. Part of the problem is the colors used for different years (they’re too similar). It’s also hard to see all the different profiles. I can see that 2014 and 2015 subsurface temperature maxima go along with salty anomalies. And the 2017 (I think) surface was warm and fresh. But the 2014 and 2015 surface layer was very fresh and not anomalously warm, and the 2019 subsurface temperature maximum was fresher than the 2003–2009 average. To clarify these points, it would help to show T/S diagrams. Also mark the vertical profile times on Fig 2a, b, and distinguish the different year colors more.

Line 122: It says “The positive correlation of large temperature anomalies with OWF (open water fraction) for the years with fresh halocline waters, while this was the case for the saline halocline waters (Fig. S3), demonstrates the relationship between reduced summer sea ice and increased heat input into the upper ocean upstream of the shelf mooring.” I think I understand the sentence (following lines 98–100), but it should be made clearer, especially the part about saline halocline waters. In particular,

explain the rationale for splitting the temperature anomaly/OWF correlations into fresh and salty groups.

Line 142: What salinity is used for the “freezing point of seawater”? Is it fixed?

Line 157: It says “Observed ocean temperature anomaly from similar depths in the West Spitsbergen Current (WSC) also shows a positive anomaly in subsurface temperature in 2016-2018, however, with a smaller amplitude than observed in the eastern EGC (Fig. 5b)”. Is this figure reference correct? There are no WSC data in Fig. 5b. Should it be Fig. 6e?

Line 180: It says “…processes demonstrate the crucial role of the ice-albedo feedback”. But what about other sea ice processes unrelated to ice-albedo feedback, like suppression of air/sea fluxes by sea ice? This seems to be consistent with Fig. 3b for instance (strong correlation between open-water fraction and cumulative heat flux).

Lines 188–190: It says “the correlation between winter ESIT (effective sea ice thickness) at the eastern ice edge of the EGC with ocean temperature at 3°W in winter increased from 0.65°C to 1°C”. This doesn’t make sense. How can the correlation increase from 0.65 to 1oC?

Lines 201–205: These lines are unclear to me. The first sentence is “The time series for the downstream sites at given lags relative to the observed temperature changes in the Fram Strait demonstrates that the resultant SIC anomalies downstream in the EGC could be as much as 30%”. 30% of what? Reword to clarify. The second sentence is: “The former showing a failry (sic) gradual change in time, and the latter showing the biggest changes as of 2015 following the detected shift in Fram Strait.” Again, reword to clarify.

Lines 213–214: It says “we ascribe these (negative sea ice thickness anomalies) to the increased ocean warming in (late) summer 2017 and 2018 as well as the increased presence of AW”. Why can’t thinner ice upstream (e.g., in the transpolar drift) cause the thickness deficits? I don’t understand why there must be a link to the nearby warming and remote effects are ruled out.

Figure 1: What do the different “EGC” arrows in (a) and (b) mean?

Figure 3: It says “when seasonal T anomaly was associated with S<33”. Make clear that this means the monthly salinity anomaly at 55m from the mooring (presumably). Similar problems occurs on other

figure captions, like Figs. 5 and S3, It's unclear when "temperature" or "salinity" mean from the mooring, or from another source.

Figure 6: State that the temperature data are from mooring F11 (right?).

Figure S4: The x-axis should be longitude in degrees East, not West. What are the vertical lines? Why isn't sea ice visible on the Hovmuller diagram? It would be useful to add it.

Typos etc.

Line 11: Reword "more vulnerable". It's a bit unclear what's meant.

Lines 55, 62: Clarify "eastward SIE".

Line 114: There's a missing word somewhere.

Line 203: Fix "failry"

Line 256: Missing figure number in "Fig. a".

Line 304: Fix "rom".

Throughout: Use appropriate salinity units.

Reviewer #2 (Remarks to the Author):

Review: Ocean heat increase and sea ice reduction in the Fram Strait conveys Arctic Ocean change, by de Steur et al.

The manuscript discusses data collected by two ocean moorings in the western Fram Strait to show there has been an increase in upper ocean temperature of the East Greenland Current in the Fram Strait between 2003 and 2019.

There is no doubt that such studies and data are extremely valuable. However, it is the responsibility of the authors to present their results in a more accessible and comprehensible way for readers. I have a few critical comments, which are listed below. Although I find this study interesting, I think it falls short of the journal's level because it lacks a clear and new conclusion. I cannot recommend it for publication unless there is substantial improvement.

My suggestions are mainly about the overall presentation of the manuscript, and I hope they can help the authors. After improving this aspect, I think any reviewer can better judge the achieved scientific results.

Title:

From the title I do not get what I am supposed to expect from the paper. Bring your message to the title or be more specific (e.g., unusual/significant temperature increase in the Fram strait...between 2003-2018) .

Abstract:

I wonder why the authors miss talking about using “observations” in the abstract. The entire abstract needs to be-rewritten. In the current form, the story is not clear. Again bring your main message to the abstract. Line 8-10 does not add much value to your work unless you point it out why those line are relevant.

Main:

- Until line 48, I as a reader feel lost and wonder what is the paper about. Provide more background about the topic by mentioning about the oceanography of the region, the ocean currents, any previous observations or modelling works related to the Fram strait (if any), and how these data are important and give us more information about the Arctic Ocean change.

I did a small search on the topic and found this page: https://www.npolar.no/en/projects/fram-strait-arctic-outflow-observatory/#toggle-project-dataset

I wonder why the authors do not use the moorings-related figure in this link (or a schematic figure like that). Such a figure with some additional explanations about water masses and currents will help the reader to follow the story.

- A minor comment in addition:

Do not use PW for polar water as it can be mixed with the Pacific water. You can use AtlW for the Atlantic and ArcW for the Arctic.

Results:

Stick to the story and connect your results in a systematic way from point A to Z. In the current form, there is no unified story. There are also some wrong statements (Line 60-61; Line 63-65) and unclear text (e.g., Line 111-126).

Figures:

1, 2 and 4 need to be improved.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper reports important observations of changes in the oceanographic properties in Fram Strait over the last 20 years. In particular, the temperature of the upper East Greenland Current (EGC) has increased significantly. On the continental shelf, the Polar Water (PW) has warmed in summer (Fig 2), which is linked to reduced sea ice upstream one month earlier and greater ocean heat content (Fig. 3). On the slope, warm Atlantic Water (AW) now occurs year-round, not just in summer (Fig. 4). The change is linked to warm sea-surface temperatures in the central Fram Strait one month earlier (Fig. 5). The change occurred as a step-like regime shift in summer 2015 (Fig. 6). Collectively, the Fram Strait temperature increases are linked to sea ice reductions downstream in subsequent months (Figs 7, 8).

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The paper is well written and carefully reasoned. The figures are clear. There are a few minor issues, mostly to do with clarity, and some typos etc. There are no major weaknesses. However, I have a couple of comments that are more significant. Overall, I think a minor revision is needed then the paper should be accepted.

We thank the reviewer for supportive and very constructive comments. We reply to each point below in italic red.

Major Comments

1. Some statements depend implicitly on the reference temperature used to compute the heat flux or heat content. For example, line 28 says “a near doubling of heat content in the Beaufort Gyre halocline”. Another example is at line 141, which says “PW in the upper 55 m contained ten times more heat”. The “doubling” and “ten times” statements depend on the arbitrary reference temperature. Therefore, they don’t have robust physical significance because of the sensitivity to reference temperature. The statements should be revised to avoid this ambiguity.
We acknowledge that heat content can be ambiguous. Both statements on heat content referred to were both calculated relative to the freezing point of seawater (locally depending on salinity) and integrated within a given salinity range. Therefore these are not per se ambiguous in the way presented here, i.e. comparing heat content quantified in one location, within a fixed salinity (Beaufort Gyre) or depth range (Fram Strait), and relative to the freezing point from time t_0 to time t_1. We simplified the first statement to: 'significant warming of the halocline in the interior Beaufort Gyre', but left the second statement on 'ten times more heat' since it is explicitly given: a) relative to the freezing point of seawater and b) within the upper 55 m (a fixed depth range).

2. The paper shows in-situ measurements of temperature, salinity and ice draft. I presume the moorings carried current meters as well. What about these velocity measurements? Velocity measurements provide important context for the temperature changes. Specifically, what current changes (if any) are associated with the temperature changes? Does the 2015 regime change reflect a change in current (e.g., its direction or variability)? The answers to these questions may illuminate the speculation on line 114 about eddies.
We thank the reviewer for this constructive comment. Indeed, velocity measurements are available

and analysis of the volume and freshwater transport of the EGC has been presented in Karpouzoglou et al., 2022. We now discussed this work with a the reference at the end of the section 'Inreased AW presence in winter'. In addition, we included a figure panel of upper ocean mean velocity in the EGC in the regime shift detections in former Figure 6 which we now moved to SI, as Figure S6: where we now also show the (normalized) mean velocity averaged over the upper 150 m across the EGC (between 8°W-2°W): this shows a shift in 2015 too, though a couple months later than the shift detected in ocean temperature at 3°W (mooring F11), 7°E (mooring F4) and the SST at 2°W. This points to a general reduction in the southward transport of the EGC while at the same time the AW spread westward. The reference to eddies as a source for subsurface temperature maxima (associated with higher salinity (S>33 psu) at 55 m is removed and generalized to warmer and saline AW derived watermass.

Minor Comments

Lines 11–12: State the season for the upper ocean temperature increase? (summer on the shelf from Fig 2 and year-round in the eastern EGC from Fig 4). Or connect the sentences starting "We show that" and "While Polar Water". The novice reader might not grasp that Polar Water and Atlantic Water refer to the upper EGC.

We solved it as follows and believe it has clarified the abstract:
We show that the upper ocean temperature across the East Greenland Current in the Fram Strait has increased significantly between 2003 and 2019: while Polar Water contains more heat in summer due to lower sea ice concentration and longer periods of open water upstream, warm returning Atlantic Water has shown a greater presence in the central Fram Strait in winter, impacting winter sea ice thickness and extent.

This should be more clear now to the reader as well since we also added a new Figure 1 with panel (b) showing a CTD cross section of the Fram Strait illustrating these two watermasses across the EGC and the mooring locations after recommendation of Reviewer 2.

Please note that in response to Reviewer 2, the Introduction now starts with a better introduction and description of the EGC in Fram Strait, and text on this (earlier Lines 38-43) has now been moved up here.

Lines 99–102: It says about Fig 2e, f: "These profiles demonstrate that anomalously high temperatures in the upper 55 m toward the surface are related with a thicker layer of fresh upper halocline water, while subsurface temperature maxima are associated with saline halocline water." I don't see this in Fig 2e, f. Part of the problem is the colors used for different years (they're too similar). It's also hard to see all the different profiles. I can see that 2014 and 2015 subsurface temperature maxima go along with salty anomalies. And the 2017 (I think) surface was warm and fresh. But the 2014 and 2015 surface layer was very fresh and not anomalously warm, and the 2019 subsurface temperature maximum was fresher than the 2003–2009 average. \l
To clarify these points, it would help to show T/S diagrams. Also mark the vertical profile times on Fig 2a, b, and distinguish the different year colors more.
We improved Figure 2e and f (now Figure 3a and f) by marking the years to the profiles explicitly, while keeping the same color scale. We also marked the times associated with the vertical profiles in Fig. 3a and b. We have to acknowledge our text was unclear regarding how we distinguished 'saline' vs 'fresh' profiles: this is not the salinity at/near surface but the salinity at the depth of 55 m which is the depth of the moored instrument of which we have the continuous time series (Fig. 3a and b).

To clarify this we also added a horizontal line to Fig. 3e and f marking the 55 m depth, in addition to the vertical dashed lines indicating Tfreezing (in panel e) and the practical salinity S_p=33 (in panel f) and improved the text on this. Based on the salinity at 55 m depth, we distinguish the saline profiles (2014 and 2015) from the 'fresh' profiles, which are related to a different upper halocline structure.

Line 122: It says "The positive correlation of large temperature anomalies with OWF (open water fraction) for the years with fresh halocline waters, while this was the case for the saline halocline waters (Fig. S3), demonstrates the relationship between reduced summer sea ice and increased heat input into the upper ocean upstream of the shelf mooring." I think I understand the sentence (following lines 98–100), but it should be made clearer, especially the part about saline halocline waters. In particular, explain the rationale for splitting the temperature anomaly/OWF correlations into fresh and salty groups.
*During text editing the word *not* was accidentally removed, it should be: '..while this was* **not** *the case for the saline halocline waters ....". We have now corrected this and made the text clearer with what we mean by fresh and saline, i.e these are distinguished based on the vertical CTD profiles but then used for correlation of the T mooring timeseries with OWF. We hope the text is clearer now.*

Line 142: What salinity is used for the "freezing point of seawater"? Is it fixed?
The freezing point of seawater was calculated based on the observed salinity profile for each year. It is not fixed. We clarified this in the text by adding: ".... the freezing point of seawater (based on the salinity from the respective CTD profiles)."

Line 157: It says "Observed ocean temperature anomaly from similar depths in the West Spitsbergen Current (WSC) also shows a positive anomaly in subsurface temperature in 2016-2018, however, with a smaller amplitude than observed in the eastern EGC (Fig. 5b)". Is this figure reference correct? There are no WSC data in Fig. 5b. Should it be Fig. 6e?
Indeed it should have been Fig. 6e. This is now corrected and this Figure as a whole has been moved to SI, so Figure S6. In addition, we now show monthly mean T anomaly for the EGC/3°W in Fig S6c (instead of daily values), similar to the data presented for WSC/7°E in Fig. S6e such that these can be compared directly.

Line 180: It says "…processes demonstrate the crucial role of the ice-albedo feedback". But what about other sea ice processes unrelated to ice-albedo feedback, like suppression of air/sea fluxes by sea ice? This seems to be consistent with Fig. 3b for instance (strong correlation between open-water fraction and cumulative heat flux).
It was misleading to say 'processes'. The sentence is now rewritten to reflect that in 2017 and 2018 the large amount of open water just upstream of the mooring array and the associated large increase of upper ocean heat content led to a delay in freeze up in autumn and winter, demonstrating the impact of OWF well after the summer season.

Lines 188–190: It says "the correlation between winter ESIT (effective sea ice thickness) at the eastern ice edge of the EGC with ocean temperature at 3°W in winter increased from 0.65°C to 1°C". This doesn't make sense. How can the correlation increase from 0.65 to 1oC?
Apologies, this was a bad textual mistake indeed, we removed the °C.

Lines 201–205: These lines are unclear to me. The first sentence is "The time series for the downstream sites at given lags relative to the observed temperature changes in the Fram Strait demonstrates that the resultant SIC anomalies downstream in the EGC could be as much as 30%". 30% of what? Reword to clarify.
Here, it was meant as anomalies as much as 30% SIC (i.e. SIC expressed as a %). We added this.

The second sentence is: “The former showing a gradual change in time, and the latter showing the biggest changes since June 2015 following the detected shift in Fram Strait.” Again, reword to clarify.
The sencence indeed did not make sense here in relation to the downstream effects as we do not demonstrate that here (i.e. gradual vs stepwise change in SIC). The sentence is redundant here given the following paragraph were we summarize the main findings. Hence we removed the sentence.

Lines 213–214: It says “we ascribe these (negative sea ice thickness anomalies) to the increased ocean warming in (late) summer 2017 and 2018 as well as the increased presence of AW”. Why can’t thinner ice upstream (e.g., in the transpolar drift) cause the thickness deficits? I don’t understand why there must be a link to the nearby warming and remote effects are ruled out.
In our previous paper (Sumata et al., 2022) we examined temporal changes of SIT in and upstream of Fram Strait by a combination of upward looking sonar (ULS) data, backward sea ice trajectory calculations, and ice thickness estimated from remote sensing (CryoSat-2 thickness products). In this analyses, we calculated temporal evolution of SIT that arrived at Fram Strait, and found that the strong SIT reduction in Fram Strait (e.g., observed in 2018) was not caused by SIT changes in the far upstream area (the central Arctic), but caused by a sudden reduction of SIT that occurred in the northern vicinity of Fram Strait (shown in Fig. 4 and suppl. material Fig. S1-S6 in Sumata et al., 2022). In this analyses, 2018 SIT stayed within the range of standard deviation (2011-2017 mean SIT) when the ice floes stayed in the central Arctic, while a sudden reduction of SIT occurred when it reached in the vicinity of Fram Strait (83°-80°N), indicating strong influence of ocean heat flux for melting the ice in and north of Fram Strait. We have now included a sentence on these results with reference to this work at the end of this paragraph.

Figure 1: What do the different “EGC” arrows in (a) and (b) mean?
These arrows are simply meant to illustrate the flow direction of the EGC along the shelf slope. They were in different locations but not purposely meaning anything different. The meaning of the arrows are now described in the caption.

Figure 3: It says “when seasonal T anomaly was associated with S<33”. Make clear that this means the monthly salinity anomaly at 55m from the mooring (presumably). Similar problems occurs on other figure captions, like Figs. 5 and S3, It’s unclear when “temperature” or “salinity” mean from the mooring, or from another source.
We clarified this in caption of the original Figure 3, which now became Figure 4, as well as in original Figure 5, now Figure 6, as well as caption of S3.

Figure 6: State that the temperature data are from mooring F11 (right?).
Correct. Figure 6 has changed with now monthly mean temperature from the mooring F11 (instead of daily) as well as monthly mean (normalized) velocity from mooring F11 and this is reflected in the caption. Please note that this figure has now been moved to SI as Figure S6.

Figure S4: The x-axis should be longitude in degrees East, not West. What are the vertical lines? Why isn’t sea ice visible on the Hovmuller diagram? It would be useful to add it.
X-label is corrected and we added the 0.5 SIC filled contour on top of it showing the near-permanent sea ice cover on the western end of the section and the moorings in the EGC.

Typos etc.

Line 11: Reword “more vulnerable”. It’s a bit unclear what’s meant.
That sentence has been replaced with another one without using 'vulnerable'.

Lines 55, 62: Clarify “eastward SIE”.

We changed it to '...reduction of the SIE in the northeastern Fram Strait in winter.'

Line 114: There’s a missing word somewhere.

We added 'which is ' to the sentence.

Line 203: Fix “failry”

We removed this word as a whole since it was vague. We just write 'gradual' now.

Line 256: Missing figure number in “Fig. a”.

Fixed to Fig. 3a

Line 304: Fix “rom”.

Done

Throughout: Use appropriate salinity units.

We have now clarified that we present practical salinity (S_p) throughout the text and figures which is unitless.

Reviewer #2 (Remarks to the Author):

Review: Ocean heat increase and sea ice reduction in the Fram Strait conveys Arctic Ocean change, by de Steur et al.

The manuscript discusses data collected by two ocean moorings in the western Fram Strait to show there has been an increase in upper ocean temperature of the East Greenland Current in the Fram Strait between 2003 and 2019.

There is no doubt that such studies and data are extremely valuable. However, it is the responsibility of the authors to present their results in a more accessible and comprehensible way for readers. I have a few critical comments, which are listed below. Although I find this study interesting, I think it falls short of the journal's level because it lacks a clear and new conclusion. I cannot recommend it for publication unless there is substantial improvement.

My suggestions are mainly about the overall presentation of the manuscript, and I hope they can help the authors. After improving this aspect, I think any reviewer can better judge the achieved scientific results.

We thank the reviewer for taking the time to read the manuscript and giving suggestions on the presentation. We address each individual point below.

Title:

From the title I do not get what I am supposed to expect from the paper. Bring your message to the title or be more specific (e.g., unusual/significant temperature increase in the Fram strait...between 2003-2018) .

*We have changed the title to: **'Upper ocean warming and sea ice reduction in the East Greenland Current from 2003 to 2019'** thereby clarifying the content of the study and from what time frame the observations are from. The journal format, however, states the title should be 15 words or fewer and as such it is up to the journal if this new suggested title is allowed or if we should remove the last four words.*

Abstract:
I wonder why the authors miss talking about using “observations” in the abstract. The entire abstract needs to be-rewritten. In the current form, the story is not clear. Again bring your main message to the abstract. Line 8-10 does not add much value to your work unless you point it out why those line are relevant.
In the abstract we now state more explicit 'Observations show that' ..., which cannot be interpreted differently than that since we do not mention anywhere that these are model results. We modified - but also left some of the initial Lines 8-10 - to set the context of recent ongoing wide-spread changes in the Arctic with relation to sea ice cover and ocean temperature to introduce the topic and set the stage for the two main changes we present in this paper, namely summer warming of Polar Water and increased AW presence in winter, which the Abstract then continues with. Please note that the format of the journal limits the abstract to 150 words.

Abstract
The sea ice extent and sea ice thickness in the Arctic Ocean have declined consistently in the last decades. The loss of sea ice as well as warmer inflowing Atlantic Water have major consequences for the Arctic Ocean heat content and the watermasses flowing out from the Arctic. Observations show that the upper ocean temperature across the Arctic outflow the East Greenland Current in the Fram Strait has increased significantly between 2003 and 2019. Polar Water contains more heat in summer due to lower sea ice concentration and longer periods of open water upstream. Warm returning Atlantic Water has a greater presence in the central Fram Strait in winter since 2015, impacting winter sea ice thickness and extent. Combined, these processes result in a reduced sea ice cover downstream along the whole east coast of Greenland with inevitable consequences for wintertime ocean convection and ecosystem functioning.

Main:
- Until line 48, I as a reader feel lost and wonder what is the paper about. Provide more background about the topic by mentioning about the oceanography of the region, the ocean currents, any previous observations or modelling works related to the Fram strait (if any), and how these data are important and give us more information about the Arctic Ocean change.
We have improved this now by starting the Introduction with a better description of the EGC and some text (earlier Lines 38-43) is now moved up front. As such the storyline has become clearer in our view. We like to add that we follow the (rather short) format of this journal, and hence it may appear different from what the reviewer expects in a longer research article, as we follow this concise format.

I did a small search on the topic and found this page: https://www.npolar.no/en/projects/fram-strait-arctic-outflow-observatory/#toggle-project-dataset
I wonder why the authors do not use the moorings-related figure in this link (or a schematic figure like that). Such a figure with some additional explanations about water masses and currents will help the reader to follow the story.
We like to thank the reviewer for this suggestion and we added a new Figure 1 showing a cross section of the Fram Strait (upper 1000 m) showing the PW in the EGC and AW in the central and eastern Fram Strait, i.e. the relevant watermasses and the mooring locations, clarifying the geographical setting for the reader. In addition, we start the Introduction now with a paragraph on the EGC and its relevance (see also our response to Reviewer 1 above), followed by the general Arctic changes which provide the context to our observations, and relevance for downstream processes..

- A minor comment in addition:

Do not use PW for polar water as it can be mixed with the Pacific water. You can use AtlW for the Atlantic and ArcW for the Arctic.
We introduce the acronyms PW and AW in the start. Since we do not present or discuss Pacific Water in this manuscript and since Reviewer 1 did not find these acronyms problematic, we leave the definitions as they are: PW for Polar Water and AW for Atlantic Water. These are used widespread in the literature as well.

Results:
Stick to the story and connect your results in a systematic way from point A to Z. In the current form, there is no unified story.
There are two story lines in fact 1: the observed changes of temperature in the cold Polar Water in summer, and 2: the increased presence of warm Atlantic Water in winter. Both are near-surface and both have an impact on sea ice but have different origins. With also adding a sentence on this that this is a general cause for increased heat content in the Arctic (surface insolation due to reduced sea ice, and warmer AW in the Arctic) we better introduced these processes which have become evident in the Fram Strait in the last decade. We demonstrate that that effect is not just local (in Fram Strait) but has an impact on downstream sea ice for several months after the anomalies are observed in Fram Strait, and in both seasons - so both summer as well as winter anomalies have impact on observed downstream SIC. We expanded the text in the Introducion to clarify and better introduce these two watermasses. While the warming of the two watermasses originates from different regions and processes, they are both important for the regional and downstream changes of ocean heat and sea ice cover.

There are also some wrong statements (Line 60-61; Line 63-65) and unclear text (e.g., Line 111-126).
-We modified largest to large in original Line 60-61 but otherwise we do not understand what is wrong here:
Large northward retreat of the SIE up to 79.8°N in the EGC was observed in August 2017, and a much reduced eastward SIE and a vast open water area northwest of Svalbard was present in August 2018 (Fig 2a).
-We removed the part" While the maximum Arctic SIE is typically reached in March" from original Lines 63-64.
-Original Lines 111-126 have now been improved and content made clearer as a whole in this paragraph.

Figures:
1, 2 and 4 need to be improved.
We have now indeed added a new Figure 1 with a map (panel a) and a cross section of the Fram Strait (panel b) to clarify the setting of the moorings and the watermass structure. Figure 2, now Figure 3, has been improved after constructive suggestions from Reviewer 1. Figure 4, now Figure 5, has been clarified with years explicitly added to the seasonal temperatures (c and d) in response to the comments from Reviewer 1. The captions of Fig 3 and 5 have been clarified with stating better that the upper four panels are observations from moorings and the bottom two panels are hydrographic CTD profiles at the mooring sites.

31st May 23

Dear Dr de Steur,

Your revised manuscript titled "Upper ocean warming and sea ice reduction in the East Greenland Current from 2003 to 2019." has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Heike Langenberg, PhD

Chief Editor

Communications Earth & Environment

On Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have responded to the first review in a thoughtful, satisfactory way. I recommend the paper is now published.

Reviewer #2 (Remarks to the Author):

2nd-Review: Upper ocean warming and sea ice reduction in the East Greenland Current

from 2003 to 2019, by de Steur et al.

This is the review of the revised version of the manuscript. I want to thank the authors for taking into account most of my previous comments and I feel like the manuscript has greatly improved since the last version. However, I still have few more comments and some minor suggestions.

Main comment

-The study covers the period of 2003-2019. However, it is not clear why the authors calculate the time-series mean in each figure for different time spans. If there is a possibility to calculate the mean over the same period (e.g., 2003-2019 or 2004-2015) in most of figures, then please do so. If not possible, please specify why you use different time frames. The same applies for showing standard deviations over a specific period. Also when you use only 4 points as in Figure 5e,f I am not sure if it makes sense to show the mean±std. Moreover, be consistent and careful when you show the mean over a specific period or you are referring to upper and lower ranges.

-I miss a clean time series plot for year to year variability of observed data without the annual cycle (annual-min and annual-max from 2003-2019). Then you can also add the sea ice area/extent and SST time series for the same period. This helps the reader to visually understand what is happening.

Minor comments and suggestions

Title: Nice and clear

Abstract:

line 11 “Observations…” mention what observation e.g., Our recent mooring observations...

Some text as lines 53-58 is more useful in the abstract if there is space left.

Line 26: “which is responsible for the mild climate…” add a reference

Line 28-31: revise

Line 32-33: sea ice has not declined only in the satellite era. Revise the sentence.

Line 38-41: “ The ice-albedo ...Beaufort Gyre.” was already mentioned. Remove.

Line 45: “...increased winter convection ??in where?? and upward heat flux ??in where??…

Line 46: correct the citation 727

Line 50: remove “Here”

Line 52: “...Fram Strait ??mention over which period??

Line 64: Following my main comment, why do you calculate the mean over 2004-2015?

Line 85: why the mean over 2003-2009?

From analysis related to Figure 3 and 4, can you say something about stratification? For instance 2018 is more stratified?

Line 205-206: “...thinning of sea ice that arrives from the Arctic…” you meant, less sea ice export?

About figures where salinity is shown as “Practical salinity”. Authors know better than me but isn’t it better to say “Salinity (psu)” in your axis labeling?

We thank the editor and reviewers for positive feedback to the revised version. We reply to the comments of Reviewer #2 below in blue:

Reviewer #2 (Remarks to the Author):

2nd-Review: Upper ocean warming and sea ice reduction in the East Greenland Current from 2003 to 2019, by de Steur et al.

This is the review of the revised version of the manuscript. I want to thank the authors for taking into account most of my previous comments and I feel like the manuscript has greatly improved since the last version. However, I still have few more comments and some minor suggestions.

Main comment
-The study covers the period of 2003-2019. However, it is not clear why the authors calculate the time-series mean in each figure for different time spans. If there is a possibility to calculate the mean over the same period (e.g., 2003-2019 or 2004-2015) in most of figures, then please do so. If not possible, please specify why you use different time frames. The same applies for showing standard deviations over a specific period. Also when you use only 4 points as in Figure 5e,f I am not sure if it makes sense to show the mean±std. Moreover, be consistent and careful when you show the mean over a specific period or you are referring to upper and lower ranges.

First of all, we find that the mean SIE maps of Figure 2a-b should be indeed between 2003-2015 and we have corrected that (from 2004-2015). For the time series from the moorings: we apply different time spans for averaging (2003-2009 for F14 and 2003-2014 for F11) to obtain a baseline mean seasonal cycle on the shelf (F14) (Fig. 3a, c and d and Fig. 5c and d) or multi-year profile means (Fig 3d-f. and Fig 5d-f) This is based on the fact that the changes at mooring F14 on the shelf occured after 2010, and at mooring F11 in the deep EGC after 2015. That is our motivation for applying the different averaging periods of 2003-2009 and 2003-2014 for the 'background state' marked with gray contours in Figures 3 and 5c-d. We acknowledge that mean profile as we first showed for the winter based on so few data points in Fig 5e-f does not add much value and therefore we removed the mean gray shading (of 1std). We realized the motivation for the averaging periods was not sufficiently explained in the text body and we have clarified that in some instances in the text in particular for the PW on the shelf (F14) case.

-I miss a clean time series plot for year to year variability of observed data without the annual cycle (annual-min and annual-max from 2003-2019). Then you can also add the sea ice area/extent and SST time series for the same period. This helps the reader to visually understand what is happening.

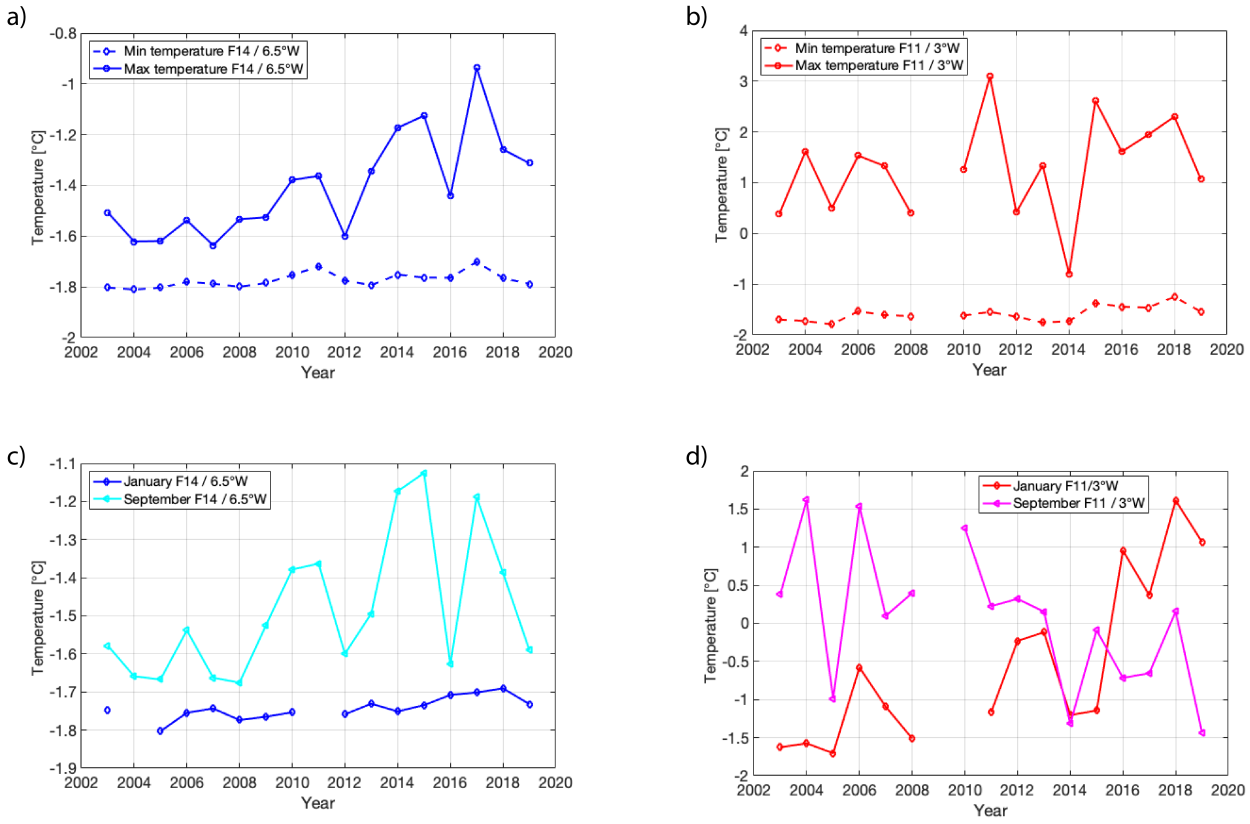
Thanks to the reviewer for this input. We have worked on this and come to the following: if we take the annual min/max ocean temperature observed at the moored instruments it is clear for the PW how it changes in time at F14 (ie. summer increase in ocean T), on the other hand, it does not necessarily help to understand what happened with the AW at F11. This is because the annual min/max temperature does not describe the change to increased AW presence in winter. As demonstrated in the paper Figure 5 we believe that our main finding can be more clearly described by the monthly mean time series combined with the AW presence (orange diamonds in Fig. 5a, b).

Shown below in the extra added figure panels a-b we show what the annual min/max for each site looks like (monthly means used for that purpose) and that this figure does not demonstrate our main point for what is happened in the deep EGC at mooring site F11 at 3°W where AW presence has increased in winters since June 2015. This is better illustrated by showing the monthly mean ocean temperature fixed for January and September as done in Figure panels c-d below, however, this again could be misleading since it looks like just the ocean temperature has increased but this is not

the point: the point is the increase of AW presence in winter (at the cost of PW) due to a westward movement of the front as demonstrated in the current paper Figure 5.

We find that our current Figures 3 and 5 demonstrate these main points in a clear way, by highlighting first the total time series including the trend at F14 in summer (Fig 3a, b) and the shift at F11 in winter (Fig 5a, b), and showing the change in seasonality in time (Fig. 5c, d), as well as providing context in the vertical based on full depth CTD profiles (Fig 5e, f). We therefore would like to keep the original figure panels as they were.

Figure caption: plotted are the monthly mean ocean temperature for: a) annual min/max at F14 (6.5°W) , b) annual min/max at F11 (3°W), c) January/September at F14 (6.5°W), d) January/September at F11 (3°W).



Minor comments and suggestions
Title: Nice and clear

We are happy to hear the title has become clearer now.

Abstract:
line 11 “Observations…” mention what observation e.g., Our recent mooring observations...
Some text as lines 53-58 is more useful in the abstract if there is space left.

We detailed what kind observations we use in the abstract as follows: *'Sustained observations from ocean moorings show that ...'*

Line 26: “which is responsible for the mild climate…” add a reference

For this purpose we added the reference nr (5) Stouffer et al., 2006 *(Stouffer, R. J., and Co-authors, 2006: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. J. Climate, **19**, 1365–1387, https://doi.org/10.1175/JCLI3689.1).*

Line 28-31: revise

We are not fully certain what R2 exactly wanted to see revised in this sentence but we edited it as follows:

Besides reduced thickness of the ice exported from the Arctic Ocean, either by thinning upstream or nearby the Fram Strait (ref 7), warming of the Nordic Seas (refs 8, 9)expected to further reduce the sea ice cover east of Greenland, implying this region will be more exposed to winter-time ventilation (refs 10, 11).

Line 32-33: sea ice has not declined only in the satellite era. Revise the sentence.

That is true but we limit our statement on the existing data from the satellite era. Hence we have clarified that as follows:

During the satellite era since 1979, sea ice extent (SIE), sea ice concentration (SIC) and sea ice thickness (SIT) in the Arctic Ocean have declined rapidly. ~~*during the satellite era since 1979*~~

Line 38-41: " The ice-albedo ...Beaufort Gyre." was already mentioned. Remove.

We agree there was too much repetition in the two sentences at (original) lines 33 - 36 and 38 - 41. We fine tuned the first sentence to explain the general emergence of surface-based Arctic amplification with the reduction of sea ice as follows:

'Reduced sea ice cover has led to warming of the ocean's surface, and enhanced heat fluxes from ocean to atmosphere resulting in surface-based Arctic amplification (ref 15)'

and left the second sentence as it was to highlight explicitly the effect of the feedback on upper ocean heat that is now present in the Beaufort Gyre even in winter:

The ice-albedo feedback allows for increased surface ocean heating, leading to increased sea surface temperatures (ref 18), which leaves an imprint also in winter as a near-surface temperature maximum in the Canada Basin, and has amounted to significant warming of the halocline in the interior Beaufort Gyre (refs 19, 20).

Line 45: "...increased winter convection ??in where?? and upward heat flux ??in where??…

We revised the sentence to clarify the areas that the sentence describes.

Line 46: correct the citation 727

We corrected this, the citations here are now 8 and 28 (since one was added to the paper) with a space in between.

Line 50: remove "Here"

Done

Line 52: "...Fram Strait ?? mention over which period??

Done we added: *....covering the period 2003 to 2019.*

Line 64: Following my main comment, why do you calculate the mean over 2004-2015?

As mentioned already in our reply above to the first main comment of R2: We acknowledge it should have been 2003-2015 and we corrected that. With this Figure 2a and b showing maps of Sea Ice Extent (SIE) we demonstrate that in particular after 2015, large changes in both the summer (August) and winter (January) SIE occurred in the Fram Strait. To relate this to our ocean observations and identify the impact, or cause of this, we show the monthly mean Aug. and Jan. SIE

up to 2015. To explain this better to the reader we added a sentence at the start of that pararagraph as follows: *Since 2015, significant changes have occurred in the SIE in the Fram Strait*.

Line 85: why the mean over 2003-2009?

We want to demonstrate that at F14 the Polar Water summer temperature started to increase after 2010 mostly and that the seasonal cycle of temperature was quite 'steady' until then. We clarified this in the text by changing it to:

Compared to the mean seasonal cycle before 2010, when little change occurred, the PW temperature ....

From analysis related to Figure 3 and 4, can you say something about stratification? For instance 2018 is more stratified?

This is implicit to the fact that for those years (2016 through 2019) have a thicker, fresher upper halocline layer (identified also as Sp at 55 m < 33) Figure 3f. We do not mention stratification here since that is a little dependent on how you define that; e.g if one looks at the stratification in S (and hence density) for the years 2014 and 2015 (Figure 3f), the very upper near-surface layer is very fresh, fresher even than the years when there is a thicker, fresh halocline layer. The integral of the upper water column has more buoyancy in the latter case (2016-2019). We decided to not include a discussion on this here as it takes away attention from the main message about temperature change on the shelf at F14 (6.5°W).

Line 205-206: "...thinning of sea ice that arrives from the Arctic…" you meant, less sea ice export?

No, we meant a general thinning of the sea ice that arrives from the Arctic. Which does imply that the ice export became smaller too but the point is that the thinner and fragile ice is more vulnerable to heat supply from the warm AW and hence impact of AW increases. To clarify this we modified the sentence to:

We therefore suggest that with a general thinning of sea ice that arrives from the Arctic, the impact of warm returning AW on the sea ice cover in the Fram Strait has increased.

About figures where salinity is shown as "Practical salinity". Authors know better than me but isn't it better to say "Salinity (psu)" in your axis labeling?

This used to be practice to use psu for (practical) salinity but is not done anymore. It is in principle a unitless measure. If we had shown absolute salinity it would have had the units [g/kg/]. To clarify what we use, we state Practical salinity in the labels and text.