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Interactive comment on "The coherence of the oceanic heat transport through the Nordic seas: oceanic heat budget and interannual variability" *by* Anna V. Vesman et al.

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The authors investigated the heat flux in several sections northward in the Nordic Seas along the pathways of Atlantic Water into the Arctic. This was done using the ARMOR3D dataset that derives from in-situ temperature and salinity data and satellite data. The heat flux variability is discussed in relation to atmospheric forcing that includes different weather regimes and North Atlantic Oscillation. The topic is of high scientific interest and this work could contribute to our understanding of the heat transport toward the Arctic. However, it is not clear what is the new findings in this paper. This should be more highlighted and discussed in the paper. The paper is well struc-

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tured but the discussion should be improved (as mentioned above) and there are also too many errors or unexplained (or not shown) statements in the paper (see my comments below) to be accepted for publication.

Response:

Thank you for your comments and well-deserved critique. We added more thorough discussion to the paper, all shortcomings were addressed and missing information added. More detailed answers are added below.

Detailed comments

[1] Since the ARMOR3D and mooring observation have monthly values and there is strong seasonality in both data sets, there is not unexpected that the correlation between them is relatively high (Line 231-245 and figure 5). To compare the two datasets for interannually variability the seasonal signal should be removed before the correlation analysis.

Response:

It is true that seasonality plays significant role, however, as in this study we are looking both at the seasonal and interannual variability it was important to see how good reanalysis aligns with in-situ data on both time-scales. For study of the interannual variability the seasonal signal was naturally removed. We used two methods. As the first method, we averaged data to annual means (in figure 5 one can find both monthly and yearly values). For U and V components correlation coefficients between ARMOR and the mooring data increase slightly compared to the monthly means, as the month-to-month variability, strong in the mooring data, was smoothed.

Added a sentence:

Line 250: “The monthly mean current velocities, derived from the mooring data, also show a significantly higher variability compared to altimetry based ARMOR3D data. For annual mean U and V components, which are of the main interest for this study, correlations between the data-sets increase (in the presented example, from 0.5 to 0.7 and from 0.6 to 0.7, respectively). Removing long-term trends from the time series results in slight decrease in the correlations for the cross-flow U component (to 0.4), while does not change that for the along-flow V component and for water temperature."

[2] Line 56-58: Several currents are mentioned but the East Iceland Current transports Arctic water and what is the West Icelandic Current? the (North-Icelandic) Irminger Current seems to be more relevant. Also, what is the Norwegian Atlantic Coastal Current? The location of the most central currents should be included in the map (Fig. 1.).

Response:

Authors corrected names of some of the currents. The phrase was changed to:

"The Faroe, East Icelandic and West Icelandic currents merge together (Fig.1) and carry a total of about 8–9 Sv into the Norwegian Current, including both, the NwAFC and the NwASC (Dickson et al., 2008; Rossby et al., 2017)."

Figure 1 was modified

[3] Line 90: What stands ARMOR3D for? There are many abbreviations without explanation (e.g. ARMOR3D, CMEMS, NACLIM, CLIMODE, COARE, . . .).

Response:

Explanations for abbreviations were added to the text: A 3D multi-observations T,S,U,V product of the ocean (ARMOR3D) dataset, Copernicus Marine Environment Monitoring Service (CMEMS), North Atlantic Climate: Predictability of the climate in the North Atlantic/European sector (NACLIM) project, European Centre for Medium-range Weather Forecasts (ECMWF), Coupled Ocean–Atmosphere Response Experiment (COARE), CLIVAR (climate variability and predictability) and mode water Dynamics (CLIMOD), Marine Boundary Layer (MBL), Coupled Boundary Layer Air-Sea Transfer (CBLAST) experiments

[4] Line 119: "Vangengeim suggested. . .". Reference is missing.

Response:

Reference was added to the list: Vangengeim, G.Y. Application of Synoptic Methods to the Study and Characterization of Climate. Izvestia GGO, 2, 3-16, 1933 (in Russian)

[5] Line 130: "Vangengeim – Giers classification. . ." What is this classification?

Response:

A more comprehensive description of the referenced classification was added to the Supplementary materials, in the manuscript the link to Supplementary material. The phrase is added to the main text: "More in depth information about Vangengeim – Giers classification is provided in the Supplimentary materials."

""Vangengeim – Girs" classification is based on the analysis of hybrid-kinematic maps (Huth et al., 2008). The process of building a hybrid-kinematic map includes: registering the centers of cyclones and anticyclones, as well as positions of linear-like depressions and ridges from the daily synoptic pressure charts; drawing the demarcation line between the areas with high concentration of cyclones and depressions, and the areas with a high concentration of anticyclones and ridges. To reproduce kinematics of this process, trajectories of the baric formations are traced.

In 1933, Vangengeim suggested a set of indices characterizing atmospheric circulation. He introduced the concept of an elementary synoptic process (ESP). ESP is an evolution of the atmospheric pressure field during which the geographic distribution of the sign of the pressure anomalies and the direction of the main air transports are preserved within the Atlantic-European sector. All ESP could be further clustered in three main types of atmospheric circulation patterns: the western (W), the eastern (E) and the meridional (C) circulation types.

The description is based on Barashkova et al., 2015.

The particular feature of the western type (W) is the existence in the troposphere of waves with a relatively small amplitude moving fast from the west to the east. The baric features also move eastwards: cyclones – in the polar and mid-latitudes, anticyclones – in the subtropics. The high-pressure belt in the subtropics and the low pressure belt further north are well pronounced. This configuration of the atmospheric pressure results in predominantly zonal atmospheric transport. The meridional air-mass exchange weakens and negative temperature anomalies are observed in the polar regions (radiative cooling), positive – in tropical region (radiative warming).

The meridional type (C) is characterized by large amplitude waves in the troposphere. The northwards transport of the warm air along the western part of the ridges (to the Arctic), and the southwards transport along the eastern side, leads to high temperature contrasts, convergence of the high-altitude winds and dynamically linked growth of the sea-surface pressure. Areas of high temperature contrasts are favourable for formation of fronts and an enhanced cyclonic activity. During the circulation type C, the Icelandic lows is practically nonexistent due to a development of the high-pressure anomaly over the north Atlantic, the so called Atlantic Ridge. Further east, the Siberian Anticyclone strengthens and becomes connected with the Polar Anticyclone.

Similar to type C, the eastern type (E) is characterized by the tropospheric waves of large amplitude. However, the localization of ridges and troughs, as well as the distribution of the temperature anomalies, change to the opposite. Islandic low is now well developed. The Scandinavian Ridge is formed, while the winter Siberian anticyclone weakened and shifted west.

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., KyselÃ¡, J. and Tveito, O.E., Classifications of atmospheric circulation patterns: recent advances and applications. Annals of the New York Academy of Sciences, 1146(1), pp.105-152., 2008

Barashkova N.K., Kuzhevskaya I.V., Polyakov D.V. Classification of forms of atmo-

spheric circulation: textbook. Tomsk: Publishing house of Tomsk University, 2015. (in Russian)"

[6] Line 151: The depth interval and the reference temperature for the heat fluxes are missing.

Response:

The caption for Figure 3 was changed to:

"Figure 3. a - interannual and b - seasonal variability of the heat fluxes in the AW layer (ref T = 0°C) across Jan Mayen section computed for different positions of the western and the eastern boundaries of the study region: blue – the section extends from the Scandinavian coast to the Jan Mayen island, red – the section starts at the Scandinavian shelf break goes west up to the western edge of the NwAFC jet (estimated as the first minimum of the modulus of the current velocity west of the jet), see Figure 2)"

[7] Line 160-162: "...even a small change in the position of the transect can lead to a significant change in the integral flux through the section.... These uncertainties must be taken into account when calculating balances within the studied areas" I cannot see that this has been done or have been discussed.

Response:

As there is almost an infinite amount of variations of the transects positioning, it is impossible to give a precise estimation of the uncertainties connected to this issue. We have performed a number of experiments, some of which are presented in the Figure below (added to the Supplement). The results show that, though sometimes affecting the absolute values of the fluxes, the variations of the transect positions or the parameters practically do not change neither the character of the interannual variability, nor the long-term trends, which are the focus of this study. This means that the results of the correlation drops and the character of the cycles discussed in this study are robust, independent of the variations in the section shapes described above.

Lines 168-176 were changed to “The heat fluxes through the western boundaries of the regions are most challenging to calculate with sufficient precision. The instability of the NwAFC, a relatively large (monthly) period of data averaging, the medium resolution of the available data, and anaccounted ageostrophic component can lead to a significant change in the integral flux through the section even with a relatively small change in the position of the transects. These uncertainties are taken into account when discussing the values of the ocean heat convergence in the subregions, limited by the transects: A (limited by the transects Svinoy and Jan–Mayen transects); B (between Jan-Mayen and Bear Island); C (between the transects Bear Island – Sorkapp); D (the transects Sorkapp and Fram strait). However, the trends and the interannual variability patterns are preserved (Fig. 3). More examples for different positions of the transects and variation of the reference temperature are presented in the Supplementary materials (Figure S1). ”

Figure S1. Examples of integral heat flux in AW layer depending on transects position and choice of reference temperature

[8] Line 188-189: The authors use potential density thresholds for the definition of AW. Table 2 seems to be unnecessary and has several errors: Mork and Blindheim (1999) does not exist, Orvik et al. 2001 only studied the Svinøy section and not the whole Norwegian Sea (the ref. is also missing), Orvik and Niiler (2001) used 30 cm/s currents as AW pathways (not as definition of AW), reference of Furevik et al (2007) is missing, etc.

Response:

Following the reviewer comment we have corrected a few errors in the table: Mork and Blindheim (1999) is changed to Mork and Blindheim (2000), for Mork and Blindheim (2000) and Orvik et al. (2001) information that criteria was given based on Svinoy section was added, Orvik and Niiler (2001) was removed, missing reference of Furevik et al (2007) was added to the reference list. However, we disagree that this table is

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unnecessary. The table gives a first comprehensive information on a variety of the criteria used for studying the same phenomena by different authors. The information is also used for our choice of the lower limit of the AW layer, and justifies the choice of different isopycnals along the Aw pathway north.

[9] Line 205-208: The reason for why dz=100 m was chosen is lacking? "dT is the temperature differences between the lower boundary of AW and surrounding waters" Is the surrounding waters 100 m (=dz) below the boundary of AW?

Response:

dz = 100 m was chosen simply because at the depths of few hundreds of meters the vertical layers in ARMOR3D dataset have spacing of 100 meters.

The phrase is changed to: "dT is the temperature differences between the lower boundary of AW and the first level below the selected AW limit"

[10] Line 209-229: I don't see that this calculation is necessary. Why not just use the constant value from Fer et al. with the reference. The uncertainties of Kz is probably less important than compared to other variables (e.g., dT and dz) or the chose of the reference temperature in eq. 1.

Response:

Kz varies in a wide range depending on the regional water dynamics and the stratification. Fer et al. presents estimations of Kz only for a specific region of the Lofoten basin. This value might not be representative for broader areas. To verify this we also estimated Kz via its well-known dependence on the Richardson number used in a variety of numerical models.

[11] Line 286-288: "The imbalance account to 10-20% . . .that reflect the warming of AW. . .We should take into account uncertainties. . ." I cannot see that the uncertainties are discussed in the paper (e.g., what will be the uncertainties), and if this imbalance reflects the warming, how much will this be (in temperature/heat). This should then be

compared with other works.

Response:

Figure 6. was corrected and uncertainties were added to the plot

Figure 6. Fluxes $\pm$ errors of the means (at the 95% confidence level).

Estimations of imbalances are now presented in the panels, however, as it was stated previously, the values, may vary depending on multiple factors (position of transect, reference temperature, depth of AW layer and etc.). This also forms problems in comparison of the integral fluxes presented with other studies. In particular one cannot compare such estimated with those of the regions with different vertical sections of depth limits. To our knowledge, the similar complete estimate of the balance of the heat fluxes in the suggested boundaries have not been performed. The heat imbalances are presented in the centers of the plots.

[12] Line 300: "...dropping to insignificant levels...". What is the significant level?

Response:

Significance of the correlation coefficients was tested with p-value ($p > 0.05$), which is the 95% significance level. The significant coefficients are now highlighted in the table 2.

[13] Line 301-303: That the correlation drops between Svinøy and Jan Mayen sections might also be due to the AW lies deeper and has longer residence time in the Lofoten Basin (e.g., Nilsen and Falck, 2006; Skagseth and Mork, 2012).

Response:

Thank you for pointing this out. How we see the story, the principle oceanic heat flux across the Jan Mayen section rather results from the direct water advection from the Svinoy by the two branched of the NwAC along the topographic guides (continental slope and the underwater ridge chain), rather than water entering the central basin and then being re-trapped by the current to continue its journey north. The long residence time would rather result in a stronger heat loss from the central parts of the basins due to ocean-atmospheric exchange and the vertical mixing.

Lines 330-335 were changed to:

“The strongest correlation loss is found between Voring and Jan Mayen sections, while another one is between Isfjord and Fram sections. The correlation loss between Voring and Jan Mayen sections along the NwAC can be explained by an exceptionally high ocean eddy dynamics, which are effectively generated west of the Lofoten Islands (Isachsen, 2015) and redistributes the incoming heat over the area of the Lofoten basin, further released to the atmosphere (Dugstad et al., 2019; Raj and Halo, 2016). We may expect somewhat similar reasons for the correlation loss between Isfjord and Fram sections (von Appen et al., 2015, Bashmachnikov et al., 2020).”

[14] Line 306-307: “. . .the cross-correlation analysis suggests the maximum correlations at zero time lag”. Is this done?

Response:

Cross-correlation analysis has been performed, but as it hasn’t provide us with any new information as the maximum positive cross-correlations were always obtained at zero time lag (see Figure S3 below).

Figure S3. Example of the cross-correlation’s results (lag in months) for pairs Svinoy – Jan Mayen sections and Svinoy – Fram sections

[15] Line 381-382: “. . . is mostly shaped by the variations in the current velocity. . .” This should then be shown.

Response:

This sentence was removed

[16] Line 385-387: Could the 10-20% of the incoming heat be due to reduced air-sea

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heat loss? See also my comments on Line 286-288.

Response:

Variations of air-sea heat fluxes are already taken into account, while the eddy transport is not directly addressed in this study. However, other studies (ex.Raj et al., 2020; Bashmachnikov et al, 2020) suggest that eddies may be responsible for this.

[17] Figure 1: the position of NwAFC is wrong.

Response:

Figure 1 was modified to add more information and correct errors

[18] Figure 2: Are the currents from ARMOR3D? At which depth? Is it same as for temperature (50m)?

Response:

Yes, mean currents are computed for the same depth-level (i.e. 50 m). Caption for the figure was changed to: "Figure 2. ...Black arrows indicate the mean currents at 50 m....."

[19] Figure 7. The correlation should also be done with time lags. While the velocity might have no or short time lag the temperature might have 1-2 year time lag (see e.g., Holliday et al., 2008; Skagseth et al., 2008; Chafik et al., 2015) which was also mentioned by the authors.

Response:

Addressed in the response to comment [14]

[20] Figure 9. The figure with wavelet amplitudes seems to be wrong. The amplitude should only be positive. Why is the heat flux integrated to 500 m? Why not use the boundary level of AW defined in the paper?

Response:

The word “amplitudes” was incorrectly chosen when in fact the color-scale represent normalized values of the wavelet coefficients, the caption for the figure was corrected. 500 meters in majority of cases represents AW layer, but it’s true that this part of the caption was misleading, since all computations were done for AW layer. This was corrected too.

Figure 9. Time series (a, b) and wavelet diagrams (c, d) of interannual variations of heat fluxes: on the left – Svinoy section, on the right – Fram section, e – cross-wavelet diagram between the Svinoy and Fram sections.

[21]Table 2. What is the significant level

Response:

Significance of the correlation coefficients was tested with p-value. Caption changed to: “Table 2. Correlation coefficients of heat fluxes with climatic indices (bold italic – significant values, $p > 0.05$)”

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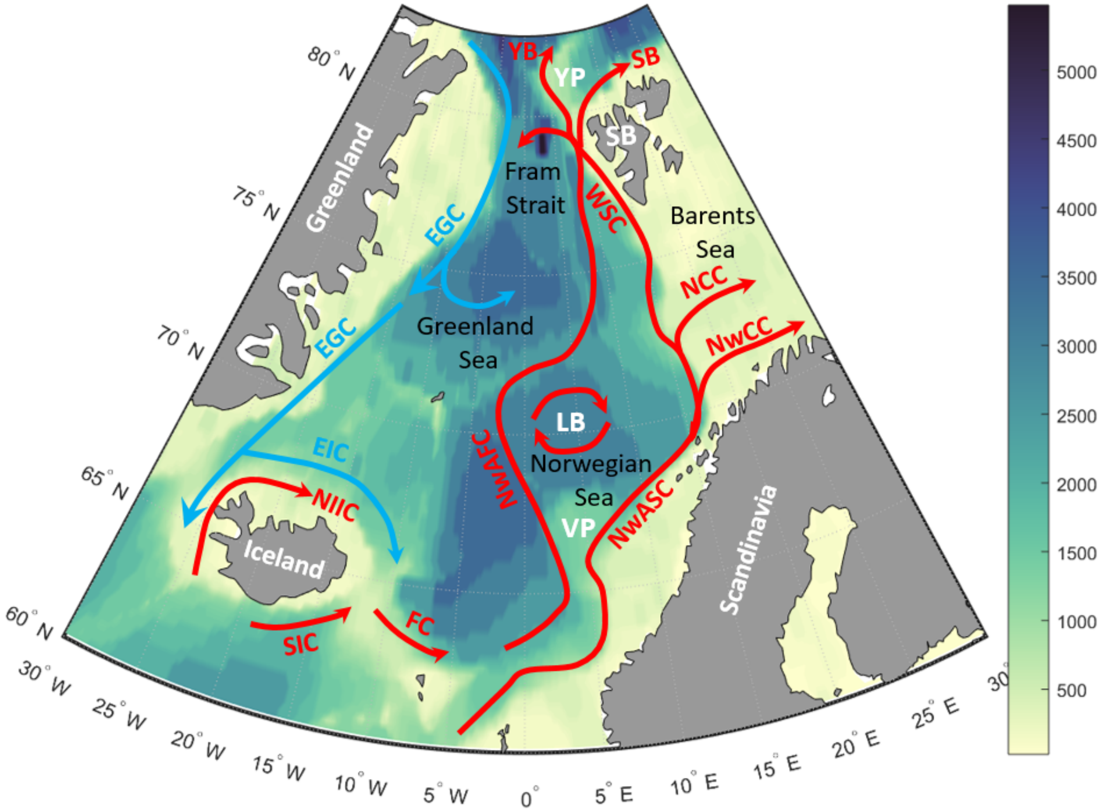

Fig. 1. Figure 1. Schematic map of oceanic circulation in the study region

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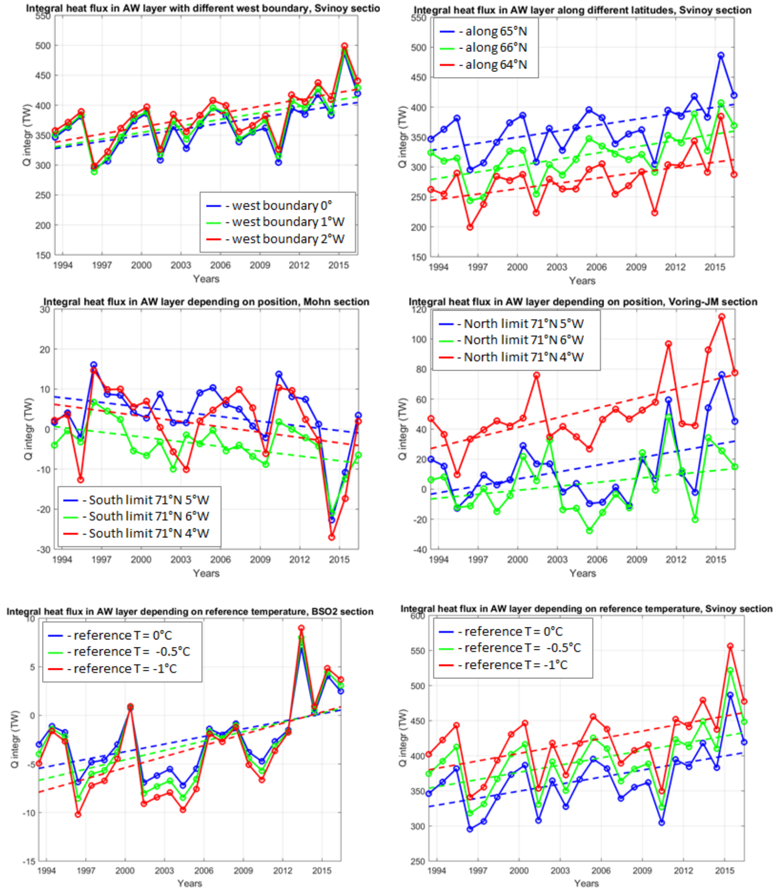

Fig. 2. Examples of integral heat flux in AW layer depending on transects position and choice of reference temperature

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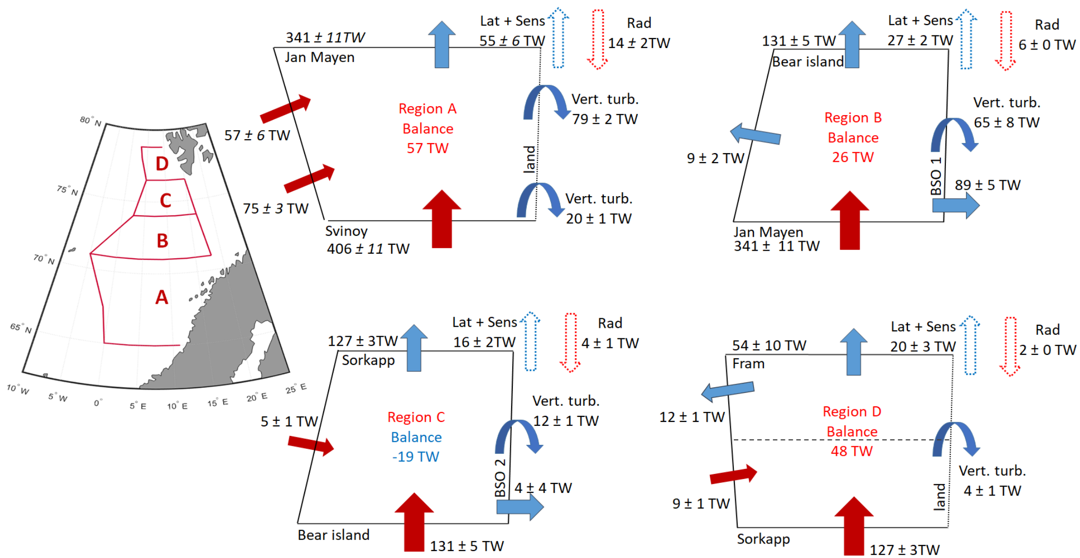

Fig. 3. Figure 6. Fluxes ± errors of the means (at the 95% confidence level).

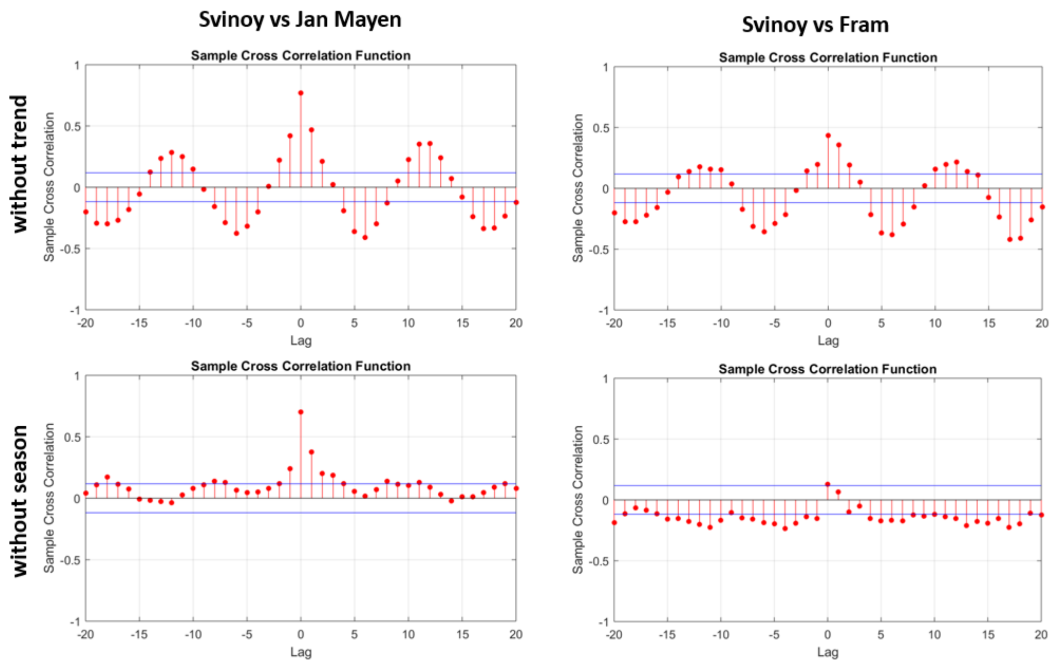

Fig. 4. Figure S3. Example of the cross-correlation's results (lag in months) for pairs Svinoy – Jan Mayen sections and Svinoy – Fram sections

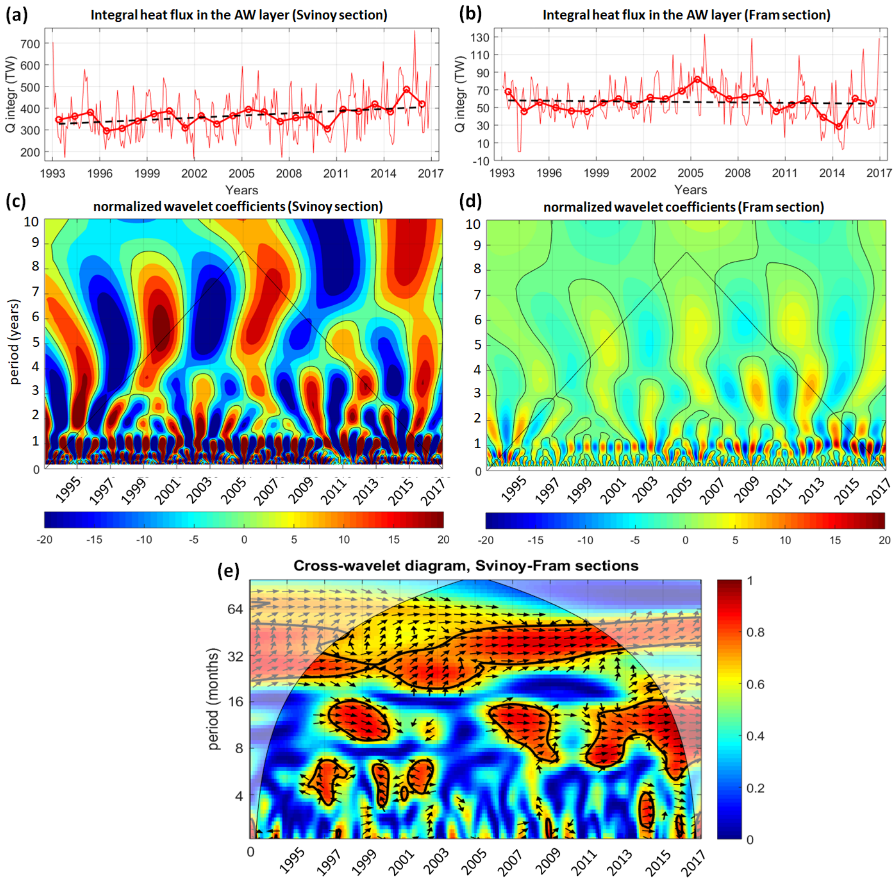

Fig. 5. Figure 9. Time series and wavelet diagrams of interannual variations of heat fluxes