1. Comments from referees
2. Authors response
3. Additional comments on changes in manuscript with page-reference to diff-file

Answers to review #1

The paper investigates the variability of the of ssh and heat content in the “Atlantic” (Eastern) part of the Nordic Seas, the main connection of heat and salt to the Arctic Ocean. A main conclusion is that the decadal variability in this Atlantic domain can be explained by a model solely forced with the Atlantic inflow temperature variability and setting the time scale of the considered volume to some years. While this result might not appear surprising, the scaling discussion of the relative influence of the volume flux vs temperature effect on the heat content and ssh is interesting, novel and warrants publication. Also, the paper is well written and easy to follow. With this overall positive impression, there are some points listed below that I hope the author will consider.

We thank the reviewer for the constructive comments and careful inspection of our manuscript and results. The insightful comments by the reviewer have been taken into account. We also note (as the reviewer points out) that we have been brief at some places and we have now made an effort to include the necessary details. The replies to each of the comments by the reviewer can be found in the attached pdf below in blue.

The author should clearly state what time scales these results applies to. In the data and method section they should describe how the data are processed before going into the analysis. I find some information for the ssh and hydrography data (for atmospheric data little information is given). It is necessary to provide more details on this, e.g how are the data de-seasoned, are the results sensitive to the choice of method.

We thank the reviewer for pointing this out. Additions to clearly point out the time scales considered, in both Section 1 and 4, will make the paper easier to grasp and also express novelty. See also further comments below. We now also extend Section 2 to include more information on how the ssh, hydrographic and air-sea heat flux data have been processed before the analysis.

To clearly point out what time scales the analysis concerns, the title has been changed to include the word “decadal”. The first two paragraphs of Section 4 have also been revised to strengthen this message.
Additions to the data processing have been added at P3 L8-9, P4 L19-20.

A main conclusion of the paper is that a simplified model of ocean heat convergence, with only upstream temperature measurements at the inflow to the Nordic Seas as input, is able to reproduce key aspects of the decadal variability of the Nordic Seas. The authors briefly mention that the residual could be related to changes in vertical heat flux or volume flux, but none of these are investigated. Their argument based on the decadal comparison of surface fluxes to exclude the heat fluxes in their forward model integration seems weakly justified. Adding to this, Mork et al. (2015) concluded that air-sea heat fluxes explained about half of the interannual (year-to-year) variability in heat content tendency. Further, from the hydrographic data the authors could check their assumption of a similar AW temperature and outflow temperature. Since a number of papers already have pointed to the importance of temperature anomalies from the North Atlantic propagating through the Norwegian Sea, I think more conclusive results on what mechanism explaining the residual variability (i.e. not explained by inflow-T) would make the paper more novel. E.g. by extending the model to include some of the above points?

Answer: We thank the Reviewer for these comments. The decadal comparison of surface fluxes essentially rules out the role for air-sea fluxes for driving the heat content anomalies. This comparison should not be compared to the study by Mork et al. (2015) because of the different time scales, interannual vs. decadal. The latter is the focus of our study, where the decadal comparison shows a minor role for air-sea fluxes, which further suggests that on these time scales advection of temperature anomalies by ocean currents from the North Atlantic dominates the heat budget. The decadal time scales considered also adds to the novelty.

We have decided to not explore how well the mean AW temperature is related to the outflow temperature, defined at the northern boundary of our domain located roughly in the Lofoten Basin. For variations with time scales of a few years this should be a reasonable assumption, since at low frequencies the temperature anomalies in the AW tend to have large horizontal scales.

In response to questions from both referees on the residual in the conceptual model, we have expanded the discussion on the relative importance of anomalies in volume flow and temperature. We have changed some text on page 8 and 9: We now state that observations of Mork and Skagseth (2010), Berx et al. (2013), Bringedal et al. (2018), and Østerhus et al. (2019) suggest an increase of the Atlantic inflow to the Nordic Seas from the mid 1990:s to the early 2000:s. Further, we now write that this increase in volume transport can qualitatively explain why the observed temperatures are higher than those in the conceptual model (which is forced only by temperature variations) in the early 2000:s.

Regarding the residual variability, Fig. 6 now also includes the temperature anomaly forcing needed to reproduce the observed heat content (see P10 L11-14, P10 L23-25 and Fig 6) and the possible relation between the volume inflow and the residual is discussed (P11 L1-6).

Third, the authors find that the correlation between the ssh and heat content is low (provide number). The authors have used a fixed depth 657m to calculate the heat content. However, as the Atlantic Layer in the Lofoten Basin extend deeper than this, and is time-varying, the authors should assure that their results are not a sensitive to the choice of heat content integration depth. This could be tested calculating the heat content down to e.g. 1000m. Also, regarding the interpretation of the baroclinic transport function (Fig2b) as a strengthening of the Baroclinic Front Branch at the expense of the Slope Branch. It seems that the positive anomaly is quite far from the slope. The core of this anomaly seems to match the Lofoten Eddy (that varies both in strength and position). Can you exclude that this is not the signature of the Lofoten Eddy that is smoothed in the hydrographic data set?

Answer: We thank the author for this suggestion concerning the sensitivity to the integration depth. We already had a sentence about the integration depth (end of Section 2.2), but this only concerned the spatial pattern of the heat content, and not the correlation with the SSH. After testing the correlation to the heat content integrated to 1000m, it does not seem to be sensitive to the choice of depth. We have now extended the discussion on the sensitivity to integration depth.

About the signature of the Lofoten Eddy: the largest trend of the potential energy (as well as the steric height, now shown in the revised Fig. 2) in the central part of the Lofoten Basin indeed coincides with where the Lofoten Vortex resides. As suggested by the referee, the larger-scale positive trend seen in potential energy, steric height, and heat content (Skagseth and Mork, 2012) in time- and spatially-averaged hydrographic data sets may reflect an increase in intensity and number of mesoscale anticyclonic eddies in the Lofoten Basin (Köhl, 2007, Raj et al., 2015). These eddies have warm cores and locally yield positive anomalies in heat content, steric height and potential energy. Strengthening of the intensity of a generally dominating anticyclonic eddy, known as the Lofoten Eddy or Vortex (Søiland et al., 2016) can be important, but this appears to be linked to periods with a higher number of anticyclonic eddies entering the

Lofoten Basin from continental slope. To point to this slightly different perspective of warming trend in the Lofoten Basin, we have added at the end of section (3.1):

“The broad-scale positive trend in heat content, steric height and potential energy in the Lofoten Basin, recorded in the time-averaged and space-interpolated hydrographic data, may reflect an increase in intensity and number of mesoscale anticyclonic eddies shed from the continental slope that propagate into the central basin (Köhl, 2007, Raj et al., 2015, Chafik et al. 2015). Higher influx of eddies from the slope can invigorate the long-lived dominating anticyclonic eddy (Köhl, 2007), known as the Lofoten Vortex, which has a strong local hydrographic signature and moves around in the central basin (Søiland et al., 2016). However, for the time-mean flow trend it does not matter if the warming in the Lofoten Basin is due to meso-scale eddy-induced or large-scale induced heat convergence.”

The mention of the correlation between the monthly time series has been removed, since that is not the relevant time scale for this work and might only confuse the reader. The last part of Section 2.2, about the sensitivity to integration depth, has been slightly extended.

The paragraph added, as seen above, has been combined with some material moved out from Section 4 and now reads (see last paragraph in Section 3.1):

“The broad-scale positive trend in heat content, steric height and baroclinic transport function in the Lofoten Basin, recorded in the time- and space-interpolated hydrographic data, may partly reflect an increase in the intensity and number of mesoscale anticyclonic eddies shed from the continental slope that propagate into the central basin (Köhl, 2007; Raj et al., 2015; Chafik et al., 2015). Higher influx of eddies from the slope can invigorate the long-lived dominating anticyclonic eddy (Köhl, 2007), known as the Lofoten Vortex, which has a strong local hydrographic signature and moves around in the central basin (Søiland et al., 2016). The associated changes in steric height (Fig. 2) in the Lofoten Basin have served to induce an anticyclonic flow anomaly carrying a larger fraction of AW from the slope current into the basin. This flow anomaly acts to enhance the near-surface heat transport by the mean flow entering the Lofoten Basin from south (Dugstad et al., 2019). In combination with alterations of eddy fluxes from the Lofoten escarpment (Spall, 2010; Chafik et al., 2015) the anticyclonic mean-flow anomaly is a plausible mechanism for the build-up of the Lofoten Basin heat content over the period 1993-2017. However, for the large-scale trend pattern it does not matter if the warming in the Lofoten Basin is caused by mesoscale eddies or by mean-flow changes.”

Page 9. Regarding the connection to the upstream North Atlantic the authors interpret this as a disconnection between the North Atlantic and the Nordic Seas after 2005. The authors could also consider the interpretation that they follow with the Nordic Seas lagging the North Atlantic. That mean that the Nordic Seas in the year to come would experience a decreasing inflow temperature and subsequent decrease in ocean heat content. Please consider this.

Answer: We thank the Reviewer for this comment. Since our data stopped in 2016, we chose not to speculate about a possible lag. Instead, we focused on the possible mechanisms for this disconnection. However, we realize that doing as the reviewers suggests could have helped the interpretation of the disconnection. Analysis (not shown) of the recent years in fact indeed hints on a lag mechanism from the North Atlantic. We have now commented on this connection in the manuscript. P12 L8-9.

Minor comments:

The authors should limit the use of phrases as “key aspects”, “definite similitude” without providing any statistical measure. When possible please quantify, and also preferable also include the effective number of freedom when claiming significance (e.g. Fig. 3).

Answer: We thank the reviewer for careful reading of our manuscript and take this into consideration in the revised version. The methods used to show significance are also added in the new version. See captions of figures 3 and 8.

Clearly describe how the data are filtered before going into further analyses, how is annual cycle removed, in what way are results sensitive to methods.

Answer: This is extended in Section 2.

Page 8, line 23-24: Asbjørnesen et al (2018) used a volume-mean time-evolving temperature as reference.

Answer: It is true that Asbjørnsen et al. (2018) used a volume-mean time-varying temperature of the Norwegian Sea. However, they concluded that they got essentially the same results if they used 0 °C as a fixed reference temperature, which was used by Orvik and Skagseth (2005). To avoid possible misunderstandings we now instead cite Orvik and Skagseth (2005) for the reference temperature.

In conclusion the authors repeat the main result both in the second paragraph and then “in the main findings”. Once is better.

Answer: The Conclusions are revised. The list of “main findings” is removed, and the last item is moved to be included in the second paragraph. This paragraph will also be modified to better clarify the proposed answer to the question on remote or local forcing.

Conclusion two last paragraphs: I like the the point about the implication for the down-stream Atlantification. However, most of the remainder should go into introduction or discussion.

Answer: The paragraph starting at L20 is moved into section 3.1, to the discussion at the end where we have also added a paragraph on the Lofoten vortex (see above).

See P5 L26-30

In general, when there are not strong arguments against it figures should show the same area.
Answer: Figures 1-3 and 5 are revised to show the same area.

Figures 2, 3 and 5 now show the same area. Figure 1 is kept with a little bit of a wider view, for orientation.

Fig 1. Consider including depth contours on the map.
Answer: Done.

Figure 2b. This is probably not potential energy, but more a Baroclinic Transport function. Change the title of figure. Define Sverdrup, Sv

Answer: The content of Figure 2 is changed and clarified. Figure 2 has been improved by also adding steric height trends. We now define Sv.

Figure 4. The time axes are different for a and b.

Answer: That is correct and was intentional. The hydrographic data used only covers the period from 1993-2016, and we still wanted to show the full altimetry data available. This could have been clearly stated in the figure caption. In the new version, the figure is modified so that the time axes are the same, but with the last data points empty for the hydrographic data, to avoid confusion.

Figure 6. Why do you use a 24-month running mean here?

Answer: A 24-month running is used to reflect inter-decadal variability; the focus of this study. For consistency, the same filter length is now also used in Fig. 4.

Figure 8. The figure caption is not clear. Assure clarity.

Answer: The caption is now revised. We thank the Reviewer for careful inspection.

Answers to review #2

Overall assessment

This manuscript treats variations of ocean heat content and sea surface height in the Atlantic domain of the Nordic Seas. It has clear illustrations and includes thorough analyses of the data sets presented as well as a relevant conceptual model. I therefore feel that it has the potential to become an important addition to the literature on the Nordic Seas. There are, however, parts of the manuscript that seem weak. I therefore feel that major revisions are required before the manuscript can be accepted for publication in Ocean Science. Below, I first address my two main concerns with the manuscript and then list some details.

We wish to thank the reviewer for the many constructive comments and for carefully reading our manuscript. We have, to the best of our knowledge, addressed all major and minor comments (see blue text below) . Doing so, we think that the comments altogether have helped to produce an improved version of our manuscript.

The causal link between ocean heat content and sea level height

The manuscript links changes in sea surface height, SSH, to changes in ocean heat content below each square meter, H, i.e. to steric height changes. This seems to be one of the main conclusions of the manuscript and is stated explicitly several times:

1. “the trend in SSH is to a first approximation caused by a uniform warming of the AW” (page 4, line 19).

2. “the steric height changes related to the variation in heat content is the main reason for the observed decadal changes in SSH trends” (page 10, line 31-32).

3. “the most plausible cause of changes in SSH and heat content decadal trends is a change of temperature of the Atlantic source waters entering the Nordic Seas over the Greenland–Scotland Ridge” (page 11, line 3-4).

4. “the main reason for the shift in decadal trends in the SSH is the steric height changes related to heat content.” (page 11, line 11-12).

That warming of ocean water causes expansion and thus increasing steric height is a well established fact, as long as salinity changes do not compensate too much. In the Atlantic water entering the Norwegian Sea, salinity variations have usually been parallel to temperature variations. So, there is compensation, but only partial. Thus, a warming of the Atlantic water is expected to give increased steric height. There is noth- ing new in that, so this cannot be one of the main conclusions of the manuscript. But, what then are the authors claiming? In spite of the many statements of this causal link listed above, it is not clear to me more precisely what they are claiming and how they justify their claim. The only justification I find for claiming that steric height changes (i.e., expansions/contractions) are the main cause of the SSH changes is Figure 4 and the discussion on it. This figure does show a qualitative correspondence between SSH and H for the defined domain, for the period 1993-2002 (although not really after that or on shorter time scales). To claim that steric height changes are the "main" cause of the SSH changes needs a quantitative justification as well, however. I therefore find it strange that there is no calculation of the steric height changes associated with the heat content changes. This should be easy to calculate from their hydrographic data set. Why does the right panel in Figure 2 show potential energy rather than steric height. It may well be that the potential energy "largely mirrors the trend in steric height (not shown)" (page 4, line 12), but this choice makes it difficult to make a quantitative comparison between the two panels in Figure 2 and verify that steric height changes are the "main" cause of the SSH changes. Personally, I doubt that there is a quanti- tative justification for this claim. Using the two trend lines for the 1993-2002 period in Figure 4, the ratio between SSH change and H change is: ΔSSH/ΔH ≈ 4·10-11 m3 J-1. I don't have the hydrographic data set used by Broomé et al., but using CTD data from a standard section in the Faroe-Shetland Channel, I found a high correlation (R > 0.97) between ΔSSH calculated as steric height and ΔH, but regression analyses gave ΔSSH/ΔH < 2·10-11 m3 J-1, i.e. only around half of that in Figure 4 or less. For a vertically homogeneous water column, it is easily seen that the ratio between steric height and energy changes is ΔSSH/ΔH ≈ α/cp where α is the isobaric expansivity and cp the specific heat per volume. Since α increases strongly with temperature, a ratio as high as implied in Figure 4, requires considerably warmer water than generally found in the (depth averaged) specified domain. But, more fundamentally: If Figure 4 is the justification, then the authors must imply that SSH changes in the specified domain are mainly caused by expansions/contractions within this domain. Why link SSH in the region to heat content in the region, otherwise? As argued above, there is some (not overwhelming) qualitative support for that but no quantitative justification. I doubt, however, that this can be their claim. Most of the water that was within the domain in 2002, was outside it in 1993 (probably west of the Iceland-Scotland Ridge). Thus, much of the expansion caused by warming from 1993 to 2002 will have occurred outside of the domain, perhaps in the southeastern boundary of the SPNA. This in- terpretation would be consistent with the statement in bullet point 3 above but, if they are really claiming that the SSH changes in the specified domain are mainly caused by expansions/-contractions upstream of the domain, then why use the local heat content in the domain (Figure 4)? Why not discuss heat content over a wider region upstream of the domain (which would be warmer and therefore have a ∆SSH/∆H ratio more consistent with Figure 4)? But, then it would of course also be necessary to evaluate the effect of circulation changes (e.g., subpolar gyre). It is well known that steric ef- fects (thermal expansion) are an important component of recent global sea level rise (e.g. IPCC). That does not imply that the warming in a small region, as the one treated here, is the main cause of sea level rise in that region as apparently claimed. As ar- gued above, the results presented in this manuscript rather imply the opposite. One might argue that this is a question of semantics. As defined by Eq. (1), the steric height is a mathematical construct with a value depending on the reference density, Eq. (3). Establishing a mathematical relationship with another parameter (ocean heat in the specified region) is of course fully justified. The problem arises when words like "mechanism", "cause", and "reason" are used because they imply a causal physical relationship. From a physical point of view, the statement "the main reason for the shift in decadal trends in the SSH is the steric height changes related to heat content" (page 11, line 11-12) must mean: "the main reason for the shift in decadal trends in the SSH is the expansion/Ânˇcontraction due to temperature changes". When SSH (which is a physical parameter; not a mathematical construct) is linked to steric height, it is linked to the physical mechanism of expansion/contraction and it has to be clearly stated where this mechanism operates. And justified based on that. The question of steric height variation in the Nordic Seas has been addressed by various authors as referred to in the manuscript. Nevertheless, I feel that the data presented in this manuscript may contribute to this topic. For that purpose, the authors need, however, to be more precise. If they want to maintain a strong causal link between steric height and SSH, they need to specify where the associated expansions/Ânˇcontractions have occurred and they must justify their claim quantitatively as well as qualitatively.

Answer: We thank the referee for a detailed and insightful discussion on the physical link between ocean heat content and sea level.

The reviewer is correct in pointing out that it is well established that ocean warming causes increasing (steric) sea level height. We have modified the manuscript to more clearly convey that the novel results on this subject concerns decadal time scales and the importance of advection of temperature anomalies from the North Atlantic, which appears to be dominating over local air-sea fluxes on decadal timescales. Air-sea heat fluxes are important for inter-annual ocean temperature anomalies in the eastern Nordic Seas as have been shown in several previous studies.

Points 3 and 4 in the Reviewers quotes are both changed in the new version.

The reviewer is correct in stating that the sea level cannot uniquely be divided in a steric height component and bottom pressure component as one has to select a somewhat arbitrary reference density. However, when one considers changes in the sea level, the steric changes can be tied to the observed changes in density, and this measure of steric height changes is essentially insensitive to the reference density (as long as it is taken to be a typical mean ocean value). In section 2.2, we now describe how the sea level can be partitioned into a steric height and a bottom pressure component and that changes in steric height are causally linked to the vertically-integrated changes in density. Here we now cite Gill and Niiler (1973), which describes the theoretical underpinning of these concepts.

This new and more careful derivation and discussion in section 2.2 should clarify that the steric height changes are tied to the local vertically-integrated changes in density (or buoyancy), which in turn can be due either to local air-sea fluxes or due to oceanic buoyancy convergence caused for instance by advection of upstream water with anomalous buoyancy. We believe that this answers the referee's question about the role of expansion caused by warming in the North Atlantic south of the Nordic Seas: this steric height signal is tied to the buoyancy anomaly of water advected northward.

The referee asks whether the thermal expansion due to the heat content changes can explain the altimetric sea level changes in Figure 4, and provide some back of the envelope estimates. We have now added the steric height variations calculated from the hydrographic data (EN4 data set provided by the UK Met Office) in Figure 4. This shows that the steric height and ocean heat content variations in the hydrographic data are strongly correlated (as expected) and that the steric height variations explain main parts of the inter-decadal variations in the altimetric sea level. We now also cite Chafik et al. (2019), who show that inter-decadal variation in the surface wind stress explain some of the sea level variation in the eastern Nordic Seas (P6 L20-21).

Also in Figure 2, we now show the trend in steric height calculated from the hydrographic data.

The conceptual model

The conceptual model in Sect. 3.2 is an appropriate component of the manuscript and helps justify the three last main findings as summarized on page 11. It raises a few questions, however:

Firstly, why use 700 m for the depth of the AW here (page 9, line 6), when 657 m is used elsewhere in the manuscript ?

Secondly, the last part of Eq. (14) defines τ in terms of the volume inside the chosen Atlantic domain, which you must have calculated (from Figure 1 and the arguments on page 8, line 10-12, it seems to be ≈ 5·1011 m2 · 657 m) and the volume transport. Using 5 Sv (page 8, line 10), this gives τ≈2 years. I understand why you chose to use higher values, but it might be appropriate to include a sentence or two to justify this.

Thirdly – and most importantly – the arguments on page 8 for neglecting transport variations relative to temperature variations seem weak. With the uncertainties involved, the ratio 0.3/0.4 is hardly different from 1. Also, it would have been more appropriate to consider the ratio between the two driving terms in Eq. (12) rather than in Eq. (14). Then Eq. (15) would have ∆T' instead of Ti', which I assume would make the ratio closer to (or above ?) unity. To utilize this, you would, of course, need time series of volume transport in addition to temperature. From page 8, lines 28-30, you might already have this available from altimetry, but, if not, Figure 10 in Østerhus et al. (2019) provides a time series of Atlantic inflow to the Arctic Mediterranean and most of that enters between Iceland and Scotland i.e. into your Atlantic domain (Figure 9 in Øster- hus et al. (2019)). As stated in your manuscript (page 8, line 27-28) this transport is highly stable on decadal time scales, but the observations do indicate an increase of at least 0.5 Sv from the mid-1990s to the early 2000s, i.e. in the period where you observe the largest increase in heat content. A back-of-the-envelope calculation indi- cates that including such an increase (followed by constant transport or the time series in Østerhus et al. (2019)) might give a considerably better fit than the one seen in the lower panel of Figure 6. In connection with this, the two sentences "Equation (14) is based on the reasonable assumption that the low-frequency ocean heat convergence is dominated by changes of the AW circulation" (page 8, line 4-5) and ". . .variations in temperature are slightly more important than variations in volume flow" (page 8, line 14) seem contradictory.

Answer:

Conceptual model

First point: 657 m is the depth in the hydrographic data base closest to 700. We now state this. P10 L20

Second point: There is some degree of arbitrariness in defining the limits of the Atlantic Volume in the conceptual model. Taking the box indicated in Fig. 1 gives an area about $6x10^{11}$ m^2, which with H~700 m and a transport of 5 Sv, one obtains a time scale of 2.6 ≈ 3 years. On page 8 after discussing the residence time scale we have added a sentence which clarifies that, by taking these specific number for the Atlantic Water properties the residence time-scale defined in Eq. (14) gives value comparable to the ones estimated by for example Kozalka et al. (2013) P9 L6-8

Third point: We agree with the referee that our scaling arguments based on the conceptual model do not firmly show that temperature anomalies are dominating over volume transport anomalies for driving Atlantic Water temperature anomalies in the Nordic Seas. Instead, given the qualitative nature of scaling arguments it is reasonable to conclude that temperature- and transport-anomalies are potentially of equal importance. On P8 L19 we have therefore changed "can be more important for ocean heat convergence" to "can be equally important for ocean heat convergence". However the important point (P8 L20), which we want to make clear, is that for heat transport through a section, volume variations completely dominates over temperature variations (Asbjørnsen et al., 2018). We stress this difference between heat transport and heat convergence since it is important for rationalising the simple scenario where only forcing from temperature anomalies in the conceptual model is considered.

To give a more detailed view on the relative importance of anomalies in volume flow and temperature, we have changed some text on page 8 and 9: We now state that observations of Mork and Skagseth (2010), Berx et al. (2013), Bringedal et al. (2018) and Østerhus et al. (2019) suggest an increase of the Atlantic inflow to the Nordic Seas from the mid 1990:s to the early 2000:s. And further, we now write that this increase in volume transport can qualitatively explain why the observed temperatures are higher than those in the conceptual model (which is forced only by temperature variations) between in the early 2000:s. P11 L1-6

Finally, we think the referee's point concerning contradictory statement in relation to Eq. (14) can be solved by writing: "Equation (14) is based on the reasonable assumption that the low-frequency ocean heat convergence is dominated by changes of the AW circulation, *rather than air-sea heat fluxes*" P9 L10

Details

Including both "time-varying" and "trends" in the title seems a bit of an overkill and makes the title ambiguous. Do you mean "time-varying trends" ? Perhaps rephrase the title.

Answer: Yes, we do mean "time-varying trends", but did not realize this wasn't clear. The title will be changed to: "Mechanisms of the time-varying trends in sea surface height and heat content in the Nordic Seas"

After further revision, we changed the title to: “Mechanisms of decadal changes in sea surface height and heat content in the eastern Nordic Seas”

In the text, the Nordic Seas are sometimes treated as plural (are/have) and sometimes as singular (is/has). I prefer plural, but in any case, choose one.

Answer: We thank the Reviewer for pointing this out.

Page 1, line 5: can “slowdown” -> “weakening”

Answer: Done.

Page 1, line 21: “Chafik and Rossby (2019)” -> “(Chafik and Rossby, 2019)”

Answer: Done.

Page 2, line 8: “have” -> “has”

Answer: Done.

Page 2, line 13: “carry” -> “carries”

Answer: Done.

Page 2, line 24: “stagnant” -> “slowly-increasing”

Answer: Done.

Page 2, line 26: “variations” -> “variation”

Answer: Done.

Page 2, line 32-33: Do you actually use “Absolute” (rather than SLA) altimetry data ?
Answer: Yes.

Page 3, line 6: Non-standard reference

Answer: Fixed.

Page 4, line 2: “have” -> “has”

Answer: Done.

Page 4, line 8: “dynamic sea surface height” -> “sea surface height”

Answer: OK.

Page 4, line 22: “extent that” -> “extent than that”

Answer: No, this is supposed to be what it is. Reformulated to avoid confusion P5 L9

Page 4, line 29: “mean flow heat transport” ?????????
Answer: Changed to: “Heat transport by the mean flow” P5 L16

Page 5, line 17: “seasonal variation in heat content” -> “seasonal variation in heat content and wind forcing”

Answer: OK.

Page 6, line 19: “average” -> “averaged”

Answer: Done.

Page 6, line 29: “show” -> “shows”

Answer: Done

Page 7, line 1: “data is” -> “data are”

Answer: Done.

Page 7, line 13-17: Defining the overbar parameters as “time-mean” (line 13) is inconsistent with Eq. (11) (line 15) before you neglect second order terms (line 17). I suggest to move this assumption up. Then Eq. (11) follows naturally and is not a “choice”.

Answer: This is adjusted.

Page 11, line 18: “seem” -> “seems”

Answer: Done.

Page 11, line 18: “maintain” -> “maintains”

Answer: Done.

Page 14, line 16: Non-standard reference

Answer: Fixed.

Figure 3 and Figure 8: It is nowhere stated, how statistical significance is estimated, specifically whether it takes serial correlation into account. If it does take this into account, this should be stated (e.g. in the figure captions). If it does not, the significance should be re-calculated and the figure modified or the dots in Figure 3 and circles in Figure 8 should be removed as well as any reference to statistical significance in the captions and text.

Answer: For Fig. 3, two-sided p-values are calculated using the Wald test, which is provided by the SciPy linregress routine (Oliphant, 2007*). The significance test in Fig. 8 will be revised to take into account the effective number of degrees of freedom.

*Oliphant, T. E. (2007). Python for scientific computing. Computing in Science & Engineering, 9(3), 10–20. doi: 10.1109/MCSE.2007.58

See figure captions for Fig. 3 and 8.

The two panels in Figure 6 are labeled a) and b). In other two-panel figures, you use left/right or upper/lower. Be consistent.

Answer: We thank the reviewer for this. Done.

Mechanisms of ~~the time-varying~~ decadal changes in sea surface height and heat content ~~trends~~ in the eastern Nordic Seas

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Abstract. The Nordic Seas ~~is~~ constitute the main ocean conveyor of heat between the North Atlantic Ocean and the Arctic Ocean. Although the decadal variability of the Subpolar North Atlantic has been given significant attention lately, especially regarding the cooling trend since the mid-2000s, less is known about the potential connection downstream in the northern basins. Using sea surface heights from satellite altimetry over the past 25 years (1993-2017), we find significant variability on multiyear-to-decadal time scales in the Nordic Seas. In particular, the regional trends in sea surface height show signs of a ~~slowdown since~~ weakening since the mid-2000s, as compared to the rapid increase in the preceding decade since early 1990s. This change is most prominent in the Atlantic origin waters in the eastern Nordic Seas and is closely linked, as estimated from hydrography, to heat content. Furthermore, we formulate a simple heat budget for the eastern Nordic Seas to discuss the relative importance of local and remote sources of variability; advection of temperature anomalies in the Atlantic inflow is found to be the main mechanism. A conceptual model of ocean heat convergence, with only upstream temperature measurements at the inflow to the Nordic Seas as input, is able to reproduce key aspects of the decadal variability of the Nordic Seas' heat content. Based on these results, we argue that there is a strong connection with the upstream Subpolar North Atlantic. However, although the shift in trends in the mid-2000s is coincident in the Nordic Seas and the Subpolar North Atlantic, the eastern Nordic Seas ~~has~~ have not seen a reversal of trends but instead maintain elevated sea surface heights and heat content in the recent decade considered here.

1 Introduction

The Nordic Seas, a collective name for the Greenland–Iceland–Norwegian Seas, are the link between the Atlantic and the Arctic Oceans and are recognized to play an important role in the global climate system (Drange et al., 2005). Warm and saline waters of Atlantic origin cross the Greenland–Scotland Ridge (Fig. 1) and flow northward through the eastern part of the Nordic Seas before entering into the Arctic Ocean (Mauritzen, 1996; Orvik and Niiler, 2002; Skagseth et al., 2008; Furevik et al., 2007), affecting the local sea ice and atmosphere on its way. The densest waters sustaining the lower limb of the Atlantic Meridional Overturning Circulation ~~Chafik and Rossby (2019)~~ (Chafik and Rossby, 2019) are also produced in this region, by heat loss to the atmosphere, before flowing southward at depth across the Greenland–Scotland Ridge into the North Atlantic Ocean (Mauritzen, 1996; Hansen and Østerhus, 2000).

Since the Nordic Seas ~~is~~ make up a major source of heat for the Arctic Ocean it is important to understand the thermal variability and the mechanisms behind it. The Nordic Seas experience intrinsic variability on many time scales (e.g. Siegismund et al., 2007; Mork et al., 2014; Glessmer et al., 2014; Eldevik et al., 2009; Årthun et al., 2017; Shi et al., 2017). Carton et al. (2011) find several warm and cold events on multiyear timescales in an extensive 60 year hydrographic record. Segtnan et al. (2011) use reanalysis to examine the heat and freshwater budgets and find the largest water mass modifications to occur in the eastern part of the Nordic Seas. Asbjørnsen et al. (2018) use a consistent model framework to set up a closed heat and freshwater budget. A common question that these studies, and many others, address is if the source of variability is local, by interaction with the atmosphere, or remote and advected into the Nordic Seas. Anomalies have been found to propagate from the North Atlantic over the Greenland–Scotland Ridge (Årthun and Eldevik, 2016; Furevik, 2000; Koszalka et al., 2013) and the Atlantic inflow is tightly linked to dynamics of the Subpolar Gyre (Hátún et al., 2005). Interestingly, the Subpolar North Atlantic ~~have~~ has recently experienced strong decadal variability (Robson et al., 2016; Piecuch et al., 2017; Ruiz-Barradas et al., 2018) but the possible impacts of this further north are not well established. The focus of this study is on recent decadal variability in the Atlantic water domain in the eastern parts of the Nordic Seas, with emphasis on the mecanisms behind the variability.

For a couple of decades now, we have been able to monitor sea level change and study key aspects of ocean dynamics using satellite altimetry. The dynamic sea surface height (SSH) retrieved from satellites ~~carry~~ carries information on ocean circulation, as it represents streamlines of the surface geostrophic currents, as well as sea level. The SSH reflects both steric height and dynamic bottom pressure (Broomé and Nilsson, 2016); regional sea level change can be related to warming/cooling and freshening/salinification by air–sea fluxes but also due to redistribution of mass, heat and freshwater by time-varying ocean currents ~~(Stammer et al., 2013)~~(Gill and Niller, 1973; Stammer et al., 2013). On time scales from days to months, local wind forcing and rapidly propagating waves are the main drivers of variability in sea level (Stammer, 1997). On longer timescales, multiyear/interannual-to-decadal, which are relevant to this study, the steric component of the SSH due to the integrated buoyancy of the water column instead becomes the main driver of the variability in sea level (Richter and Maus, 2011). The time series of satellite altimetry is available since 1993 and is now becoming useful for studying recent decadal variability (Chafik et al., 2019).

This study aims to analyze the decadal variability of the Nordic Seas, using the altimetric time series of dynamic SSH combined with in situ data. More specifically, in section 3.1 we find that in addition to a general positive trend in sea level, the Nordic Seas ~~has~~ have had a period of rapid increase in SSH followed by a period of ~~stagnant~~ slowly-increasing SSH. This decadal variability is concentrated in the eastern, Atlantic origin waters. We show that the decadal variability in SSH is linked to heat content and through a heat budget and conceptual model in section 3.2 we argue that the ~~variations~~ variation in temperature of the inflowing Atlantic water in the south is the main contributor to the variability. A strong connection to recent decadal variability in the subpolar gyre, discussed in section 3.3, further strengthens this idea, but also raises some questions about possible variations in the connection over time.

2 Data and method

2.1 Satellite altimetry (SSH)

This study has been conducted using satellite altimetry retrieved from Copernicus Marine Service Information. We use Absolute Dynamic Topography (ADT) which is the sea surface height above the geoid, i.e. the part of the SSH related to the ocean circulation. The gradient of the ADT is directly proportional to the surface geostrophic current. The ADT has undergone several correction, calibration and homogenization processes, bringing data from several satellite missions together (Pujol et al., 2016). The ADT is distributed as daily fields on a regular 1/4° grid and has here been averaged into monthly fields from 1993 until ~~2017 and then deseasonalized~~ 2017. The monthly time series has been deseasonalized by subtracting a monthly climatology constructed from 1993-2017.

2.2 Hydrography

We use the EN4.2.0 data set provided by the UK Met Office (Good et al., 2013), with bias correction by Gouretski and Reseghetti (2010), on a 1°horizontal grid and 42 depth levels with higher resolution closer to the surface. Similarly to the ADT, we ~~make~~ construct time series of deseasonalized monthly means.

From the hydrographic data, the steric height (η_S) and a baroclinic volume transport function (ψ), proportional to the potential energy anomaly, can be calculated (Gill and Niller, 1973; Walin et al., 2004):

$$\eta_S = \int_{-h_b}^{0} \Delta\rho^*\, dz \tag{1}$$

$$\psi = -\frac{g}{f} \int_{-h_b}^{0} z\Delta\rho^*\, dz, \tag{2}$$

where

$$\Delta\rho^* = [\rho(34.9, -1, z) - \rho(S, T, z)]/\rho(34.9, -1, 0), \tag{3}$$

is a non-dimensional density anomaly that measures the density deficit of the Atlantic Water layer relative to the deep water, g the acceleration of gravity, and f the Coriolis parameter. Note that the steric height is not uniquely defined as it is specified relative to a reference density. However, changes in steric height as well as in ψ are independent of the reference density. We can decompose the ADT (say η) as (Gill and Niller, 1973)

$$\eta = \eta_S + \eta_B, \tag{4}$$

where $\eta_B = \eta - \eta_S$ and $g\rho\eta_B$ is a bottom pressure (that again depends on the reference density). Still, ADT and steric height data allow changes in sea level to be partitioned into changes due to steric height and bottom pressure.

The transport stream function ψ is the potential energy anomaly divided by f and represents the vertically-integrated thermal-wind flow from $z = -h_b$ to the surface. Note that in a 1.5-layer model with an active upper layer with the depth H, the steric height and baroclinic transport (or potential energy) are closely related and given by (Nilsson et al., 2005)

$$\eta_S = \Delta\rho^* H, \tag{5}$$

$$\psi = \frac{g\Delta\rho^* H^2}{2f}. \tag{6}$$

To capture the dynamics and heat content of the waters of Atlantic origin that occupy the eastern Nordic Seas, integrations are done down to a depth level representative for the time-mean depth of the Atlantic Water (AW), in this case the EN4 depth level 657m (see e.g. Skagseth and Mork, 2012). The deep water below the AW is colder and the thermal expansion coefficient lower, thus the contribution to the steric height is supposedly lower. By limiting the integration to 657 m, we exclude the contribution from the deep water that does not experience the same variability as the AW and is not directly affected by the North Atlantic. Similar results The depth of the AW is, however, not uniform in neither space nor time, but extends for example deeper in the Lofoten Basin than it does further south. The analysis is not sensitive to the choice of integration depth, and quantitatively similar spatial patterns and decadal variability are obtained also for integrations extending down to about 1000 m.

2.3 Air-sea heat flux

The net air-sea heat flux have has been calculated from five different sources of surface fluxes. Three are from atmospheric reanalysis: ERA-Interim (Dee et al., 2011), NCEP (Kalnay et al., 1996) and JRA-55 (Kobayashi et al., 2015). The NOC surface flux (Berry and Kent, 2009, 2011) is calculated from observations of bulk atmospheric properties and J-OFURO (Tomita et al., 2019) is satellite-derived. Here we have used monthly time series from 1993-2013, defined positive upwards, i.e. positive when the ocean loses heat to the atmosphere. All products have been regridded to a $0.5° \times 0.5°$ grid using bilinear interpolation.

3 Results and discussion

3.1 Sea surface height trends and heat content

Over the last three decades, the dynamic sea surface height in the Nordic Seas has generally been rising. Figure 2 shows the linear trend in SSH from 1993 to 2017, which is positive almost everywhere and has a local maximum in the Atlantic Water (AW) in the Lofoten basin of over half a centimeter per year. In parallel, hydrographic observations show that the steric height and the potential energy anomaly baroclinic transport function (Eqs. 1, 2) have increased during the same period; in Fig. 2 is also the trend in potential energysteric height and transport function, or equivalently baroclinic volume transport, which largely mirrors the trend in steric height (not shown)potential energy anomaly. Most of the hydrographic trend is in the Atlantic origin sector of the Nordic Seas and the local maximum is, similarly to the SSH, located in the Lofoten Basin. The heat content of the AW has also increased and a maximum can again be identified in the Lofoten Basin (Skagseth and Mork, 2012; Mork et al., 2014; Shi et al., 2017). The trends in SSH, steric height (η_S) and baroclinic volume transport (ψ) differ in the shallow shelf regions, but the broad features in areas within the AW that are deeper than 500 m are similar. The pattern of these trends resembles that of the time-mean steric height and in turn, as the buoyancy of the AW is essentially uniform, the time-mean steric height roughly map the depth of the AW layer (see Broomé and Nilsson, 2016, Fig. 3). What this reasoning suggests is that the trend in SSH is to a first approximation caused by a uniform warming of the AW. This notion is also supported by Skagseth and Mork (2012).

The pattern seen in the trends of the SSH, steric height, and potential energy resemble the pattern of the time-mean steric height, but only to a lesser extent more so than that of the time-mean SSH (see e.g. Broomé and Nilsson, 2016, Fig. 3). This indicates that the general warming of the AW during the period 1993 to 2017 also has entailed a gradual reorganisation of the circulation both at the surface and over the depth of the AW. The circulation in the AW domain consists of a current system of two branches (Orvik and Niiler, 2002); The Norwegian Atlantic Front Current (NwAFC) and the Norwegian Atlantic Slope Current (NwASC), see Fig. 1. Figure 2 reveals a strengthening of an anticyclonic flow anomaly in the Lofoten Basin, which tends to divert water south-east of the LB Lofoten Basin (LB) towards the outer NwAFC branch, flowing along the western limit of the Lofoten BasinLB. Thus, near the Lofoten Basin LB the trends in AW density serve to strengthen the outer NwAFC branch at the expense of the inner NwASC branch. This is expected to augment the mean flow heat transport heat transport by the mean flow that enters the Lofoten Basin LB from south (Dugstad et al., 2019). Potentially, this could also increase the residence time of the AW in the region as an increasing fraction of the AW tends to follow the NwAFC, taking a longer path along the western edge of the Lofoten BasinLB. Periods with long-term trends of AW cooling and densification can be expected to show similar patterns of trends in SSH and baroclinic flow as seen in Fig. 2 but with the reversed sign.

The broad-scale positive trend in heat content, steric height and baroclinic transport function in the Lofoten Basin, recorded in the time- and space-interpolated hydrographic data, may partly reflect an increase in the intensity and number of mesoscale anticyclonic eddies shed from the continental slope that propagate into the central basin (Köhl, 2007; Raj et al., 2015; Chafik et al., 2015). Higher influx of eddies from the slope can invigorate the long-lived dominating anticyclonic eddy (Köhl, 2007), known as the Lofoten Vortex, which has a strong local hydrographic signature and moves around in the central basin (Søiland et al., 2016). The associated changes in steric height (Fig. 2) in the Lofoten Basin have served to induce an anticyclonic flow anomaly carrying a larger fraction of AW from the slope current into the basin. This flow anomaly acts to enhance the near-surface heat transport by the mean flow entering the Lofoten Basin from south (Dugstad et al., 2019). In combination with alterations of eddy fluxes from the Lofoten escarpment (Spall, 2010; Chafik et al., 2015) the anticyclonic mean-flow anomaly is a plausible mechanism for the build-up of the Lofoten Basin heat content over the period 1993-2017. However, for the large-scale trend pattern it does not matter if the warming in the Lofoten Basin is caused by mesoscale eddies or by mean-flow changes.

3.1.1 Decadal variability

Analysis of the time series of satellite altimetry reveals that the positive trend is not constant in time. Fig. 3 shows the linear trend in SSH for two decades, one from 1993 to 2002 and the other from 2004 to 2013. These two periods have very different patterns; the first period has a pronounced positive trend in the AW and also in the Greenland Sea while the second period has smaller amplitudes and no clear sign of trend in the AW. It is clear that most of the linear increase seen in Fig. 2 occurs in the first of these periods.

It is also apparent that the greatest change in trend between the two decades occurs in the Atlantic water domain south of the Barents Sea ~~opening~~ Opening (BSO). To identify the Atlantic water variability we define the AW area, shaded ~~gray~~ grey in Fig. 1, as the area between 63.5 and 72.5°N that is enclosed by the time-mean position of the 35.0 surface isohaline. The defined area comprises the AW from the southern section where different inflows over the Greenland–Scotland Ridge merge into the eastern boundary current system, up to and including the deep pool of AW in the Lofoten Basin. North of this, the AW fractionates between the Barents Sea and the continental slope towards the Fram Strait.

The SSH is averaged over the defined AW area, resulting in the time series shown in Fig. 4. The data have been deseasonalized to remove the otherwise dominant seasonal cycle of high sea surface height in summer and low in winter, reflecting the seasonal variation in heat content and wind forcing. A large monthly variability remains in addition to a long term trend of about 0.3 cm yr^{-1}. Around 2004 or 2005, the area averaged SSH shifts from a period of high variability and positive trend to a stagnant period of smaller variability and no trend.

The variations in the SSH on multi-year and longer time scales is closely related to heat content (Richter and Maus, 2011; Shi et al., 2017) and Fig. 4 shows a corresponding AW time series of heat content. ~~Although the correlation between the monthly time series of SSH and heat content is low, there is a definite similitude in the decadal trends~~The variability on decadal time scales is similar to the SSH; in Fig. 4 there seems to first be a period of strong positive trend of about 5 Wm^{-2} followed by a stagnant period, with the shift in the mid of the 2000s. This indicates that the observed decadal variability in the SSH is mainly a steric signal, a conclusion made also by Shi et al. (2017)~~.~~, but with some contribution from changes in wind forcing (Chafik et al., 2019). This is further supported by the low frequency variation of the steric height, shown in grey in the lower panel of Fig. 4, which closely follows that of the heat content. The exception is around 2010-2011, when the steric height decreased while the heat content kept increasing, in connection with a strong increase in salinity as seen for example in Fig. 3 in Mork et al. (2019).

The selection of the two periods is somewhat arbitrary, and the trends are generally sensitive to the endpoints. Therefore, the periods should only be considered as guidelines and the full time series is included for transparency. Here, the altimetric time series has been the basis for the choice. There is an anomalous high event in the SSH around 2003 in Fig. 4, which is well correlated with a deepening of the AW layer, mostly in the Lofoten Basin, and less with temperature or heat content (Skagseth and Mork, 2012). We have therefore chosen to exclude the year 2003 from the periods.

In the next sections we will discuss the mechanisms behind the changes in trends between the two decades. First, a heat budget will be set up to discern the relative influence of ocean advection and air-sea heat fluxes. Second, based on the heat budget, we will discuss a simple conceptual model to show that changes of the temperature of the Atlantic origin inflow is a likely source of decadal variability. Third, we will analyse the connection between the AW in the Nordic Seas and the upstream subpolar North Atlantic.

3.2 Simple heat budget

A simple heat budget might give insight to the causes of the decadal variability. We consider the heat budget for a fixed volume of Atlantic Water in the Nordic Seas (V_{AW}), defined by the lateral boundaries in Fig. 1 and down to a fixed depth representative of the depth of the AW. The heat content is defined by

$$H \stackrel{\text{def}}{=} c_p \int\limits_{V_{AW}} T \, dV, \tag{7}$$

where c_p is the heat capacity per unit volume for sea water and T the temperature, and the heat budget is

$$\frac{dH}{dt} = C - Q. \tag{8}$$

Here, C is the ocean heat convergence and Q the upward net heat flux at the sea surface.

Let us now use the heat budget to examine the heat content for the two decadal periods of interest here, called 1 (first) and 2 (second). Subtracting the budget in Eq. (8) for each period, we can write

$$\frac{1}{A} < \frac{dH}{dt} >_1 - \frac{1}{A} < \frac{dH}{dt} >_2 = \frac{< C >_1 - < C >_2}{A} - \frac{< Q >_1 - < Q >_2}{A},$$

where $<>_{1,2}$ are the averages over period 1 and 2, respectively, and A the surface area of the AW domain. The heat content of the AW volume (Fig. 4) has a linear increase during the first period per unit area of about 5 W m^{-2} and about 0 W m^{-2} during the second period, i.e.

$$\frac{1}{A} < \frac{dH}{dt} >_1 - \frac{1}{A} < \frac{dH}{dt} >_2 \approx 5 \text{ W m}^{-2}. \tag{9}$$

To analyze if the surface heat flux Q can explain the observed decadal variability, we use observations of net air-sea heat flux. However, the estimates available of surface heat flux differ significantly in pattern, variability and mean state (see e.g. Carton et al., 2018). To demonstrate this, we use five different estimates of the net flux, defined positive upwards, ~~and average~~ averaged over the two periods of interest and over the AW area, see Table 1 and Fig. 5. In an annual mean, the whole AW area loses heat to the atmosphere but the mean heat loss in Table 1 varies about 20 W ~~/m^2~~m^{-2}, or 25-30%, between the products. To explain the observed variability, assuming in turn that the ocean heat ~~flux~~ divergence is zero, the second decade would have to experience a higher heat loss to the atmosphere, i.e. $-(< Q >_1 - < Q >_2)/A > 0$. This is true for one of the surface flux products (NOC), while the other estimates are close to zero or almost 10 W/m^2 in the other direction. The spatial patterns of the difference in surface heat flux between the two periods (Fig. 5) also vary significantly between the data sets, and none of these patterns match the SSH trend pattern (Fig. 2) with its distinct peak in the Lofoten Basin.

Several observational studies have found that the surface heat flux can only explain a smaller part of the low-frequency variations of the AW heat content in the Nordic Seas (Carton et al., 2011; Skagseth and Mork, 2012; Shi et al., 2017). A study of a physically consistent ocean state estimate also ~~show~~ shows that surface heat flux is not the main source of AW heat content interannual variability (Asbjørnsen et al., 2018). Although the surface heat flux data is are not conclusive, we argue that the surface heat flux is not the main source of the change in decadal trends. We will thus continue by considering the other possible source in our heat budget, namely the ocean heat convergence. In the next section we will quantify the convergence and try to disentangle the contribution from variations in temperature and transport respectively.

3.2.1 Conceptual model of ocean heat convergence

We will now show that temperature variations of the AW, flowing across the Greenland–Scotland Ridge and into the southern border of the Nordic Seas AW domain, can explain a significant fraction of the observed heat content variability. To demonstrate this, we model ocean heat convergence as

$$C = c_p \Delta T \Psi, \qquad \Delta T \stackrel{\text{def}}{=} T_i(t) - T_0(t), \tag{10}$$

where T_i/T_0 is the temperature of the in/outflowing AW and Ψ the volume transport. Using this, the heat budget in Eq. (8) becomes

$$\frac{dH}{dt} = c_p \Delta T\, \Psi - Q. \tag{11}$$

We write the variables in the heat budget as a sum of a time-mean part (overbar) and a time varying part (prime): $\Delta T = \overline{\Delta T} + \Delta T'$ $(= \overline{\Delta T} + T_i' - T_o')$, and similarly for Ψ and Q. We choose $\overline{\Delta T}$, $\overline{\Psi}$ and $\overline{Q}$ so that

$$c_p \overline{\Delta T}\,\overline{\Psi} = \overline{Q}$$

This implies that the time-mean heat budget is $\overline{C} = \overline{Q}$, i.e. in the time-mean the heat convergence is balanced by the upward surface heat flux. The linearised Eq. (11), neglecting Using these definitions and neglecting the non-linear $\Delta T'\Psi'$, then becomes

$$\frac{dH}{dt} = c_p \Delta T' \overline{\Psi} + c_p \overline{\Delta T} \Psi' - Q'.$$

term, we obtain

$$\frac{dH}{dt} = c_p \Delta T' \overline{\Psi} + c_p \overline{\Delta T} \Psi' - Q', \tag{12}$$

where we have used the fact that the linearised steady-state heat budget is $0 = c_p \overline{\Delta T}\,\overline{\Psi} - \overline{Q}$. Further, we set

$$\frac{dH}{dt} = c_p V_{AW} \frac{dT}{dt} = c_p V_{AW} \frac{dT'}{dt} \tag{13}$$

where T' is the mean AW temperature anomaly. We will now make two simplifying assumptions. First, since the center of mass of the AW is located near the Lofoten Basin, close to our AW domain's northern boundary, we assume that the outflow temperature $T_o'(t)$ is approximately equal to the mean AW temperature anomaly $T'(t)$. Second, based on the discussion of the surface heat flux in section 3.2 we will here assume that Q' is small and thereby limit the analysis to the ocean heat convergence. Using these two simplifications in Eqs. (12) and (13), we obtain the following equation for the mean AW temperature anomaly:

$$\tau \frac{dT'}{dt} + T' = T_i'(t) + \overline{\Delta T}\Psi'(t)/\overline{\Psi} \qquad \tau \stackrel{\text{def}}{=} \frac{V_{AW}}{\overline{\Psi}}. \tag{14}$$

Here, the terms on the right-hand side are the forcings due to anomalies in inflow temperature and AW volume transport, respectively~~,~~. Taking an Atlantic Water area and depth of $\sim 6 \cdot 10^{11}$ m^2 and ~~$\tau \sim$ 3–4 yearsis the residence time of the AW in the domain~~ $\sim$ 700 m, respectively, and $\overline{\Psi} \sim 5$ Sv (Mork and Skagseth, 2010) gives an e-folding time scale $\tau \sim 3$ years, which is comparable to published estimates of AW residence times of 3 to 4 years (Koszalka et al., 2013; Broomé and Nilsson, 2018).

Equation (14) is based on the reasonable assumption that the low-frequency ocean heat convergence is dominated by changes ~~of~~ in the AW circulation, rather than in air–sea heat fluxes. To examine if variations in temperature or transport dominate the variation in heat convergence, we note that the ratio between the second and first term on the right-hand side of Eq. (14) is

$$\frac{\Psi'}{\overline{\Psi}} \left(\frac{T_i'}{\overline{\Delta T}} \right)^{-1}. \tag{15}$$

This is the ratio between the two driving terms and if it is small, temperature anomalies dominate over transport anomalies in the ocean heat convergence, and conversely when the ratio is large. The Svinøy Section is roughly located at the upstream border of our Atlantic Water domain. Here, the mean AW transport is $\overline{\Psi} \sim 5$ Sv (Mork and Skagseth, 2010) and $\overline{\Delta T}$ can be estimated from the steady state heat budget (Eq. (11)) as $\overline{\Delta T} \approx \overline{Q}/(c_p\overline{\Psi})$; taking $\overline{Q}/A \sim 80$ W m^{-2} (see table 1) gives ~~$\overline{\Delta T} \sim 2$ °~~ $\overline{\Delta T} \sim 2°$C. Further, measurements in the Svinøy ~~Section~~ section indicate low-frequency flow and temperature anomalies (> 5 years) that give $\Psi'/\overline{\Psi} \sim 0.3$ and $T_i'/\overline{\Delta T} \sim 0.4$ (estimated from Fig. 7 in Mork and Skagseth, 2010). This gives a value of about 0.7 for the ratio in Eq. (15), suggesting that variations in temperature ~~are~~ can be slightly more important than variations in volume flow. We obtain similar results using observations from the Faroe–Shetland Channel ~~(Berx et al., 2013)~~(Berx et al., 2013; Bringedal et al., 2018; Østerhus et al., 2019). We note that per unit area in the AW domain, the $c_p\Delta T'\overline{\Psi}$ term in Eq. (12) gives a heat convergence of 40 W m^{-2} for a $\Delta T'$ anomaly of 1°C. Thus, a difference in inflow and outflow temperatures less than 0.5°C could explain the observed increase in heat content from the mid 1990s to around 2004.

Our considerations show that AW temperature variations can be ~~more~~ as important for the ocean heat convergence ~~than~~ as variations in AW volume transport. However, the ocean heat transport variations in sections across the AW, such as the Svinøy Section, tend to be dominated by variations in the volume transport ~~(Asbjørnsen et al., 2018)~~(Orvik and Skagseth, 2005; Asbjørnsen et al., 2 The reason is that there is a net volume transport across the sections, which requires the heat transport to be defined relative to a reference temperature. This reference temperature, characterising a return flow, is usually taken to be 0°C for AW heat transport in the Nordic Seas ~~(Asbjørnsen et al., 2018)~~(Orvik and Skagseth, 2005). Using a reference temperature of 0°C to estimate the heat transport anomaly in Eq. (12) gives an effective temperature difference $\overline{\Delta T} \sim 6$°C (the mean temperature of the section in °C), rather than $\overline{\Delta T} \sim 2$°C (the temperature difference between in- and out-flowing water) as used here for estimating the ocean heat convergence.

We also note that observations of volume transport at the southern inflows to the Nordic Seas ~~show no indication of~~ indicate no clear decadal trends over the time period ~~(Berx et al., 2013; Østerhus et al., 2019; Hansen et al., 2015)~~(Berx et al., 2013; Hansen et al., 2 The volume transport can also be estimated from the slope of SSH (Chafik et al., 2015). Over the slope in the FSC, such a barotropic calculation (not shown) gives a mean transport of just under 4 Sv (consistent with the 4.1 Sv direct estimates by Rossby and Flagg (2012)), with monthly estimates ranging from 0 to 8 SV, but no ~~decadal trends to explain the ones in the Nordic Seas, further supporting the notion that temperature variations dominate the heat convergence~~clear decadal trends. Accordingly, it is unlikely that variations of AW volume transport and air–sea fluxes have been the main drivers of the observed trends in heat content and SSH in the eastern Nordic Seas in the period presently considered.

Motivated by ~~the considerationsof the heat budget~~these considerations, we examine ~~if~~ how well the simple model defined by Eq. (14) can reproduce the evolution of the mean AW temperature anomaly, given the inflow temperature as the only forcing. We note that by converting the observed heat content anomaly (by dividing it by $c_p V_{AW}$) to a temperature anomaly, the left-hand side of Eq. (14) can be used to compute the total model forcing, defined by $T_i'(t) + \overline{\Delta T}\,\Psi'(t)/\overline{\Psi}$, and representing the forcing required to reproduce the observations. This allows us to examine both how well the inflow temperature reproduces the total model forcing and the observed AW heat content variations. For this purpose, we estimate the AW inflow temperature $T_i'(t)$ from sea surface EN4 temperatures in the Faroe–Shetland Channel and in the Svinøy Section from 1955 up to the present and integrate Eq. (14) numerically forward in time. In the calculations, we use the e-folding timescales (τ) 2.5, 3.0, and 4.0 years, which are in the range of estimated residence times in the presently defined AW domain (Koszalka et al., 2013; Broomé and Nilsson, 2018). This range of τ implies that the temperature/heat-content anomaly evolution in the model is influenced by the upstream temperature history a couple of years back in time. The heat content is related to the temperature by Eq. (13), using a mean depth of the AW layer of 700 m (note that the depth level 657 m in the EN4 data, used earlier, is the level closest to 700 m).

Figure 6 shows the proxies for the AW inflow temperature forcing $T_i'(t)$ and the resulting modelled heat content anomaly as well as the low-pass filtered AW heat content anomaly estimated from the EN4 data (from Fig. 4). The upper panel in Fig. 6 also shows the total model-forcing temperature anomaly (the right-hand side of Eq. (14)) needed to reproduce the observed heat content variations. For easy comparison, the heat content anomalies have been set to zero in 1993. The results based on the Svinøy ~~Section~~ section temperature (results are similar when the Faroe–Shetland Channel temperature is used) show that the simple model reproduces the main features of the low-frequency evolution of the AW heat anomaly. For all three values of τ, the modelled heat content anomaly increases from the mid ~~1990:s~~ 1990s to the mid ~~2000:s~~ 2000s with a more stagnant period following, in broad agreement with the observations. In effect, the model acts as a low-pass filter on the driving inflow temperature $T_i'(t)$, suppressing variability with time-scales shorter than about 4 years. Thus, the model heat anomaly is mainly forced by the general increase of the inflow temperature up to around 2003 and the more constant inflow temperature in the period thereafter. There are some obvious differences between the model and the observational estimate of the heat content. Specifically, the increase of the heat anomaly in the data from around 1997 to 2004 is weaker and possibly delayed a couple of years in the model. A strengthening of the AW volume transport with some 10–20% or a decreased surface heat loss during this period may explain the deviation between the simple model and the data-based estimate of the heat content anomaly. In any case, By comparing the forcing from the inflow temperature variations to the total model forcing (upper panel in Fig. 6), we note that the total model forcing is higher from around 1998 to 2002. Current meter observations show that the AW inflow to the Nordic Seas (Bringedal et al., 2018; Østerhus et al., 2019) and through the Svinøy Section (Mork and Skagseth, 2010) increased some 20% from around 1995 to 2000. This makes variations in AW volume transport a plausible cause for why the heat content increase is weaker in the conceptual model than in the observations in the earlier period. Nevertheless, despite the rather drastic simplifications of the conceptual model, this calculation shows that the variations of the inflow temperature at the southern boundary are important for the observed low-frequency heat content variability in the AW domain.

3.3 Connection to the upstream subpolar North Atlantic

Since our results suggest that local air-sea heat fluxes cannot explain the decadal heat content variability and that ocean advection of temperature anomalies from the south is the main cause, it is reasonable to assume a close connection to the Subpolar North Atlantic (SPNA). In this regard, several studies have documented a link between SPNA temperature variability and the Nordic Seas, mediated by advection of temperature anomalies along the eastern branch of the North Atlantic Current (Chepurin and Carton, 2012; Årthun and Eldevik, 2016; Årthun et al., 2017; Langehaug et al., 2019). We will now consider if such an advective connection can explain Nordic Seas AW temperature variations from the period from around 1993 to 2016.

Figure 7, based on Empirical Orthogonal Function analysis (Hannachi et al., 2007), shows that the leading mode of temperature variability in the SPNA (explained variance is 70%), of both surface and subsurface temperatures down to ∼400 m, is dominated by pronounced decadal variability. However, while the decadal temperature changes in the eastern Nordic Seas (Fig. 7, left panel) track those in the SPNA (Fig. 7, right panel) during the 1993-2004 period, a clear disconnection is seen after 2005. Consistent with the SSH and heat content analysis (e.g. Fig. 4), Fig. 7 shows that while the SPNA has been cooling since the mid 2000s, the Nordic Seas has not. This disconnection suggests a weak relationship of the eastern Nordic Seas to changes in the SPNA during its cooling phase (∼mid-2000s to 2016), but a strong connection, as shown here and documented by many studies (Hátún et al., 2005; Skagseth and Mork, 2012), during the warming phase of the SPNA (∼early 1990s to mid-2000s).

This weakened (enhanced) connection between the SPNA and the Nordic Seas during the recent cooling (warming) phase may be explained by the horizontal circulation and hence the shape of the subpolar gyre/front in the eastern SPNA. As the subpolar gyre strengthens (weakens) during the cooling (warming) phase, in response to several years of strong (weak) wind-stress curl (Häkkinen et al., 2011), it also expands (contracts) in size and the subpolar front shifts eastwards (westwards), which, in turn, leads to a smaller (larger) fraction of subtropical water masses spreading along the eastern boundary, across the Greenland–Scotland Ridge and into the Nordic Seas. This view is supported by a spatial correlation analysis between the leading mode of temperature variability in the Nordic Seas at 100 m against that in the wider North Atlantic, shown in Fig. 8. The resulting pattern indicates that the relationship with the SPNA is only strong and significant along the subtropical path in the eastern subpolar gyre and around its rim rather than in the central SPNA, where the correlation is weak, negative and not significant. It is thus possible that the contraction and expansion of the subpolar gyre, through its control on the northward access of warm and saline subtropical waters in the eastern subpolar gyre (Hátún et al., 2005; Häkkinen et al., 2011; Chafik et al., 2019), may have regulated the observed time-varying connection between the SPNA and the Nordic Seas (Figs. 4 and 7) and hence the rate of ocean heat content and sea surface height change in the eastern Nordic Seas on decadal scales.

The subpolar gyre linkage discussed above together with the simple model in section 3.2.1, which only includes inflow temperature variations, suggest that air-sea fluxes could not have caused the observed shift in decadal heat content trends. However, this does not rule out that atmospheric circulation anomalies may also have helped to maintain warm ocean temperatures in the Nordic Seas since mid-2000s, resulting in the stagnant period instead of the cooling seen in the SPNA. This may be consistent with conclusions from a recent study by Asbjørnsen et al. (2018), which reported that local forcing from air-sea heat fluxes are important for modulating the anomalies on their northward path. However, it is also possible that the ongoing cooling in the SPNA (Chafik et al., 2019) had simply not yet reached the Nordic Seas at the end of 2016. Although we have only speculated on the cause for this stagnant period, our simple model of heat convergence reproduced the decadal heat content variability in the eastern Nordic Seas reasonably well, despite the observed disconnection from the SPNA. This important result thus suggests that temperature conditions in the northeastern Atlantic and at the Greenland–Scotland Ridge are key in setting the decadal variability in ocean heat content and SSH changes in the eastern Nordic Seas.

4 Summary and concluding remarks

In this study of the Atlantic ~~water~~ Water of the Nordic Seas (AW), ~~decadal~~ we analyse changes in sea surface height (SSH) on decadal time scales since 1993 ~~have been analysed and underlying mechanisms have been investigated~~and investigate underlying mechanisms. Over the full period of satellite observations of SSH, 1993-2017, there is a general positive trend coincident with a warming of AW in the eastern Nordic Seas. We identify a shift in the trend of SSH in the AW, from a decade of strong positive trend to a more stagnant decade. A similar change in trend is also found in the heat content of the AW. We argue that the steric height changes related to the variation in heat content is the main reason for the observed decadal changes in SSH trends and further investigate whether the source of the decadal changes is local or remote.

Through a simple heat budget adapted to the AW, we discuss three possible reasons for the decadal variations in heat content: a difference in net surface heat flux between the two periods (local source) and a difference in either volume transport or temperature of the AW inflow at the southern boundary (remote source). We conclude that the most plausible cause of changes in SSH and heat content ~~decadal trends is a change of temperature of~~ on decadal time scales is remote and advected with the Atlantic source waters entering the Nordic Seas over the Greenland–Scotland Ridge. We also conclude that decadal-scale changes in inflow temperature, rather than in volume transport, have dominated during the period considered in this study. A quantitative estimate of the relative contributions from volume transport and temperature in the heat transport shows that a difference in inflow temperature of 0.5°C is enough to explain the decadal changes in heat content. Furthermore, we construct a simplified conceptual heat budget model to forecast the AW heat content based on a single measurement of temperature at one of the main inflow regions to the Nordic Seas, i.e. the Faroe-Shetland Channel. The model is able to reproduce the main features of the observed decadal changes of AW heat content and SSH in time and magnitude.

~~Our main findings include: The decadal variability in SSH is closely related to heat content and the main reason for the shift in decadal trends in the SSH is the steric height changes related to heat content. The source of the decadal changes in heat content is remote, and most likely associated with a change of temperature of the Atlantic source waters entering the Nordic Seas over the Greenland–Scotland Ridge. A conceptual heat budget model of the AW heat content, based on a single measurement of inflow temperature, is able to roughly capture the observed decadal changes in the AW. The AW in the~~ Interestingly, the AW in the Nordic Seas has not experienced the same reversal of trends as the upstream central Subpolar North Atlantic, but instead ~~seem~~ seems more related to the rim of the SPNA and ~~maintain~~ maintains warm ocean temperatures and high SSH during the period considered.

~~The AW center of mass in the eastern Nordic Seas is encountered in the Lofoten Basin, where the AW layer extends deeper (Skagseth and Mork, 2012; Raj et al., 2015). Here the AW warming during the period 1993-2017 is most pronounced, which via associated changes in steric height and potential energy (Fig. 2) have served to induce an anticyclonic flow anomaly carrying a larger fraction of AW from the slope current into the Lofoten Basin. This flow anomaly acts to enhance the near-surface heat transport by the mean flow entering the Lofoten Basin from south (Dugstad et al., 2019). In combination with alterations of eddy fluxes from the Lofoten escarpment (Spall, 2010; Chafik et al., 2015; Dugstad et al., 2019) the anticyclonic mean-flow anomaly are plausible mechanisms for the build-up of the Lofoten Basin heat content over the period 1993-2017.~~

We have connected decadal variability to upstream conditions, which has implications for decadal climate predictability in the Nordic Seas. It is equally important to note that the conditions observed in the AW of the Nordic Seas can have impact further downstream (Polyakov et al., 2017; Smedsrud et al., 2013; Sandø et al., 2010). For example, discussions in the past few years have referred to an "Atlantification" of the Barents Sea and Arctic Ocean as a cause of sea ice loss (see e.g. Årthun et al., 2012; Polyakov et al., 2017), highlighting the importance of upstream AW conditions. Last but not least, this study shows that the satellite absolute dynamic topography can be used to study decadal variability in heat content, which is useful since the satellite data is accessible, has no summer bias and generally has better and more even resolution in time and space than hydrography.

Data availability. The absolute dynamic topography data are available from http://marine.copernicus.eu/services-portfolio/access-to-products/ with the product identifier: SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047.

The EN4 hydrographic data are available from https://www.metoffice.gov.uk/hadobs/en4/.

The ERA-Interim, NCEP/NCAR and JRA reanalysis along with the NOC surface flux are available from the Research Data Archive: https://rda.ucar.edu/. The J-OFURO data are available from https://j-ofuro.scc.u-tokai.ac.jp/en/.

Author contributions. SB carried out the analysis from an original idea of LC and with continuous input from LC and JN. SB wrote the bulk of the paper, with JN as main author of section 3.2 and LC of section 3.3.

Competing interests. The authors declare no competing interests.

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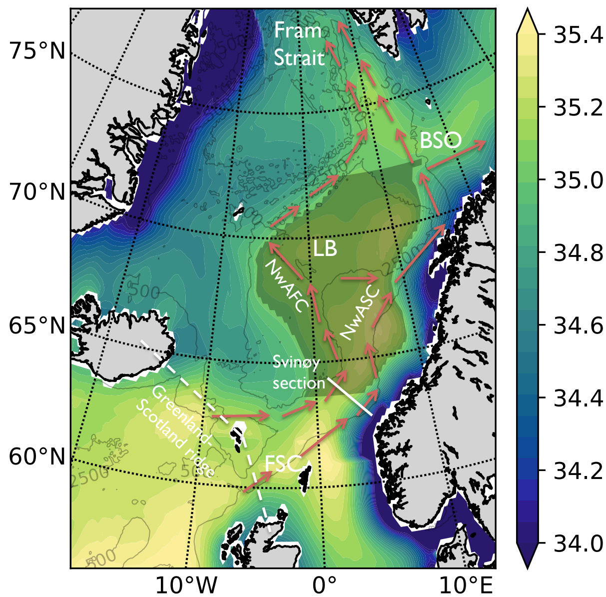

Figure 1. Map of the Nordic Seas with average surface salinity (Zweng et al., 2013) in shading. The general pathways of the Norwegian Atlantic Front Current (NwAFC) and the Norwegian Atlantic Slope Current (NwASC) are indicated together with the Lofoten Basin (LB), Barents Sea Opening (BSO), Fram Strait, parts of the Greenland-Scotland ridge, the Faroe-Shetland channel (FSC) and the Svinøy hydrographic section. The darker shaded region is the area enclosed by the mean location of the 35 surface salinity isohaline between 63.5 and 72.5°N. This area represents the Atlantic Water area in the current study. Grey contours are bathymetry (Becker et al., 2009).

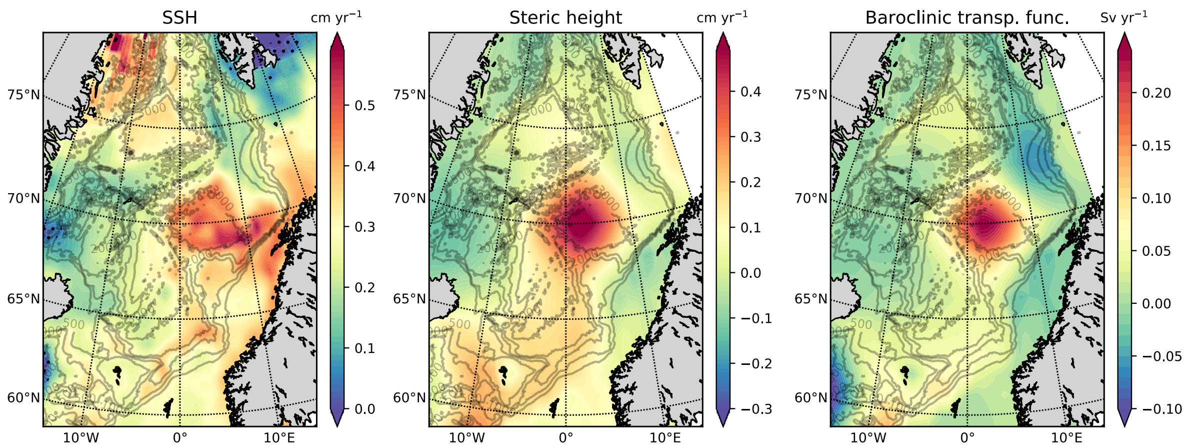

Figure 2. Left panel: Linear trend in SSH [cm yr^{-1}] over the full altimetry period 1993-2017. Middle panel: Linear trend in steric height [cm yr^{-1}] (see Eq. (1)) from 1993-2016. Right panel: Linear trend in ~~potential energy~~ baroclinic transport function [Sv yr^{-1}, Sv (Sverdrup): 10^6 m^3 s^{-1}] (see Eq. (2)) from 1993-2016. ~~Gray~~ Grey contours are bathymetry (Becker et al., 2009).

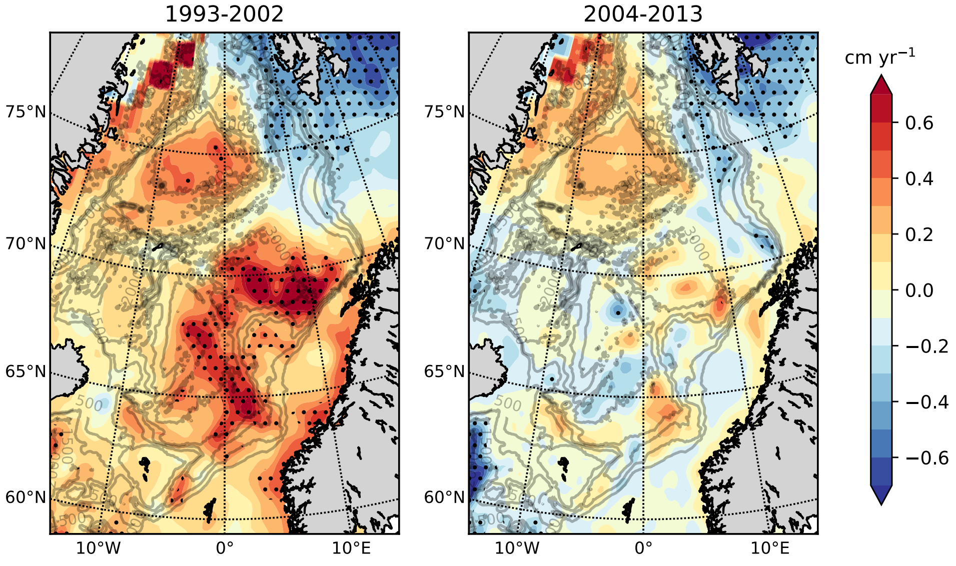

Figure 3. Linear trend in SSH [cm yr^{-1}] for (left) 1993-2002 and (right) 2004-2013. A global trend for the full altimetry period 1993-2017 has been removed from the data. Dotted areas are significant at a 95% confidence level, determined using the two-sided hypothesis Wald test with t-distribution (Oliphant, 2007). Gray Grey contours are bathymetry (Becker et al., 2009).

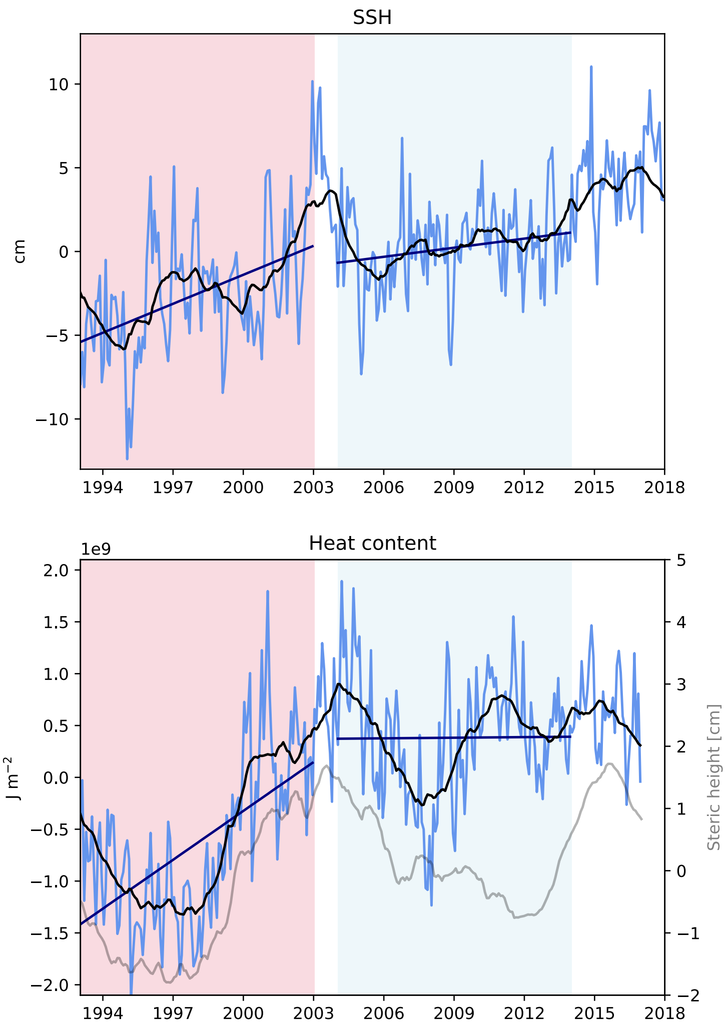

Figure 4. Upper panel: Monthly (light blue) and 24 month lowpass filtered (black) SSH [mcm] from 1993-2017 averaged over the AW area (see fig 1). The SSH has been deseasonalized. In dark blue are the linear trends of the SSH for the two periods 1993-2002 and 2004-2013. Lower panel: Monthly (light blue) and 24 month lowpass filtered (black) heat content in the upper 657 m of the AW area [J m^{-2}] from 1993-2016. The heat content has been deseasonalized. In dark blue are the linear trends for the two periods 1993-2002 and 2004-2013. In grey is the deseasonalized, 24 month lowpass filtered steric height [cm].

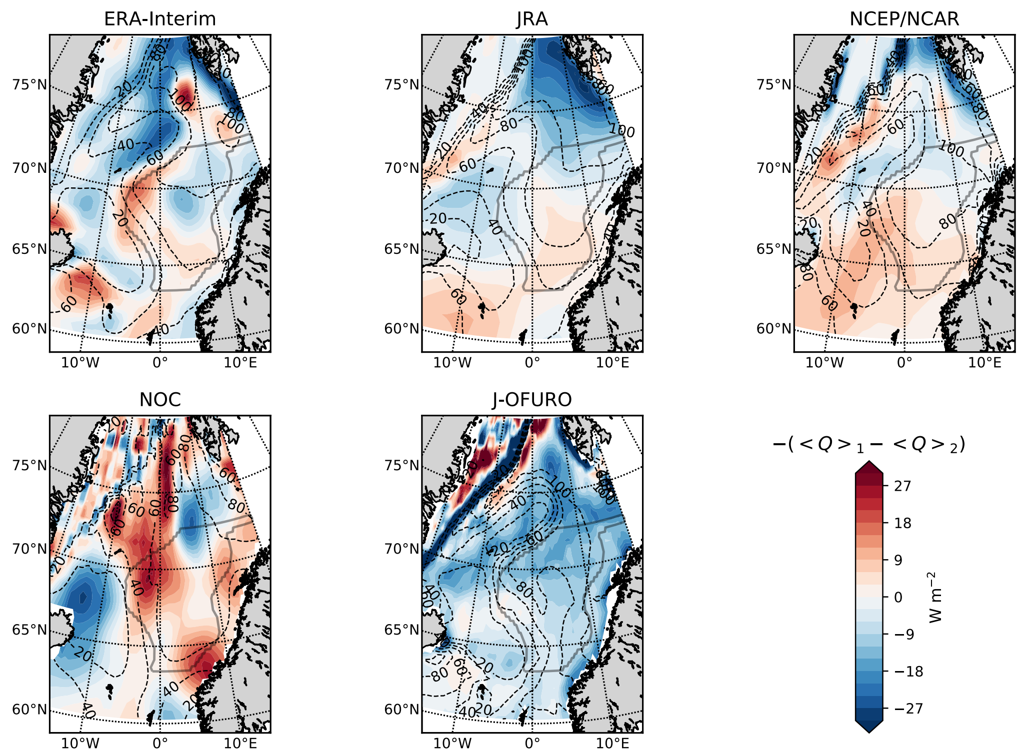

Figure 5. Net surface heat flux Q [W m^{-2}], defined positive upwards, for five different products (ERA-Interim, JRA-55, NCEP/NCAR, NOC Surface Flux Dataset, J-OFURO). Shading represents the difference between the periods 1993-2002 and 2004-2013, i.e. $-(<Q>_1 - <Q>_2)$, overlaid by the climatological mean net surface heat flux 1993-2013 (dashed contours). The solid ~~gray~~ grey line depicts the AW domain, cf. Fig. 1.

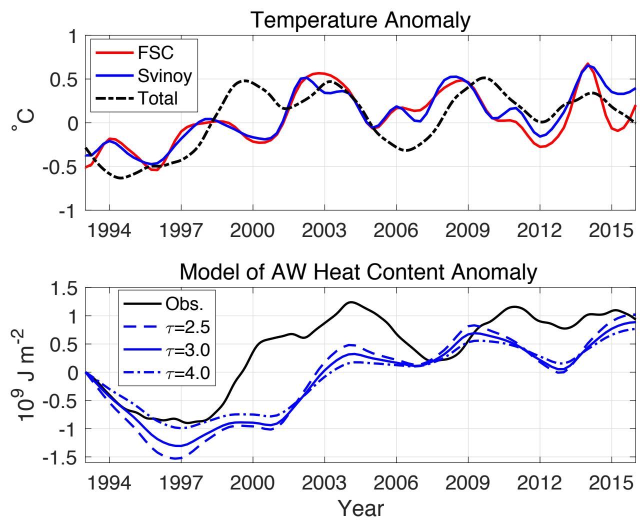

Figure 6. a) Upper panel: Sea surface EN4 temperature anomaly (°C) in the Faroe–Shetland Channel (FSC, red) and in the Svinøy Section (Svinoy, blue), used as proxies for the inflow temperature anomaly $T_i'(t)$. bThe dashed black line shows the total model forcing temperature needed to reproduce the observed AW heat content anomaly (black line in lower panel). Lower panel: Modelled AW heat content anomaly (blue), which is obtained by integrating Eq. (14) forward in time, using the Svinøy Section temperatures and the e-folding timescales (τ) equal to 2.5, 3.0, and 4.0 years. The black line shows the heat content AW anomaly estimated from the EN4 data; same data shown in Fig. 4 but here low passed with a 24 month running mean.

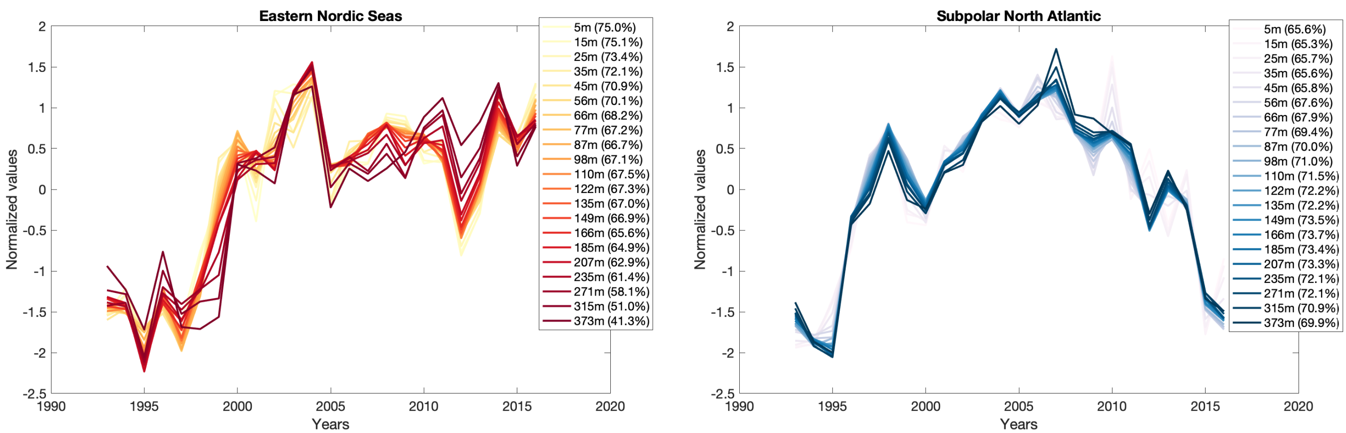

Figure 7. The Leading mode of variability of the deseasonalized (no trend removed) and annually-averaged temperature anomalies down to 400 m in the Eastern Nordic Seas (10°W-15°E,62-72°N, left panel) and the Subpolar North Atlantic (45-5°W, 55-65°N, right panel) for the 1993-2016 period using EN4. The explained variance of every depth can be seen in parentheses in the figure legend.

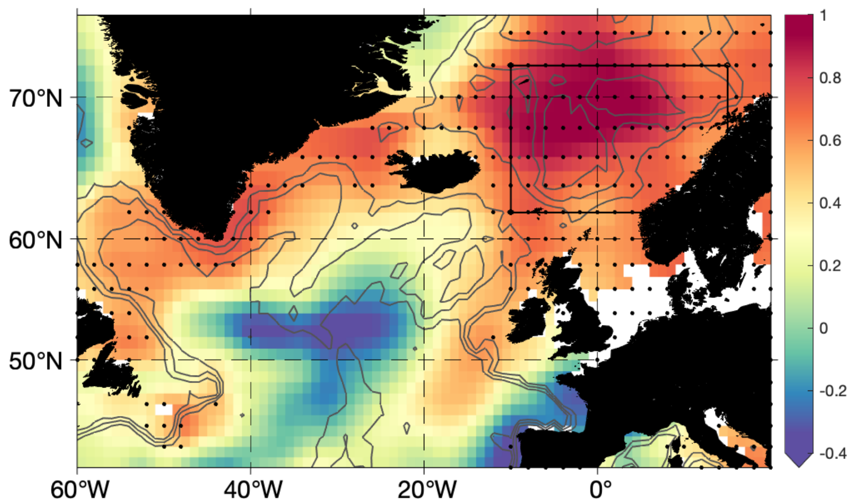

Figure 8. Correlation analysis between the ~~Leading~~ leading mode of ~~variability of the deseasonalized (no trend removed) and annually-averaged~~ temperature ~~anomalies~~ variability at 100 m in the eastern Nordic Seas (~~cf. left panel of~~ see black box and Fig. 7, left panel) against temperature anomalies at every grid point ~~of that in~~ at the ~~North Atlantic using EN4~~same depth. The ~~black box encloses~~ data (not detrended) has been deseasonalized and annually-averaged before the ~~area for the eastern Nordic Seas used here~~analysis. ~~Circles~~ Black dots indicate significance at the 95% confidence level according to a random phase test (Ebisuzaki, 1997). ~~Gray~~ Grey contours ~~are bathymetry~~depict the 1000, 2000 and 3000 m depth contours.

Table 1. Net surface heat flux Q [W m^{-2}], defined positive upwards, averaged over the AW area (defined in Fig. 1) for the first period 1993-2002 ($<>_1$) and the second period 2004-2013 ($<>_2$). The AW area loses heat to the atmosphere in an annual mean. Five different products of surface heat flux are used: ERA-Interim (reanalysis), JRA-55 (reanalysis), NCEP/NCAR (reanalysis), NOC (in situ observations) and J-OFURO3 (satellite observations). See also Fig. 5.

Product	ERA-Interim	JRA	NCEP/NCAR	NOC	J-OFURO
$< \mathbf{Q} >_\mathbf{1} / \mathbf{A}$	69	83	80	61	81
$< \mathbf{Q} >_\mathbf{2} / \mathbf{A}$	68	82	82	68	74
$-(< \mathbf{Q} >_\mathbf{1} - < \mathbf{Q} >_\mathbf{2})/\mathbf{A}$	-1	-1	2	7	-7