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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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Vesman and co-authors seek to investigate the variability in transport of heat through the Nordic seas towards the Arctic Ocean using a gridded dataset of monthly temperature, salinity and velocity fields derived from in situ and satellite data, and to frame this variability in terms of atmospheric forcing of the ocean. An improved understanding of heat transport in this region would be valuable, given its significance for changing ice cover in the Arctic in the coming years. The paper is clearly structured, and well written. It is, however, difficult to assess the significance of the results presented here in the absence of any discussion of the errors associated with them, which the authors

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acknowledge are likely to be significant. The authors have attempted to provide some explanation of the physical basis behind the correlations in variability in heat fluxes that they see at various locations along the path of Atlantic Water (AW), but unfortunately this is unconvincing because the patterns of atmospheric forcing in terms of weather types that they present are inconsistent with their results. I offer some more detailed comments below, but I suggest that these shortcomings need to be addressed before the manuscript can be considered for publication.

Response:

Thank you for your comments and suggestions, we've rewritten discussion part to provide more information on atmospheric forcing and focused more on explaining the mechanisms behind connection with some weather types. Discussion of errors was also included.

Specific comments:

1. Line 123: I am not familiar with this particular categorisation. Can you provide some background – how it is derived, and why it is an appropriate description of the atmospheric patterns seen over the Nordic seas – for the benefit of readers who are unable to follow the Russian language references?

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 atmospheric circulation: textbook. Tomsk: Publishing house of Tomsk University, 2015. (in Russian)”

2. Figure 2: The maps are small and the detail difficult to make out, but it looks as if you might be losing some of the northward AW flow and periodic southward recirculation at the eastern end of some of your transects, particularly at the southern end of the Barents Sea Opening. The current is strong here, and its position varies a fair amount. (See, for example, Wang et al. 2019.) You mention at Line 160 that your results are sensitive to the position of the transects in relation to the western boundaries of your regions, but do not, so far as I can see, provide any quantification of the uncertainties associated with choice of position.

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). "

On the transects in the shelf: we have also done the computation including the transects on the shelf. However, as the ARMOR currents are based on the sea-surface altimetry, the altimetry is not reliable at a distance less than 50 km to the coast. So we did not use the points which are closer than 50 km to the coast.

3. Line 204: "the base of the upper layer". Is this the AW layer?

Response:

Yes, the base of the upper layer is the base of the AW layer, to make it more clear the line was changed to: ". . .flux through the base of the AW layer is. . ."

4. Line 232: “we compare the statistical properties of all available mooring observations. . ..with those in the nearest grid-point of the ARMOR3D dataset.” Would you see a better correlation if you compared the mooring observations with interpolated values from the ARMOR3D dataset? LaCasce 2005 found low spatial correlations between current meter readings taken from moorings only a few kilometres apart on the Norwegian Slope, and similar lack of correlation might be expected between current meter observations and ARMOR3D grid points over a similar distance. Nevertheless, the spatial resolution of satellite observations underlying the gridded dataset might be insufficient for further interpolation to offer an improvement.

Response:

Majority of moorings are situated very close to the ARMOR grid points. Comparison was done also using ARMOR results interpolated to the mooring positions. The results were practically the same (see figure below). Overall ARMOR currents, based on extrapolation of the altimetry currents down using the thermal wind relation naturally smooth the space-time variability the current velocity.

Fig.2 Comparison of ARMOR data obtained using interpolation and using closest grid point

5. Line 236: “data are binned to 100 m vertical bins”. Why 100 m?

Response:

Moored instruments change their vertical position in time (see Figure below) due to ocean dynamic (currents, storms etc.), as well as during re-deployment of the moorings (which results in a slight change of the mooring positions). Analyzing the positions of the instruments during research period, we concluded that 100 m vertical bin of ARMOR3D data covers practically all possible changes in the instrument positions around the upper, middle and lower water levels, and can be used for comparison with the variability of the moored time series over the whole period of observations.

Fig.3. Changes in the depth of moored instruments with time

6. Line 240: "current velocity...derived from ARMOR3D shows lower. . . ..variability, compared to in situ data". Variability will depend on the scale over which values are averaged. The mooring data are collected at fixed points, so one might expect them to exhibit higher variability.

Response:

That is true (see also our answer to comment 4 above), but still worth mentioning as the whole paragraph is dedicated to comparison of the datasets.

7. Line 259: The NwACC carries fresher water of Baltic origin, not AW. (Skagseth et al. 2008, in your reference list.

Response:

Thank you for correction. The corresponding information is missing in Skagseth et al. 2008, but we found it in Gascard and Mork (2008) in the same book. This is added to the reference list sentence was changed to:

"The heat advection across the section is split between three main cores of the warm waters: the coastal branch at 10° E (NwACC) that carries a fresher water of the Baltic origin, further affected by the freshwater runoff off the Norwegian coast (Gascard and Mork, 2008), the slope branch between 5 and 6° E (NwASC) and the polar frontal branch between 2 and 3° E (NwAFC)."

8. Lines 261/2: Are these long term mean heat fluxes?

Response:

Yes, these are long term means. Specification added:

Line 279: "Our analysis shows that the largest mean (over the study period) heat flux is directed northward along with the NwASC."

9. Figure 6: Balances can only be given to the precision of the least precise of the inputs, not to 0.1 of a terawatt. But more seriously, what are the error estimates for these calculations?

Response:

Figure was corrected and uncertainties are added to the plot

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

10. Figure 8. Are these mean sea level pressure fields, as the caption says, or anomalies? (The values on the colour bar are too small to be legible.) If you wish to relate variability in ocean transports to variability in atmospheric forcing, do you not wish to look at the anomalies from long term mean?

Response:

We agree with the reviewer that the anomalies may often be more clear. We replaced the pressure patterns with anomalies of the wind stress curl, averaged over the corresponding wind patterns of each of the weather types. However, we think that anomalies of the wind vector will not provide the necessary information, as they often do not reflect the direction of the real wind, important for the discussion.

Figure 8. Anomalies of the wind stress curl (red – increase of the sea level, blue – decrease of the sea level in meters), dominant wind patterns (vectors) over the North Atlantic associated with circulation types: a - W, b - C and c – E, dashed lines – bathimentry, red arrows – AW pass

11. Lines 331-3: This doesn't seem quite right. The colour shading in Figure 8a. obscures the wind vectors, but they appear to point slightly northwards along the coast at Svinøy, but offshore at Spitsbergen. So we might expect to see some build up of sea level against the coast and consequent enhancement of the shelf current at Svinøy, but no similar Ekman effect at the more northerly transects.

Response:

The reviewer discusses here only one effect of the wind – a sea-level change due to the Ekman convergence/divergence near the cost. However, there is also another effect: Ekman convergence below the anticyclonic wind stress curl and divergence below the cyclonic one. This is particularly important for the NwAFC, but also should be considered for the NwASC, as the shelf break is often relatively far from the coast. We added the following text discussing these results in detail:

Lines 363-391:

"Along with the sea-level drop/increase near the coast, which depends on the direction and intensity of the along-coast wind component, we consider convergence/divergence of the Ekman flux in the open ocean (Ekman pumping), which is proportional to the wind stress curl. In the first case, the sea-surface vertical velocity can be estimated as w= τ/fL, while in the second case Ekman related at the sea-surface w= - 1/f rot(τ), where τ is the wind stress curl, τ is the wind stress curl component along the coast, is the mean water density, f is the Coriolis parameter and L is the distance from the coast. We are interested in the anomalies of the vertical velocity relative to the climatic mean wind fields associated with weather types W, C, E (Fig. 8). Accelearion/deceleration of the currents are formed by changes in the sea-level gradients across the axis of the branches of the Norwegian Current, forced by the wind fields characteristic for a particular weather type. In Figure 8, changes in the sea-level for each of the weather types relative the climatic mean state are presented as the vertical velocity anomalies, the gradients of which are of the main interest below.

Along the Norwegian coast, the acceleration of the along-shore branch of the Norwegian Current due to the sea-level build-up (forced by the southwesterly winds) is expected for weather types E (Fig.8c) and W (Fig.8a), but not for type C (Fig.8b). For type W, the anticyclonic wind-stress curl also results in an anomaly of the Ekman pumping convergence along the Norwegian shelf and over the Voring plateau. The same is

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observed along the continental slope west of the Barents Sea Opening. This further increases the sea-level build-up east of the NwASC all the way to 75°N, maintaining a higher current velocity and a stronger heat advection. The opposite tendency is observed for types E and C, diminishing the effect of the near coast sea-level build-up for type E, or enhancing the negative near-coast sea-level anomalies for type C. Further north of the Norwegian shelf, type C favours a stronger warm AW outflow into the Barents Sea, while the opposite situation is observed for type W (and E).

West of Spitsbergen, for type W, the clear positive effect of the wind-stress curl on the NwAFC and the WSC transport is observed at 79°N, while further south an acceleration of the NwASC may be compensated by a deceleration of the WSC. For weather type E, an acceleration along the southern part of the island is accompanied by a deceleration further north. For weather type C a clear deceleration of both, the WSC and the NwASC is governed by a northeastwards sea-level drop (i.e. a northeastwards increase of the negative vertical velocity forced by Ekman pumping).

In summary, the analysis above suggests that the Ekman pumping forced by the wind stress curl, together with a near-coast sea-level build-up (mostly along the Norwegian coast), should increase the northward current velocity practically along all its path through the Nordic seas for weather type W and decrease – for weather type C. For weather type E the current accelerations and the decelerations alternate along the current axis. With gentle winds and a relatively small variation of the Ekman pumping anomalies over the Nordic Seas, we do not expect a pronounced consistent increase or decrease of the current velocity along the northward pathways of the AW."

12. Lines 334-7: It is a convergence or divergence of Ekman transport in association with the coast that generates the sea level gradients which lead to the variability in the geostrophic slope current. Ekman transport in a southerly (along slope) direction cannot, therefore, decrease the NwASC, because it does not involve convergence or divergence of transport. It should have no effect.

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Response:

Please see our responses to comments 10 and 11. Ekman pumping at the coast does not tell the full story of the Ekman convergence/divergence patterns.

13. Line 337: The along slope winds shown for Type E in Figure 8b. do not appear to be significantly weaker than those for Type W in the same region.

Response:

Please see our responses to comments 10 and 11. Ekman pumping at the coast does not tell the full story of the Ekman convergence/divergence patterns.

14. Line 352: "since 2005 it [the heat advection] started to decrease". Figure 9b. appears to show a recovery of heat flux in the final two years. Do we not just we decadal-scale variability here, rather than any trend?

Response:

Yes, we probably observe some decadal-scale variability. Any trend in a time-limited data might be a part of a variation with a period longer then the study period. During the time interval of our study, the recovery of the last couple of years doesn't change the long-term positive trend. The sentence was changed to: Lines 404-408:

"However, the heat advection across the Fram section increases only in the beginning of the 2000s. Since 2005 it startes decreasing, with some recovery in 2016-2017. Overall, no significant long-term trend is noted during the study period. Thus, despite the general increase in the water temperature in the south of the region, the northern sections do not demonstrate a positive trend in the heat fluxes during the latest decades. This is one of the factors reducing the correlations."

15. Line 358: How sensitive are these results to choice of transect? Would they show similar periodicity and coherence if you chose the Vøring and Isfjord transects, for example?

Response:

Overall results from all transects show the same dominating period, while the amplitudes of the cycles show a gradual reduction in amplitudes. In this sense, results from Svinoy and Fram sections are sufficiently representative for the transects in-between. Wavelet diagrams from all sections along latitudes are presented in the FigureS4, added to the Supplementary material

Figure S4. Wavelet diagrams of interannual variations of heat fluxes

Technical corrections

All figures: small text is difficult to read. Can you make the labelling clearer? Colours are also difficult to distinguish in Figure 7.

Response:

We tried to make figures more clear, colors were slightly adjusted

Line 141: "the currents are strongly bottom trapped". Do you mean "topographically steered"?

Response:

Corrected (Line 296)

Line 268: "stronger northerly winds". This English expression is commonly understood to refer to winds blowing from the north, whereas I think you are talking about winds blowing from south to north. I suggest "northward-blowing winds".

Response:

Changed to "northward-blowing winds "

Line 272: Delete the comma after "heat flux". It changes the meaning of the phrase.

Response:

Changed to “On average over the study period (1993–2017), the major heat flux of 406 TW enters the Norwegian Sea across the Svinoy section.”

Line 320: “into the Barents Sea”?

Response:

Changed to “into the Barents Sea” Line 351

Line 326: “the correlations go to zero”. Go to zero, or just become small?

Response:

Changed to: “go to insignificant values close to 0” Line 346

Interactive comment on Ocean Sci. Discuss., https://doi.org/10.5194/os-2020-109, 2020.

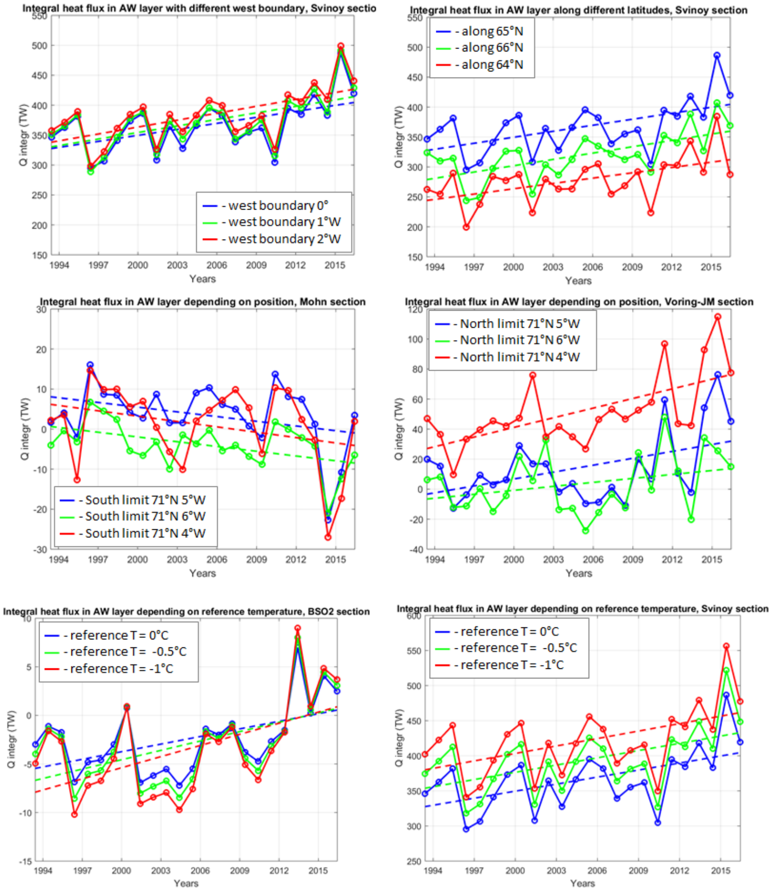

Fig. 1. Figure S1. Examples of integral heat flux in AW layer depending on transects position and choice of reference temperature

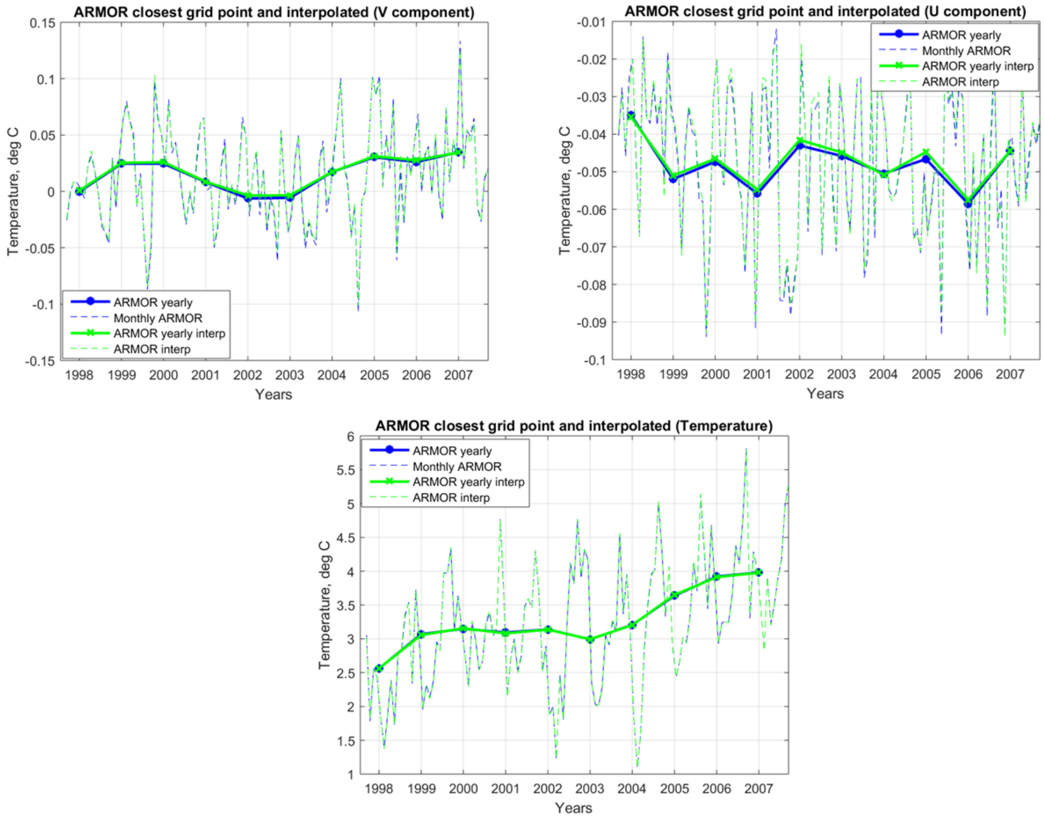

Fig. 2. Comparison of ARMOR data obtained using interpolation and using closest grid point

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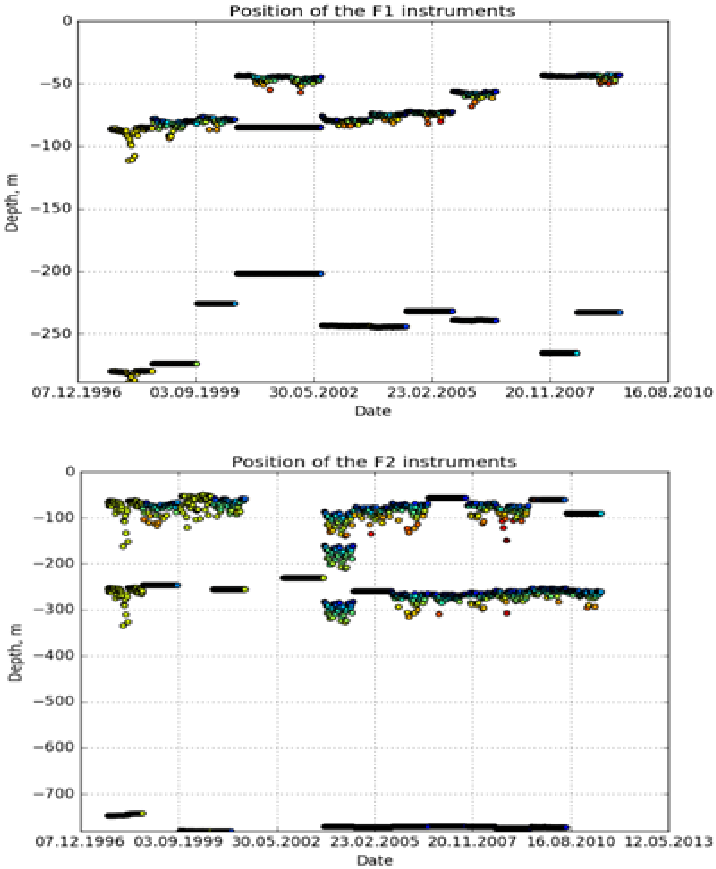

Fig. 3. Changes in the depth of moored instruments with time

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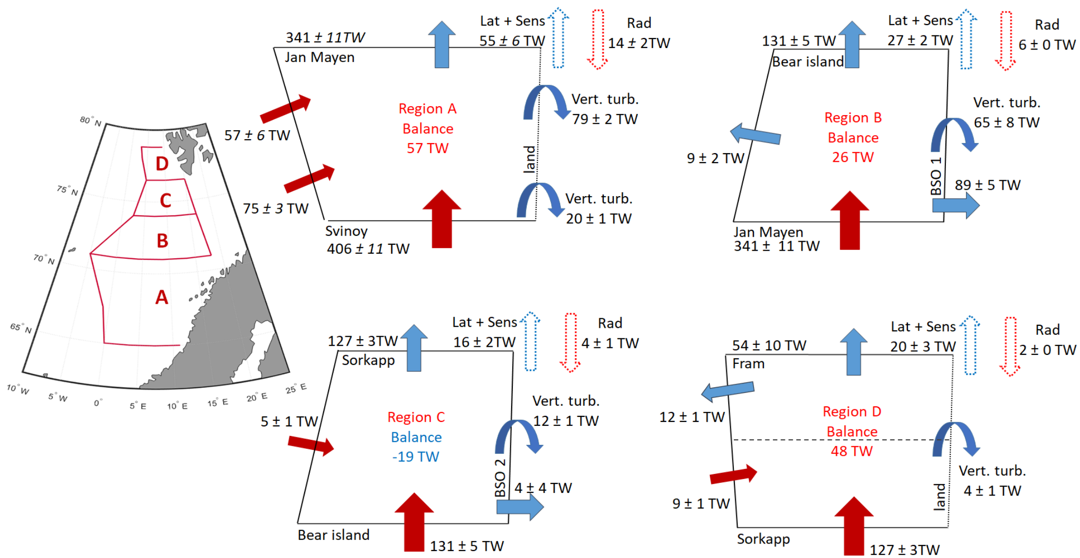

Fig. 4. Figure 6. Fluxes ± errors of the means (at the 95% confidence level).

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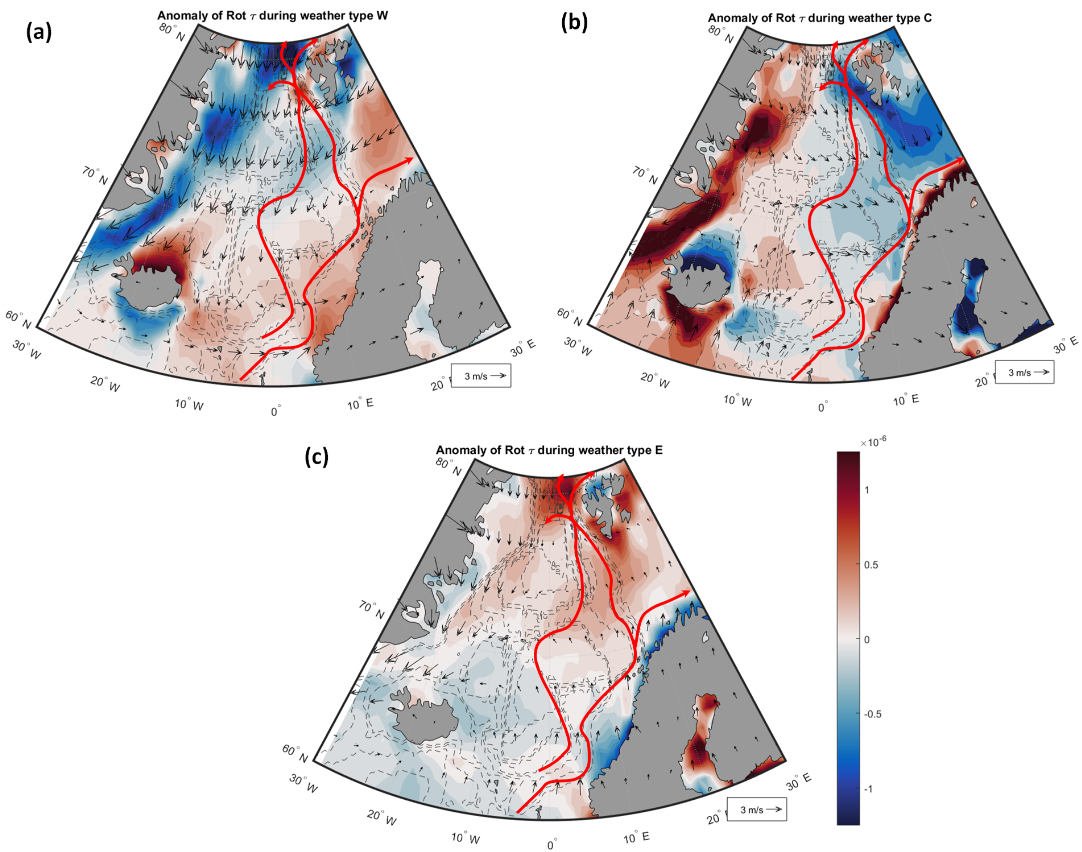

Fig. 5. Figure 8. Anomalies of the wind stress curl

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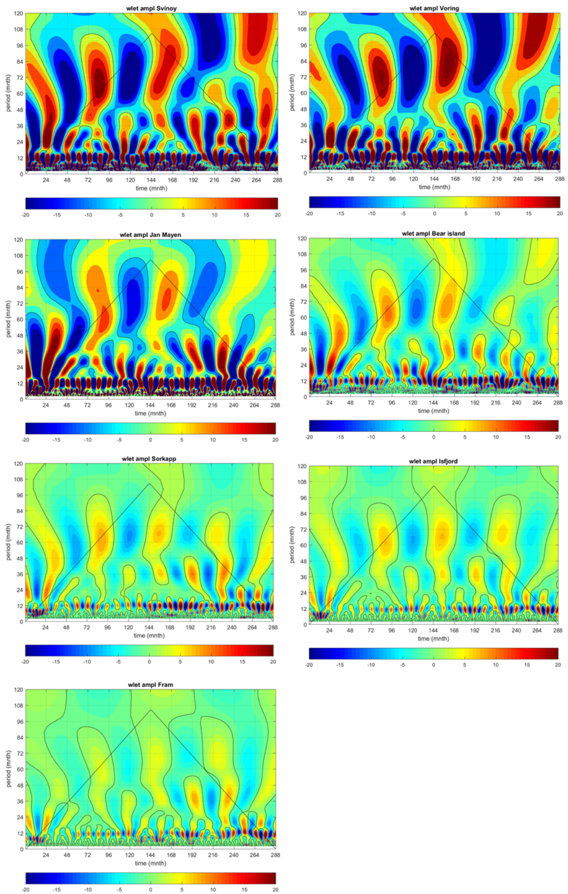

Fig. 6. Figure S4. Wavelet diagrams of interannual variations of heat fluxes

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