Dear Editor Prof. Dr. Lohmann,

Thanks a lot for your time and the effort you put on processing and reviewing our paper. We write this letter to inform you the submission of revised version of our paper based on the remarks from two anonymous reviewers.

Besides, regarding your question about “it is very hard to include all NEMO components derived from ORAS4 to close the budget”, we mean that some extra term enthalpy (e.g. heat transport related to eddy induced velocity) cannot be included as those fields are not saved.

Again, we would like to thank you for reviewing our work and finding helpful reviewers. We look forward to hearing from you about the progress of the following review procedure. We are sincerely gratitude to everything you made to improve this paper.

With best regards

Yang Liu, Jisk Attema, Ben Moat, and Wilco Hazeleger

Dear anonymous reviewer #1,

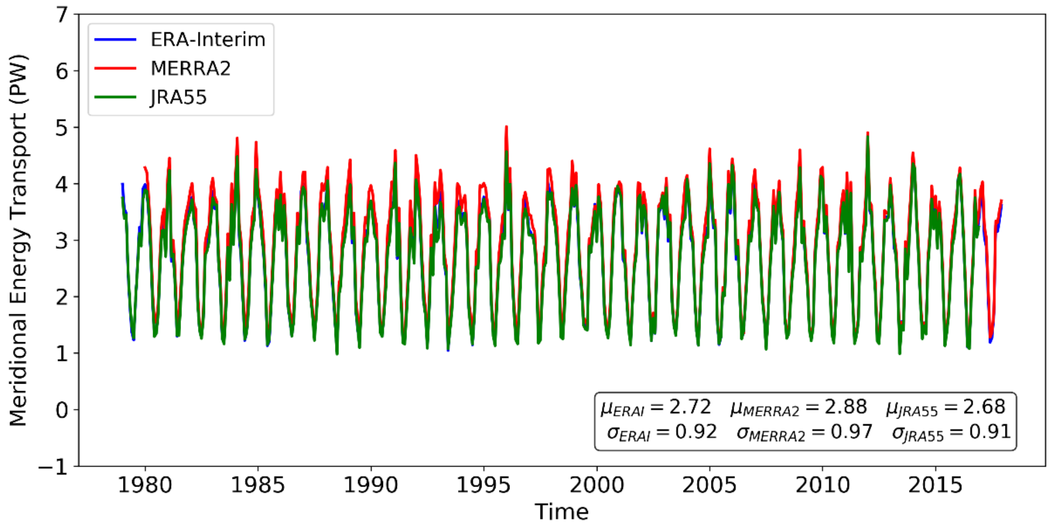
We are very glad to receive so many constructive comments and we would like to thank the reviewer for his help. We are able to address all points and will do our best to improve the quality of our paper accordingly. Below is our response to the reviewer's comments point by point:

(the *original comments* are given by *Italic gray text*, and each follows our response in plain text.)

Response to the major comments

1) Figure 3a indicates that the annual cycle of AMET from ERA-Interim and JRA55 is very different, with yearly minima in JRA55 going down to ~0.8PW,while annual minima in ERA-Interim remain closer to 1.5PW, which implies a huge relative discrepancy (>50%) in the amplitude of the annual cycle of AMET from the two products. From our own computations using basically identical scripts for both products I can tell that their annual cycle of AMET actually agrees very well (within <10%). Also, low-pass-filtered variability of AMET looks quite different from our results compared to the authors' figure 3b. Thus, I presume there is something wrong in the authors' computation of AMET (at least for ERA-Interim and JRA55, I cannot judge the results from MERRA2), possibly in the mass adjustment that they apply. I recommend to thoroughly check the chain of computations. NCAR provides a quite detailed step-by-step instruction how to perform these computations: http://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html

After thoroughly checking our script and the whole computation procedure, we find that the discrepancy between AMET from ERA-Interim and JRA55 comes from the numerical scheme used in performing the mass correction. The barotropic mass correction method involves calculations of the divergence, the inverse Laplacian and a gradient (Trenberth, 1991). We used a finite difference (central scheme) method to compute these terms. However, after some tests we noticed that it is more accurate to bring the fields to the spectral domain and compute these terms via spherical harmonics. The adjustments to the barotropic wind as results of mass budget correction based on these two numerical methods differ much in the polar regions, in particular the amplitude. Since AMETs are very sensitive to the mass budget, the results with these two different numerical schemes can lead to very different results. After recomputing the AMET fluxes from ERA-Interim, MERRA2 and JRA55 with mass correction using spherical harmonics, now the difference between annual cycles of AMET from ERA-Interim and JRA55 is very small. The results are shown in the figure below. They are consistent with the reviewer's results. In our revised paper we will use the new numerical method for the diagnostics and update the results, figures and discussion.



The low frequency series of AMET from ERA-Interim, MERRA2 and JRA55 also changed due to the implementation of mass correction via computation with spherical harmonics. But as they are still very different, the major results in our paper remains the same. Changes are made to the regressions of different variables with AMET mainly.

Trenberth, K. E. (1991). Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. Journal of Climate, 4(7), 707-722.

2) The authors note that there exist improved diagnostic equations for energy budget diagnostics (Mayer et al. 2017; Trenberth and Fasullo 2018), but do not use those. I strongly recommend to make use of these updated equations. There is no reason not to do so.

Thanks for pointing out this. At the time the initial work for this manuscript was done these improved methods were not published yet. Now, together with the implementation of mass correction via spherical harmonics, we recomputed the AMET using the improved diagnostic equations for energy budget diagnostics (Equation 24 in Mayer et. al., 2017).

Mayer, M., Haimberger, L., Edwards, J. M., & Hyder, P. (2017). Toward consistent diagnostics of the coupled atmosphere and ocean energy budgets. Journal of Climate, 30(22), 9225-9246.

3) Ocean energy budget (section 2.3.2) and discussion about reference temperature: The authors discuss the need for a reference temperature as long as the mass budget is not closed. This is indeed important and this issue has been extensively discussed in the oceanographic literature, most notably Schauer and Beszczynska-Möller (2009). However, the present study only considers oceanic transports in a zonally integrated sense. Full zonal cross-sections should have a net mass flux close to zero, making the use of a reference temperature unnecessary. The same applies for the statement about recirculation (p8 l13). In fact, for zonal integrals, there only is a small imbalance coming from P-E, leaving a small ambiguity, which in the same manner applies to the atmosphere. For that reason, the same reference temperature should be used for both atmosphere and ocean to obtain consistent results (Mayer et al. 2017). The discussion on these issues must be clarified.

We agree with the reviewer that the reference temperature is not needed when the mass is perfectly balanced. In oceanographic literature it is common to use a reference temperature when calculating OMET in both observations and model diagnostics (e.g. Bryan, 1962; Hall and Bryden, 1982; Johns et. al., 2011; van der Linden et. al. 2019). As we cannot perform barotropic correction for the ocean, we take reference temperature as a compromise. In the ocean, with its strong boundary circulations even the smallest imbalance can lead to large errors in the heat flux. Besides, it is very hard to include all NEMO components derived from ORAS4 to close the budget. Thus, we think it is still safe to take a reference temperature. However, we agree with the reviewer that when taking the zonal integral the benefit from a reference temperature is not as large as when considering a single strait transports (Schauer and Beszczynska-Möller, 2009). To make the formulation much clear, we will modify our explanation about the usage of the reference temperature as well as the statement about recirculation. We will add Schauer and Beszczynska-Möller (2009) to our reference list and discuss the mass imbalance coming from P-E (Mayer et. al., 2017).

Bryan, K. (1962). Measurements of meridional heat transport by ocean currents. Journal of Geophysical Research, 67(9), 3403-3414.

Hall, M.M. and H. L. Bryden (1982) Direct estimates and mechanisms of ocean heat transport, Deep-Sea Research, Vol. 29, No. 3A, pp. 339 to 359

Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S. A., Kanzow, T., Bryden, H. L., ... & Curry, R. (2011). Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5 N. Journal of Climate, 24(10), 2429-2449.

Schauer, U., & Beszczynska-Möller, A. (2009). Problems with estimation and interpretation of oceanic heat transport–conceptual remarks for the case of Fram Strait in the Arctic Ocean. Ocean Science, 5(4), 487-494.

van der Linden, E. C., Le Bars, D., Bintanja, R., & Hazeleger, W. (2019). Oceanic heat transport into the Arctic under high and low CO2 forcing. Climate Dynamics, 1-18.

Response to minor comments

Generally: the plural of "reanalysis" is "reanalyses", while the plural of "reanalysis dataset" is "reanalysis data sets". Please correct throughout the manuscript.

We will correct these incorrect formulations.

P2L16: Is this result based on models? Please clarify.

Their study uses reanalyses data (Yang et. al., 2010). We will further specify the details of these studies that listed in this paragraph.

Yang, X. Y., Fyfe, J. C., & Flato, G. M. (2010). The role of poleward energy transport in Arctic temperature evolution. Geophysical Research Letters, 37(14).

P2L24: In this context it might be worth mentioning that ocean reanalyses do not show a clear sign of Arctic amplification in Arctic OHC increases (Mayer et al. 2016; von Schuckmann et al. 2018)

Thanks for the comment. We will include this point.

P2L34: Please rewrite the sentence to something like: "These are representations of the historical state of the atmosphere and ocean optimally combining available observations and numerical simulations using data assimilation techniques."

We will rewrite the sentence following your suggestion.

P3L3: Please spell out this acronym (and all others).

The acronym will be spelled out.

P3L7: Please be more specific about the "model". Is this a forced ocean model run?

Yes, this is an ocean model run forced by surface fields from the Drakkar Surface Forcing data set version 5.2.

P3L23: "higher" than what?

This is a bit confusing. Here we mean we choose reanalysis products with relatively high resolution (compared to old reanalyses) as the quantification of energy transport need this. We will change "higher" to "high", just to be accurate.

P3L24: change "preferably" to "preferable"

We will change it.

P3L25: "For an inter-comparison purpose, they better not resemble each other". What is meant here exactly? Please reword.

Thanks for pointing this out. The sentence is indeed very confusing. Here we want to emphasize that we try to include various reanalyses data sets to make the comparison more informative. We will delete this sentence.

P4L7-8: Is there a reference for the statement about divergent winds? It might be worth checking Graversen et al. (2007)

Berrisfold et. al. (2011) discussed the improvement of divergent winds in their work. We will include this reference now.

Berrisford, P., Kållberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A. J., ... & Sato, H. (2011). Atmospheric conservation properties in ERA-Interim. Quarterly Journal of the Royal Meteorological Society, 137(659), 1381-1399.

P4L14: add "scheme" after "assimilation".

We will add it.

P4L22: add "upper air" before "observations"

We will add it.

P4L26: oceans -> ocean's

We will correct it.

P4L30: data with 3D-Var assimilation -> analyses with a 3D-Var FGAT assimilation scheme

We will change it.

P5L9: Not quite right. The forcing is a combination of ERA-Interim fluxes (e.g. shortwave radiation) and bulk formulae using ERA-Interim near-surface parameters. Please correct.

Thanks for the information. We will correct it.

P5L16-17: "To be consistent with the other two reanalyses datasets assessed in this study, the SODA 3.4.1 is chosen since it applies surface forcing from ERA-Interim". This statement seems to be opposite of what you say above in P3L25

We will delete the apparently confusing statement in P3L25.

P5L18: r –> R

We will correct it.

P6L5: What is the "Drakkar forcing data" based on?

Thanks for reminding. The NEMO ORCA run is forced by the Drakkar Surface Forcing data set version 5.2, which supplies surface air temperature, winds, humidity, surface radiative heat fluxes and precipitation, and a formulation that parameterizes the turbulent surface heat fluxes and is provided for the period 1958 to 2012 (Dussin et al., 2014; Brodeau et al., 2010).

Brodeau, L., B. Barnier, A. M. Treguier, T. Penduff, and S. Gulev (2010), An ERA40-based atmospheric forcing for global ocean circulationmodels, Ocean Modell., 31, 88–104, doi:10.1016/j.ocemod.2009.10.005.

Dussin, R., B. Barnier, and L. Brodeau (2014), The making of Drakkar forcing set DFS5, DRAKKAR/MyOcean Rep. 05-10-14, LGGE, Grenoble,France.

P7L21: explain u_c and v_c

These are the correction terms for zonal and meridional wind components as a result of barotropic mass budget correction. We will further explain this based on the explanation given by Trenberth (1991).

Trenberth, K. E. (1991). Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. Journal of Climate, 4(7), 707-722.

P8L10: the equation gives OHC across a certain circle of latitude. Is this meaningful? How would that relate to the transports across that latitude? Did the authors mean OHC integrated across the area north of a given latitude?

The equation here is a bit confusing. We agree with the reviewer that OHC integrated in the polar cap is likely closely related to OMET at 60N (the chosen reanalysis products are all forced by surface fields from ECMWF atmospheric reanalyses.). We will update the equation here and calculate the OHC in the polar cap.

P8L11-12: I can reassure you that ocean reanalyses do have sources and sinks from temperature increments, but they do not suffer from mass inconsistencies as atmospheric reanalyses do. The divergence of ocean currents exactly balances the surface freshwater flux and local sea level variations, so there is no mass adjustment needed. Please see the NEMO documentation for details (Madec 2008).

We update this and put an accurate formulation now. However, it is very hard to include all NEMO components derived from ORAS4 to close the budget. See also van den Berk et. al. (2019) for the freshwater budget.

van den Berk, J., Drijfhout, S. S., & Hazeleger, W. (2019). Atlantic salinity budget in response to Northern and Southern Hemisphere ice sheet discharge. Climate Dynamics, 52(9-10), 5249-5267.

P9L3: Do you mean "decorrelation"?

Yes, this is what we aim to do.

P9L6: Do you mean "by a factor of 3"?

Yes.

P9L8: Why not do this the other way around? Apply filter first, and then estimate effective degrees of freedom.

Statistically, it seems to be more strict to estimate the effective degrees of freedom after applying filter. We will apply the filter first and then estimate effective degrees of freedom.

P9L10: I do not understand the statement about statistical significance

Here we mean that the relatively short records of reanalyses do not have many samples at interannual time scales, compared to outputs from numerical climate models. We will rephrase this to make it more clear.

P9L18: not only solar radiation, but also OLR. In that sense, transports balance NET radiation.

Thanks for the comment. We will correct this.

P9L26: How do you know this?

Now we notice that the latitudinal variation is due to the mass correction based on finite difference scheme. We will correct this.

P9L29: "ERA-Interim res" is not shown in the figure.

This is a mistake. We will correct this now.

P9L21: 1.21PW is probably too high (see major comment #1)

We will update this according to the results with improved methods. Now it is of the same scale as ERA-Interim.

P10L10: Here it is important to know whether you are using monthly or sub-monthly data, which should be stated in the methods section. If you use monthly means, you will miss eddy transports and consequently underestimate ocean heat transports.

With ORAS4 and GLORYS2V3, we use monthly data since only the data at monthly scales are available. For SODA3, we use sub-monthly data (5 day averaged) (which includes the eddy components). We will further explain this now after including your comment.

P10L12: What is plotted in Fig4? The poleward component of OMET? How is this obtained, if OMET is computed on the tripolar NEMO grids?

It is the poleward component of energy transport in the ocean. We regrid from curvilinear grid to lat-lon grid as we only want to emphasize the resolution and its potential influence on our results. But it seems to be a bit confusing, thus we decided to remove it. Thanks for asking.

P10L19: Is "hindcast" the appropriate term? Isn't it a forced model run?

The model is forced by (near) surface fields from historical data only. It is common to call this a hindcast in oceanographic literature (indeed, this differs from atmospheric literature). But we agree that it is also "a forced model run". We have added this description in the method section.

P11L1: correlation or regression?

We check the correlation between the total AMET and each component. So it is "correlation".

P11L5: r=0.07 seems very small (again, see major comment #1)

We will update this according to the new results.

*P11L20: With these diagnostics, you are running into problems with reference temperature, as the point-wise transports obviously do not have a zero mass flux. Figure 7d (showing T_mean*delta_v) will have much larger values when you use K instead of C, leading to a different conclusion. Which one would be correct? I suggest to remove 7c and 7d and discuss a and b in more detail. Instead of 7c and d, it would be interesting to show the difference sections also for JRA55.*

Thanks for the point. We agree that we don't have zero mass flux in this point-wise set-up. We will keep only Figure 7a and 7b.

The reason that we only show this for ERA-Interim and MERRA2 is that these two reanalyses have points at the same location in terms of pressure levels, lat and lon on the close-to-native grids that they are produced with (those grids are slightly interpolated grids compared with native grids, e.g. for ERA-Interim TL255 is roughly equal to 0.75 x 0.75 deg, and MERRA2 natively 0.5 x 0.625 deg). We only choose the points at exactly the same location. However, to include JRA55 (TL319 roughly equal to 0.5625 x 0.5625 deg) a further interpolation is inevitable, which can introduce errors. So we only make such point-wise comparison between MERRA2 and ERA-Interim, as a compromise.

P12L5: Please use a different name than "NEMO", as all your ocean products are based on NEMO.

We will change the name to “OGCM hindcast”.

P12L15ff: Similar to my above comment: I do not understand why you look at bands of OHC and not at OHC north of 60N.

The explanation is given above. But we will switch to the OHC north of 60N.

P13L9: Better use an independent SIC product. SIC from ERA-Interim is of questionable quality, which can be seen e.g. from the “disc” around the North Pole. Also, ORAS4 does not have an active sea ice model. Would you expect a correlation between OMET and SIC then?

We wish to obtain a consistent picture by regressing OMET generated with models forced by ERA-Interim fields on sea ice also from ERA-Interim. Indeed, there is no active sea ice model, but for SIC the temperature criteria are assumed to be reasonable. Of course this is not the case for thickness or volume.

P13L18: no -> not

Corrected.

P13L32: Fig 13: I am not sure what is shown here. Are these instantaneous regressions? The legend says 1-month lag - does this make sense when using 12-monthly smoothed data? At which lag do you get highest correlation?

In this regression OMET leads the sea ice by one month. We observe the highest correlation between OMET and sea ice when OMET leads by one month. But the difference between correlations are very small, as long as OMET is leading.

P14L1: I think one has to be careful with the timescales here. What timescales are the cited studies looking at?

Thanks for the reminding. These studies focus on decadal to inter-decadal scales. We will add the timescales here.

P14L25: How can you see this from the time series?

The low frequency anomalies of OMET (Figure 5b) shows that GLORYS2V3 differs a lot to ORAS4 and SODA3. By saying this we want to emphasize that the differences in OMET are reflected in the regressions on sea ice. But this seems a bit confusing. We will rephrase this.

P14L27: Be cautious: A lot of heat transported across 60N is stored in the North Atlantic or released from there through air-sea fluxes and will never reach sea-ice covered regions.

Thanks for reminding. We will rephrase this part and mention that the relation is “indirect”.

P14L28: “patterns” of what?

“Horse shoe” or “dipole” patterns of the link between OMET and SST over the Atlantic. We will add this to the text.

P14L31: remove “the” before “tropical”

We will correct this.

P15L8: “less consistent” than what?

Sorry for the typo. We mean they are not consistent with each other. We change “less consistent” to “not consistent”.

P15L24-26: Hard to understand. Please rewrite the sentence.

We mean the sink and source in reanalyses cause large uncertainties in the computation of energy transport. We will rephrase this part.

Again, we’d like to express our gratitude to the time that the reviewer spent on it. Thank you very much!

With best regards

Yang Liu, Jisk Attema, Ben Moat, and Wilco Hazeleger

Dear anonymous reviewer #2,

First, we'd like to thank the reviewer for the time and effort on reviewing our paper. We manage to address all the points from the reviewer and try our best to improve the quality of our paper. Below is our response to the reviewer's comments point by point. We will revise the manuscript accordingly.

(the *original comments* are given by *Italic gray text*, and each follows our response in plain text.)

Response to the major points

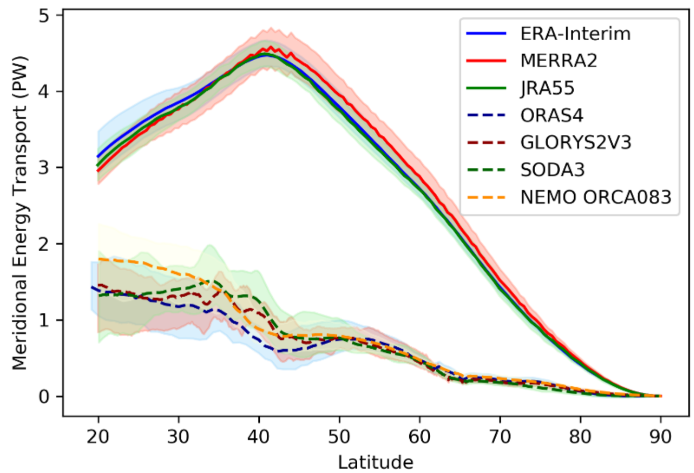
Computation of an energy transport from reanalysis can be difficult due to lack of mass / energy conservation, sampling problems, or numerical schemes different from the original. It seems from figure 2 that MERRA2 and JRA55 suffer from large errors ("noise" on the curves) of the order of O.1-0.2 PW for the long-term mean. Unfortunately, this means these products will be unusable to study the variability of the transport. Indeed, it is evident on Fig. 3 that the interannual variability at 60N is of the same order as this long-term noise.

There are 2 possibilities:

- This problem comes from the reanalysis themselves: the conclusion is then that only ERA-interim is useable. This would be a useful result in itself; but the study of the differences between ERA and the other reanalyses becomes pointless and the paper could instead concentrate more on the impacts on the Arctic.

- This is a problem in the calculations from the reanalysis data, which then has to be solved, and the other results corrected accordingly.

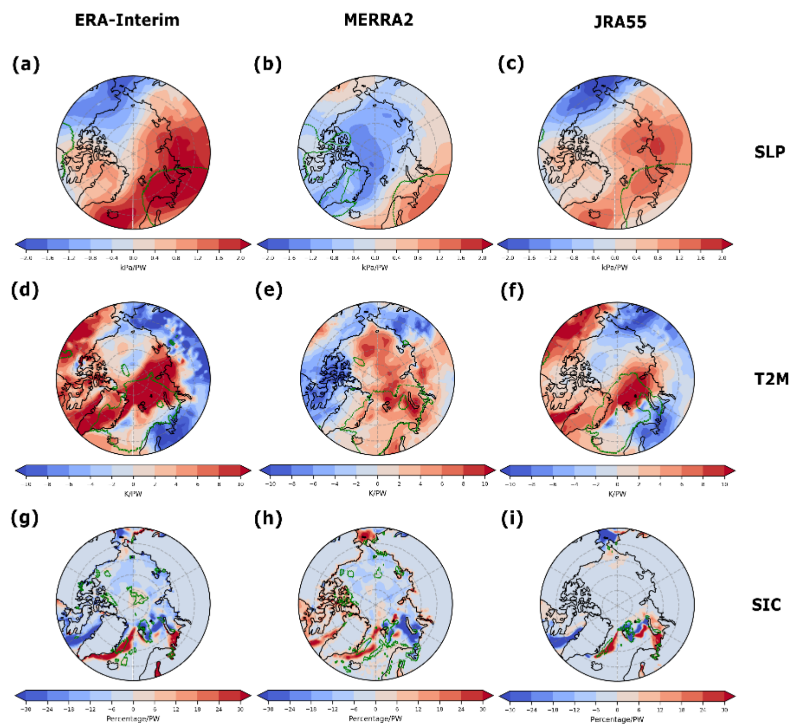
Thanks for the comment. We also have concerns about the noisy annual mean AMET from MERRA2 and JRA55. After thoroughly checking our script and the whole computation procedure, we find that the "noise" in annual mean AMET from MERRA2 and JRA55 in Figure 2 comes from the numerical scheme used in performing the mass correction. The barotropic mass correction method involves calculations of the divergence, the inverse Laplacian and gradients (Trenberth, 1991). We used finite difference (central scheme) method to compute these terms. However, after some tests we noticed that it is more accurate to bring the fields to spectral domain and compute these terms using spherical harmonics. The adjustments to the barotropic wind as results of mass budget correction based on these two numerical methods differ much in the polar regions. Since AMET are very sensitive to the mass budget, the results with these two different numerical schemes can lead to very different results. After recomputing the AMET fluxes from ERA-Interim, MERRA2 and JRA55 with mass correction using spherical harmonics, now the noise in annual mean AMET has been removed. The results are shown in the figure below and will be included in the revised manuscript.



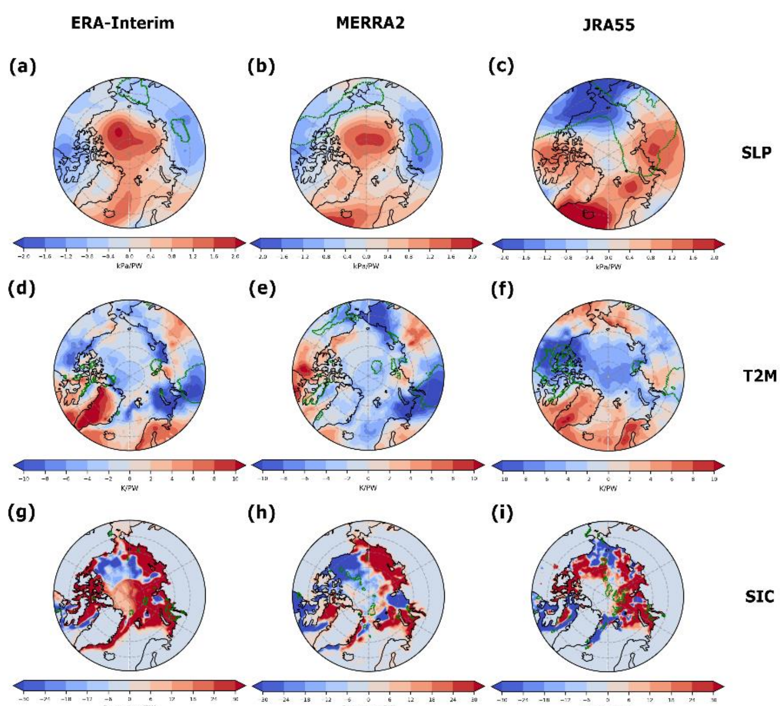
The other results are corrected accordingly. The difference between annual cycles of AMET from ERA-Interim and JRA55 becomes smaller, but the low frequency AMET remains different. Hence the study of the difference between the chosen reanalyses remains informative. As the main point of this paper is to raise a caveat about using low frequency MET from reanalyses, the major results in our paper remains the same. Changes are made to the regressions mainly.

(B) Impacts on the Arctic (section 3.3) The problem of this section is that it gives a few quick examples of regressions of characteristics of the Arctic climate on energy transports, but that they are too short to be really useful. - Show at least the winter and summer seasons, as results could be quite different. - Why show SLP and temperature for AMET, but sea-ice for OMET? Why not show the same variables for both for comparison? (at least sea ice and slp).

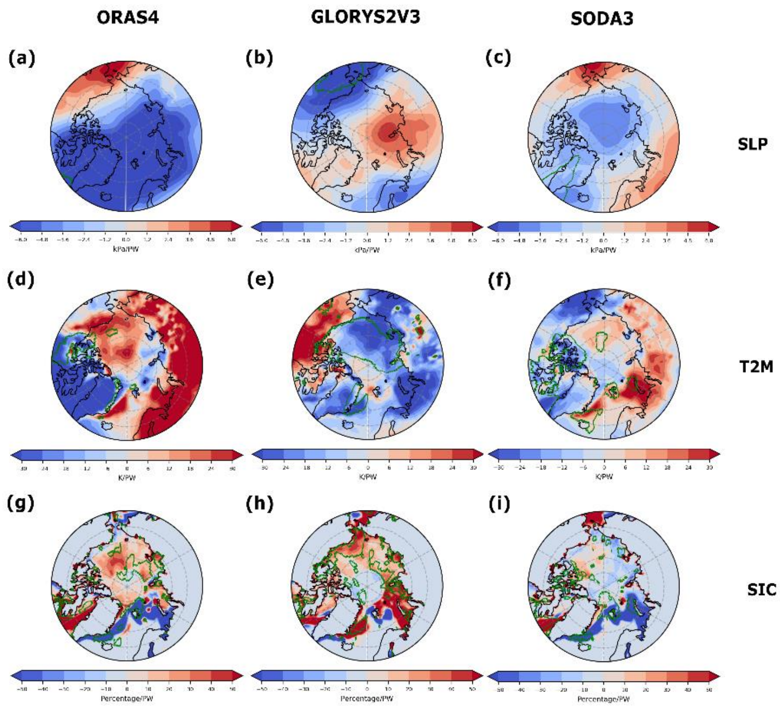
We agree with the reviewer more results are needed to provide more insights about the link between MET and the Arctic and potentially causal relations. Hence, we will include regressions of SLP, SIC for both AMET and OMET in summer and winter and interpret them. In summary they are shown here already and we will further explain these regressions in our revised manuscript:
(the strange-looking colors near the pole for regressions on sea ice in ERA-Interim are due to the quality of sea ice fields in ERA-Interim, see our response to the last small remark.)



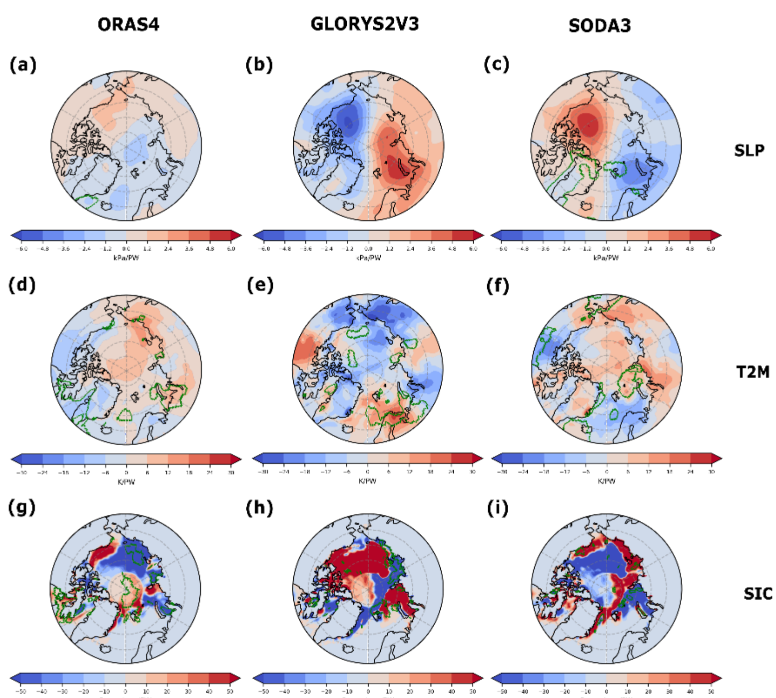
Regression of SLP (a-c), 2 meter temperature (T2M) (d-f) and SIC anomalies on AMET anomalies at 60 N at interannual scale with no time lag in winter (DJF). The monthly mean fields are used here after taking a running mean of 5 years. From left to right, they are the regression of fields on AMET of ERA-Interim, MERRA2 and JRA55. The green contours indicate a significance level of 95%.



Regression of SLP (a-c), 2 meter temperature (T2M) (d-f) and SIC anomalies on AMET anomalies at 60 N at interannual scale with no time lag in summer (JJA). The monthly mean fields are used here after taking a running mean of 5 years. From left to right, they are the regression of fields on AMET of ERA-Interim, MERRA2 and JRA55. The green contours indicate a significance level of 95%.



Regression of SLP (a-c), 2 meter temperature (T2M) (d-f) and SIC anomalies on OMET anomalies at 60 N at interannual scale with ocean leading by one month in winter (DJF). The monthly mean fields are used here after taking a running mean of 5 years. From left to right, they are the regression of fields on OMET of ORAS4, GLORYS2V3 and SODA3. The green contours indicate a significance level of 95%.



Regression of SLP (a-c), 2 meter temperature (T2M) (d-f) and SIC anomalies on OMET anomalies at 60 N at interannual scale with ocean leading by one month in summer (JJA). The monthly mean fields are used here after taking a running mean of 5 years. From left to right, they are the regression of fields on OMET of ORAS4, GLORYS2V3 and SODA3. The green contours indicate a significance level of 95%.

Response to the other remarks

p.3 line 24: "it is preferable that they incorporate the latest..."

p.3 line 25: "they better not resemble each other" well, you certainly hope that different reanalyses would be consistent with each other!

Thanks for pointing out this. The sentence is very confusing indeed. Here we want to emphasize we try to include various reanalyses data sets to make the comparison more informative. We have deleted this sentence.

- section 2.3.1 : what is the value of Lv used here ? Lv varies with T in nature, but not necessarily in models... Not sure what's used in reanalyses.

Same as recent studies (e.g. Mayer et. al., 2017, Trenberth & Fasullo, 2018), we use fixed Lv = 2264.67 KJ/Kg. We include this in the method section now.

Mayer, M., Haimberger, L., Edwards, J. M., & Hyder, P. (2017). Toward consistent diagnostics of the coupled atmosphere and ocean energy budgets. Journal of Climate, 30(22), 9225-9246.

Trenberth, K. E., & Fasullo, J. T. (2018). Applications of an updated atmospheric energetics formulation. Journal of Climate, 31(16), 6263-6279.

- p.7 : there may also be issues due to different horizontal advection schemes used in the reanalysis and in the post-treatment.

Thanks for pointing out this. We have updated this part with "All the chosen atmospheric reanalyses use Semi-Lagrangian advection schemes but this is not the case for MERRA2.", just to be accurate.

- p.8, line 6 : unit should be J/(kgC) or J.C-1.kg-1.

We will correct it.

- p.8 : reference temperature. If the unit of potential temperature Theta is in C, then substracting a reference temp. of 0 C does not accomplish anything. Are you instead converting Theta from K to C to avoid cancellation of large terms problems? This is very unclear.

Reference temperature is used to account for the recirculation and the mass imbalance. Normally people take reference temperature as 0 deg C (e.g. Zheng and Giese, 2009). Since the oceanic reanalyses used here already saved theta in deg C, this actually would not affect the computation. But conceptually a reference temperature should be taken into account.

Zheng, Y. and Giese, B. S.: Ocean heat transport in simple ocean data assimilation: Structure and mechanisms, Journal of Geophysical Research: Oceans, 114, 2009.

- p.9, l25: The differences in resolution are actually small. There must be another explanation to these variations, which are key (main point A)

Now we learn that the noise is due to the choice of finite difference scheme. We will delete this.

- p.10, l10: In ocean models that are not eddy-resolving, there is both an eddy advection (Gent-McWilliams) and a diffusive heat transport, which can be significant compared to the resolved one. How were these incorporated in these analyses? They absolutely need to be taken into account.

Thanks for the comment. In ORAS4, an eddy parameterization scheme from Gent-Mcwilliams (1990) is implemented. The implementation of this eddy parameterization scheme can lead to a big difference in volume transport and heat transport, compared to eddy-permitted models (Stepanov & Haines, 2014). However, in this case the computation of OMET with ORAS4 doesn't include the contribution from eddy-induced velocity as the fields related to the use of eddy advection schemes are not saved by ORAS4. We will include such information in our revised manuscript.

Stepanov, V., & Haines, K. (2014). Mechanisms for AMOC variability simulated by the NEMO model. Ocean Science, 10(4), 645-656.

- section 3.2 and the accompanying figures for the atmosphere is a bit pointless given the low quality except for ERA-interim.

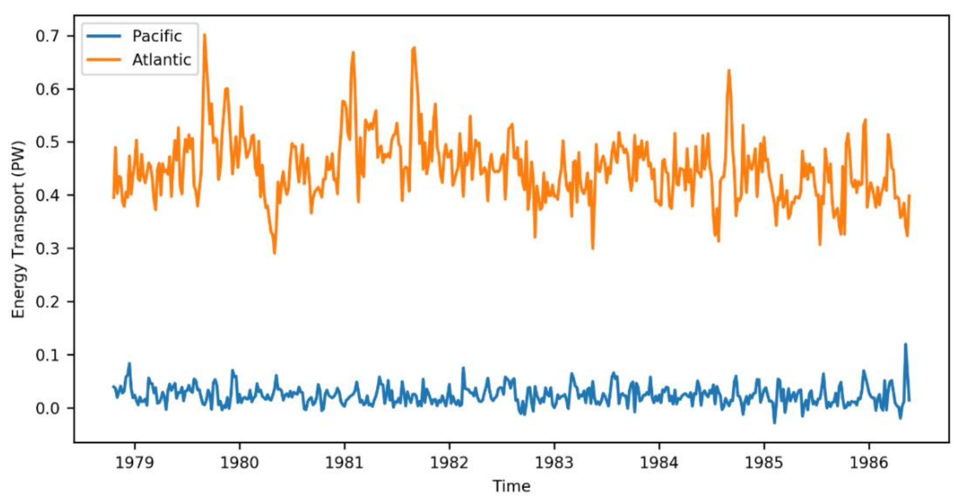
After we updated the results now these comparisons become informative. We will update this part with newly computed fluxes.

- p11, bottom: Are we looking in this section at the total OMET, or only the Atlantic OMET? It would probably be more interesting to look at Atlantic only at 60 N (in line with section 3.3), although knowing the relative roles could be good. Same question for page 13.

Thank you very much for the comment. We are looking at the Atlantic OMET in this part.

Below we show the OMET at 60N in the Pacific and Atlantic from ORAS4. It can be noticed that the OMET in the Atlantic is much larger than that in the Pacific. Note that the Atlantic OMET dominates both the mean value and the variability.

Actually, we also tried the same regressions with total OMET. The results are almost the same.



- p12 : any idea about why ORAS4 seems to work best ?

Given the big differences between chosen oceanic reanalyses as well as many factors that could potentially influence the results, we cannot explain conclusively why ORAS4 seems to work best here.

- p13, l28 : why 5-years timescale? Is it specific to the Arctic? Are the regressions on Fig.13 for 5-yr filtered data, or just year-to-year?

We are focusing on the influence of low frequency signals of OMET on the Arctic. Early studies with climate models also indicate that there are strong correlations between Arctic sea ice and OMET variations at interannual to decadal time scales (Van der Swaluw et al.,2007; Jungclaus and Koenigk, 2010). We take 5-years timescale because reanalysis time scales are relatively short, but we do intend to study variability beyond the annual time scales. Even longer windows for filtering would lead to a too small sample. Figure 13 is the regression with 5 year filtered data. We will add more details to the caption.

Van der Swaluw, E., Drijfhout, S., and Hazeleger, W.: Bjerknes compensation at high northern latitudes: The ocean forcing the atmosphere, Journal of climate, 20, 6023–6032, 2007.

Jungclaus, J. H. and Koenigk, T.: Low-frequency variability of the arctic climate: the role of oceanic and atmospheric heat transport variations, Climate dynamics, 34, 265–279, 2010.

- Figure 1 :this is hardly commented in the text: seasonal cycle, low contribution of LH (especially to the seasonal cycle)... By the way, I would replace this figure by either the components of the time-mean transport as a function of latitude, or by the mean seasonal cycle at 60 N of the different components. (With figures for the interannual variance if needed)

Thank you for the comment. We agree that the figure is not quantitatively clear for the seasonal cycles. We will replace it with mean AMET at 60N as a function of month.

- Figure 2: The dashed-line is built using annual means?

Yes, the dashed-lines are also annual means. Here we use solid lines and dashed lines to show AMET and OMET, respectively.

- Figure 3: panel b) needs confidence intervals, based on interannual variance. For panel a), do the standard deviations include the seasonal cycle or are they for interannual anomalies?

We will include confidence intervals for figure 3b.

In figure 3a the standard deviations include the seasonal cycle. (The standard deviations for interannual anomalies are included in figure 3b)

- Figure 4: not sure what is the point of these figures, apart from showing that the high-res analyses have eddies? It would be easier to copare maps integrated to the same low resolution, or time-means, and also to see the GM components.

As these oceanic reanalyses use different curvilinear grid, to integrate them to the same low resolution can introduce errors. We agree that the figures here are a bit pointless. We will delete these figures and only explain these in the text.

- Figure 6 could easily be replaced by the figures given in the text. Note that latent heat transport may not contribute much to the differences because it's low to begin with, but also because it's concentrated in the near-surface layers, so does not suffer too much from slight mass flux imbalances.

Thanks for your comment. We will replace these figures by texts.

- Figure 11, caption: I guess it is "interannual" time-scale? (i.e. year-to-year variability)

Here we use annual scale to refer to the 1-year filter we applied to the data. By saying interannual scale, we mean a 5-year filter is applied. Sorry for the confusion.

- Figures 11-13: consistent time-scales and variables, with different seasons would be nicer. Also, the green shading masks the color underneath, making it hard to read. Same-color shading maybe?

We will include consistent time scales for the regressions of AMET and OMET on SLP and SIC in summer and winter. We will change the green shading to contour lines to make it easy to read.

- Figure 13b: there are strange-looking colors (opposite the rest of the Arctic...) near the pole in all 3 plots (abrupts changes of sign...) Is this an artefact?

No, this is not an artefact. There are some quality-issues with sea ice in ERA-Interim, which can be inferred from an evaluation of reanalyses data sets concerning near-surface fields (Lindsay et. al., 2014), as ERA-Interim air-sea flux fields account for local sea ice concentration (IFS DOCUMENTATION – Cy31r1, Chapters 3 and 7). Such strange colors near the pole do not exist in figures with sea ice fields from MERRA2 and JRA55 (see response to major point 2). That's why a 'disc' appears close to the pole in some plots. We will add a note to this issue in the text.

Lindsay, R., Wensnahan, M., Schweiger, A., & Zhang, J. (2014). Evaluation of seven different atmospheric reanalysis products in the Arctic. Journal of Climate, 27(7), 2588-2606.

Again, thank you so much for the comments. We are sincerely gratitude to every point the reviewer made to improve this paper. Thanks a lot!

With best regards

Yang Liu, Ben Moat, Jisk Attema and Wilco Hazeleger

Synthesis and evaluation of historical meridional heat transport from midlatitudes towards the Arctic

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Abstract. Meridional Energy Transport (MET), both in the atmosphere (AMET) and ocean (OMET), has significant impact on the climate in the Arctic. In this study, we quantify AMET and OMET at subpolar latitudes from six reanalyses datasets. We investigate the differences between the datasets and we check the coherence between MET and the Arctic climate variability ~~from annual to interannual~~ at interannual time scales. The results indicate that, although the mean transport in all datasets agree well, the spatial distribution and temporal variations of AMET and OMET differ substantially among the ~~reanalysis datasets~~reanalyses data sets. For the ocean, only after 2010 the low frequency signals for all reanalyses products agree well. A further comparison with observed heat transports at 26.5°N and the subpolar Atlantic, and a high resolution ocean model hindcast confirm that the OMET estimated from reanalyses are consistent with independent observations. For the atmosphere, the variations among reanalyses ~~datasets~~ data sets are large. This can be attributed to differences in temperature transport and geopotential energy transport. A further analysis of linkages between the Arctic climate variability and AMET shows that atmospheric reanalyses differ substantially from each other. Among all the chosen atmospheric products, ERA-Interim and JRA55 results are most consistent with results obtained with coupled climate models. For the ocean, ORAS4 and SODA3 agree well on the relation between OMET and sea ice concentration (SIC), while GLORYS2V3 deviates from those data sets. The regressions of multiple fields in the Arctic on both AMET and OMET suggest that the Arctic climate is sensitive to changes of meridional energy transport at subpolar latitudes in winter. Our study suggests, since the reanalyses products are not designed for the quantification of energy transport, the AMET and OMET estimated from reanalyses should be used with great care, especially when studying variability and interactions between the Arctic and midlatitudes beyond ~~annual~~ interannual time scales.

1 Introduction

Poleward meridional energy transport, both in the atmosphere (AMET) and ocean (OMET), is one of the most fundamental aspects of the climate system. It is closely linked to changes of weather and climate at different latitudes. The quantification of AMET and OMET has been studied extensively. Dating back to 1970s, many efforts were made to reproduce the AMET and OMET with very limited observational data available (Vonder Haar and Oort, 1973; Oort and Vonder Haar, 1976). After entering the satellite era, further progress has been made during the recent two decades. Using the radiation at top of the atmosphere and the reanalyses data, a complete picture of AMET and OMET is given by Trenberth and Caron (2001). Following their work, rapid progress was made using similar methodologies and new data sets of observations (Ganachaud and Wunsch, 2000, 2003; Wunsch, 2005; Fasullo and Trenberth, 2008; Zheng and Giese, 2009; Mayer and Haimberger, 2012). Nevertheless, these estimations still suffered from problems like mass imbalance, unrealistic moisture budget, coarse resolution, and sparseness of observations (Trenberth, 1991; Trenberth and Solomon, 1994). Fortunately, recent improvements in numerical weather and ocean models and increased data coverage of observations provide a basis to improve estimates of AMET and OMET. There is an increase of available reanalyses products, increase in resolution, length of the time span that is covered and increase of components of the Earth system that are included in the products (Dee et al., 2011; Gelaro et al., 2017; Harada et al., 2016; Balmaseda et al., 2013; Ferry et al., 2012b; Carton et al., 2018). It is very promising to have better quantification of AMET and OMET using the latest reanalyses ~~datasets~~data sets.

To support our elaboration on MET, we also study AMET and OMET in relation to climate variability ~~from annual to~~ at interannual time scales in the Arctic region. In recent decades, the Arctic is warming twice as fast as the global average (Comiso and Hall, 2014; Francis et al., 2017). This phenomenon is known as Arctic Amplification (AA) and it has an impact far beyond the Arctic (Miller et al., 2010; Serreze and Barry, 2011). In order to understand the warming, the process behind the AA, its wider consequences and to make reliable predictions of the Arctic climate, it is crucial to understand the Arctic climate variability. Among all the factors responsible for the variability in the processes described above, meridional energy transport (MET), from midlatitudes toward the Arctic, plays a significant role (Graversen et al., 2008; Kapsch et al., 2013; Zhang, 2015). There is a large volume of published studies describing the impact of AMET and OMET on the variation of sea ice and the warming in the Arctic. Using reanalysis data, Yang et al. (2010) show that the poleward AMET is linked with the evolution of temperature in the free troposphere at ~~a decadal scale~~decadal time scales. By separating the planetary and synoptic-scale waves, Graversen and Burtu (2016) show that the latent heat transport, as a component of AMET, influences the Arctic warming with reanalysis data. Gimeno-Sotelo et al. (2019) studied the moisture transport for precipitation ~~and~~ with reanalysis data and observation data, and show the moisture sources for the Arctic region is linked with ~~inter-annual~~ interannual fluctuations in the extent of Arctic sea ice. Nummelin et al. (2017) analyse the linkages between OMET, Ocean Heat Content (OHC) and AA through the simulations within the Coupled Model Intercomparison Project Phase 5 (CMIP5). They report enhancement of OMET as a result of heat loss in the subpolar ocean and the contribution of OMET to the AA through the increasing of OHC in the Arctic ocean. Also by analyzing CMIP5 simulations, Sandø et al. (2014) show a large impact of heat transport in the Barents Sea on sea ice loss. However, ocean reanalyses don't show a clear sign of AA in Arctic OHC increases (Mayer et al., 2016; Von Schuckmann et al., 2016). Consequently, increasing knowledge on poleward AMET and OMET at subpolar and polar latitudes will aid in understanding of AA.

Global climate models indicate a compensation between variations in atmospheric and oceanic heat transports at subpolar and midlatitudes (Outten et al., 2018). This is indicative of positive feedbacks between the ocean and atmosphere and it has been associated with variations in sea ice by several studies (Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010; van der Linden et al., 2016). These studies all point out the connection between energy transport and the variations of the Arctic climate. However, these results are mostly based on numerical model simulations and they tend to differ among the models. In contrast to numerical modeling studies, here we intend to study AMET, OMET variability and the relation with the Arctic in best estimates of the historical variability.

In this paper, we quantify AMET and OMET using multiple state-of-the-art reanalyses products. These are ~~optimized~~ representations of the historical state of the atmosphere and ocean ~~based on~~ optimally combining available observations and numerical simulations using data assimilation techniques. Emphasis is placed on the variation of AMET and OMET from mid-latitudes to the Arctic ~~across annual to~~ at interannual time scales. In contrast with earlier studies, we will compare the different reanalyses ~~datasets~~data sets. Independent observations in the Atlantic from ~~RAPID ARRAY and OSNAP~~ the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID ARRAY) and the Overturning in the Subpolar North Atlantic Program (OSNAP) are included in the comparison. ~~RAPID ARRAY, which is short for the RAPID-MOCHA-WBTS program, is~~ The RAPID ARRAY is a trans-basin observing array along 26.5° N in the Atlantic (Johns et al., 2011; McCarthy et al., 2015). It operates since 2004 and provides the volume and heat transport in the Atlantic basin. OSNAP ~~, which is the abbreviation of Overturning in the Subpolar North Atlantic Program, is~~ is an ocean observation program designed to provide a continuous record of the trans-basin fluxes of heat, mass and freshwater in the subpolar North Atlantic (Susan Lozier et al., 2017; Lozier et al., 2019). Moreover, a state-of-the-art NEMO-LIM2 1/12° ocean circulation / sea ice model simulation forced by Drakkar Surface Forcing data set version 5.2 (Moat et al., 2016) is also included in the comparison. It will be referred as Oceanic General Circulation Model (OGCM) hindcast in this paper. Based on the intercomparison of ~~reanalyses~~ reanalysis data, especially with the independent observation data, we will be able to identify sources of uncertainty. To support our comparison of AMET and OMET, we also investigate the interactions between oceanic and atmospheric variations and remote responses. The correlations between the variability of AMET and OMET and the changes in the Arctic climate are compared to literature. This is motivated by previous studies with only numerical models or a single reanalysis dataset to explain those connections (Graversen, 2006; Van der Swaluw et al., 2007; Graversen et al., 2008; Jungclaus and Koenigk, 2010; Kapsch et al., 2013).

The paper is organized as follows: Section 2 presents the data and our methodology. Results and analysis are given in Section 3. It includes AMET and OMET calculated from ~~reanalyses~~ reanalysis data and an intercomparison of them. The correlation between the variability of AMET and OMET, and the Arctic climate is elaborated upon in detail. Finally, remarks constitute Section 4 and conclusions are provided in Section 5.

2 Data and Methodology

The reanalyses ~~datasets~~ data sets used in this study are introduced in this section. Moreover, the methodology for the quantification of AMET and OMET are also included in this section. The statistical tests performed in this study are elucidated in detail.

2.1 Reanalyses

In order to make use of observations and advanced numerical models, six state-of-the-art reanalyses ~~datasets~~ data sets are used in this study. The chosen reanalyses products have ~~higher~~ high temporal and spatial resolution due to the need for the computation of energy transport (see section 2.3). It is ~~preferably~~ preferable that they incorporate ~~with~~ the latest numerical models and data assimilation schemes. ~~For an inter-comparison purpose, they better not resemble each other.~~ As a result, we chose three atmosphere reanalyses ~~datasets~~data sets: ERA-Interim, MERRA2, and JRA55 (references below) and three ocean reanalyses ~~datasets~~data sets: ORAS4, GLORYS2V3, and SODA3 (references below). To avoid interpolation errors and imbalances in the mass budget introduced by regridding, the calculations are based on the data from the original model grid. Note that the latest atmospheric reanalysis ERA5 from ECMWF is not included here since the model level data has not been opened to the public yet (ECMWF, 2017). In addition, the computation is too expensive to achieve a longer time series for the study of the interannual variability of AMET using ERA5. As a synthesis, Table 1 shows the basic specifications of the reanalyses products contained in this study.

2.1.1 ERA-Interim

ERA-Interim is a global ~~reanalyses~~ reanalysis dataset produced by the European Center for Medium Range Weather Forecasts (ECMWF) (Dee et al., 2011), which covers the data-rich period since 1979. It employs the cycle 31r2 of ECMWF's Integrated Forecast System (IFS) and generates data using 4D-Var assimilation with a T255 ($\sim$79km) horizontal resolution on 60 vertical levels (Berrisford et al., 2009). Compared with its preceding reanalyses, ERA-40 (Uppala et al., 2005), ERA-Interim is superior in quality in terms of the atmospheric properties like mass, moisture and energy (Berrisford et al., 2011). The improvement in observations and the ability of 4D-Var contributes a lot to the quality of the divergent wind (Berrisford et al., 2011), which is significant for the mass budget and hence the energy budget. We use the data on the original model grid, with a 0.75° x 0.75° horizontal resolution and 60 vertical hybrid model levels. We take 6-hourly data with a range from 1979 to 2016.

2.1.2 MERRA2

The Modern-Era Retrospective Analysis for Research and Applications version 2 (Gelaro et al., 2017), in short MERRA2, is the successor of MERRA from the Global Modeling and Assimilation Office (GMAO) of the National Aeronautics and Space Administration (NASA). It assimilates observational data with the Goddard Earth Observing System (GEOS) model and analysis scheme (Molod et al., 2015; Gelaro et al., 2017). The data is produced by a 3D-Var assimilation scheme and has a coverage from 1980 till present. Unlike most of the reanalyses products, the GEOS atmospheric model includes a finite-volume dynamical core which uses a cube-sphere horizontal-discretization (Gelaro et al., 2017). The model grid has a resolution of 0.5° x 0.625° with 72 hybrid levels. For this study, we use the 3-hourly assimilation data on the native model grid from 1980 to 2016.

2.1.3 JRA55

Extending back to 1958, Japanese 55-year reanalyses (JRA55) is the second reanalyses product made by Japan Meteorological Agency (JMA) (Kobayashi et al., 2015; Harada et al., 2016). JRA55 applies 4D-Var assimilation and it is generated on TL319 horizontal resolution with 60 hybrid levels. Before entering the satellite era in 1979, the assimilated upper air observations mainly come from radiosonde data. In this project we take 6-hourly data from 1979 to 2015 on the original model level, which has a horizontal resolution of 0.5625° x 0.5625° with 60 hybrid model levels.

2.1.4 ORAS4

Serving as the historical reconstruction of the ~~oceans~~ ocean's climate, the Ocean reanalyses System 4, in short ORAS4, is the replacement of the old reanalyses system ORAS3 used by the ECMWF (Balmaseda et al., 2013). It implements Nucleus for European Modelling of the Ocean (NEMO) as ocean model (Madec, 2008; Ferry et al., 2012a) and uses NEMOVAR as the data assimilation system (Mogensen et al., 2012). The model is forced by atmosphere-derived daily surface fluxes, from ERA-40 from 1957 to 1989 and ERA-Interim from 1989 onwards. ORAS4 produces ~~data with~~ analyses with a 3D-Var ~~assimilation~~ FGAT assimilation scheme and spans from 1958 to present. ORAS4 runs on the ORCA1 grid, which is associated with a horizontal resolution of 1° in the extratropics and a refined meridional resolution up to 0.3° in the tropics. It has 42 vertical levels, 18 of which are located at upper 200m. Here we skip the first two decades and use the monthly data from 1979 to 2014 to avoid the uncertainties reported by Balmaseda et al. (2013). We will use the monthly mean fields on the native model grid.

2.1.5 GLORYS2V3

GLORYS2V3, short for GLobal Ocean reanalyses and Simulations version 3, is a global ocean and sea-ice eddy permitting reanalyses yielded from the collaboration between the Mercator Ocean, the Drakkar consortium and Coriolis Data center (Ferry et al., 2010, 2012b). It spans the altimeter and Argo eras, from 1993 till present. The NEMO ocean model is implemented on the ORCA025 grid (approximate 0.25° x 0.25° with 75 vertical levels). The model is forced by ~~surface fluxes using the~~ a combination of ERA-Interim fluxes (e.g. shortwave radiation) and turbulent fluxes obtained with bulk formulae using ERA-Interim ~~atmospheric~~ near-surface parameters. The data is generated by a 3D-Var assimilation scheme with temperature and salinity profiles assimilated from the CORA3.3 database (Ferry et al., 2012b). In this study, monthly data from 1993 to 2014 on the original ORCA025 grid is used.

2.1.6 SODA3

SODA3 is the latest version of Simple Ocean Data Assimilation (SODA) ocean reanalyses conducted mainly at the University of Maryland (Carton et al., 2018). SODA3 is built on the Modular Ocean Model v5 (MOM5) ocean component of the Geophysical Fluid Dynamics Laboratory CM2.5 coupled model (Delworth et al., 2012) with a grid configuration of approximately 0.25° x 0.25° x 50 levels resolution (Carton et al., 2018). To be consistent with the other two reanalyses ~~datasets~~ data sets assessed in this study, the SODA 3.4.1 is chosen since it applies surface forcing from ERA-Interim. For this specific version, the 5-daily data is available from 1980 to 2015. ~~reanalyses~~ Reanalysis data from this period on original MOM5 grid is used in this case.

2.2 Oceanic Observations and ~~NEMO ORCA~~ OGCM Hindcast

For the purpose of independent examination of the OMET calculated from reanalyses, observations of the meridional transport of mass and heat throughout the Atlantic basin are used here. We use data from the RAPID-MOCHA-WBTS program (Johns et al., 2011; McCarthy et al., 2015) and the OSNAP program (Susan Lozier et al., 2017; Lozier et al., 2019). The RAPID-MOCHA-WBTS program, which is known as RAPID ~~array~~ARRAY, employs a transbasin observing array along 26.5°N and it is in operation since 2004. The OMET from the RAPID ~~array~~ ARRAY available to this study is from April 2004 to March 2016. The OSNAP program has ~~a~~ an observing system that comprises of an integrated coast-to-coast array extending from the southeastern Labrador shelf to the southwestern tip of Greenland, and from the southeastern tip of Greenland to the Scottish shelf. So far, it provides OMET data from the full installation of the array in 2014 until the first complete data recovery in 2016, 21 months in total. Although it is short to provide a good estimate of interannual variability of OMET, we include it anyway as it is a unique observation system for OMET in the subpolar Atlantic.

Apart from the RAPID ~~array~~ ARRAY and OSNAP observational data, a high resolution hindcast of the NEMO ORCA ocean circulation model is also included here to provide more insights to the analysis since two of the chosen reanalyses products are also built on NEMO model (Moat et al., 2016; Marzocchi et al., 2015). This forced model simulation implements the NEMO ORCA global ocean circulation model version 3.6 (Madec, 2008). It is configured with ORCA0083 grid, which has a nominal resolution of 1/12°, on 75 vertical levels. The climatological initial conditions for temperature and salinity were taken in January from PHC2.1 at high latitudes (Steele et al., 2001), MEDATLAS in the Mediterranean (Jourdan et al., 1998), and the rest from Levitus et al. (1998). ~~The surface forcing comes~~ It is forced by the surface fields coming from the Drakkar project~~and it covers the period from~~ , which supplies surface air temperature, winds, humidity, surface radiative heat fluxes and precipitation, and a formulation that parameterizes the turbulent surface heat fluxes and is provided for the period 1958 to 2012 (dataset version 5.2) (Brodeau et al., 2010; Dussin et al., 2016). More information about this hindcast is given by Moat et al. (2016). We take monthly mean data from the hindcast, which spans from 1979 to 2012.

2.3 Computation of Meridional Energy Transport

The methods for quantification of AMET and OMET with atmospheric and oceanic reanalyses are included in this section, respectively.

2.3.1 Energy Budget in the Atmosphere

The total energy per unit mass of air has four major components: internal energy (I), latent heat (H), geopotential energy (ϕ) and kinetic energy (k). They are defined as:

$$
\begin{aligned}
I &= c_p T \\
H &= L_v q \\
\Phi &= gz \\
k &= \frac{1}{2}\mathbf{v}\cdot\mathbf{v}
\end{aligned}
\tag{1}
$$

with c_p the specific heat capacity of dry air at a constant pressure (~~J/kgK~~ $J/(kgK)$), T the absolute temperature (K), L_v the specific heat of condensation (J/kg), q the specific humidity kg/kg, g the gravitational acceleration (~~kg/ms^2~~ $kg/(ms^2)$), z the altitude (m) and v the zonal/meridional wind velocity (m/s). The northward propagation is positive. In addition, these four quantities can be divided into three groups: the dry static energy $I+\phi$, the moist static energy H and the kinetic energy k. A constant value of ~~$c_p = 1004.64 J/kgK$ was~~ $c_p = 1004.64 J/(kgK)$ and $L_v = 2264.67 KJ/kg$ were used to compute the AMET with all the atmosphere reanalyses ~~datasets.~~ data sets. In addition, recently there are some improved formulations of energy budget equations proposed by Mayer et al. (2017) and Trenberth and Fasullo (2018). We use an updated formulation of AMET as a combination of the divergence of dry-air enthalpy, latent heat, geopotential and kinetic energy transports, which is suggested by Mayer et al. (2017). Note that in this case the enthalpy transports associated with vapor fluxes are neglected.

In pressure coordinates, the total energy transport at a given latitude Φ_i can be expressed as (Mayer et al., 2017):

$$
E = \oint_{\Phi=\Phi_i} \int_{p_s}^{p_t} \underline{(c_p T + L_v q + gz + \frac{1}{2}\mathbf{v}\cdot\mathbf{v})}[(1-q)c_p T + L_v q + gz + \frac{1}{2}\mathbf{v}\cdot\mathbf{v}] v \frac{dp}{g} dx \tag{2}
$$

with p_t the pressure level at top of the atmosphere (Pa) and p_s the pressure at the surface (Pa). Since we work on the native hybrid model coordinate with each atmosphere reanalyses product, the equation can be adjusted as follows (see Graversen (2006)):

$$
E = \oint_{\Phi=\Phi_i} \frac{1}{g} \int_0^1 \underline{(c_p T + L_v q + gz + \frac{1}{2}\mathbf{v}\cdot\mathbf{v})}[(1-q)c_p T + L_v q + gz + \frac{1}{2}\mathbf{v}\cdot\mathbf{v}] v \frac{\partial p}{\partial \eta} d\eta dx \tag{3}
$$

where η indicates the number of the hybrid level. Note that difference in horizontal advection schemes can influence the results. All the chosen atmospheric reanalyses use Semi-Lagrangian advection schemes but this is not the case for MERRA2.

Unfortunately, a direct estimation of AMET based on the equations above cannot provide a meaningful energy transport obtained from ~~reanalyses~~ reanalysis data. It has been widely reported that reanalyses products suffer from mass inconsistency

(Trenberth, 1991; Trenberth et al., 2002; Graversen, 2006; Graversen et al., 2007; Chiodo and Haimberger, 2010; Berrisford et al., 2011). Spurious sinks and sources mainly come from low spatial and temporal resolution, interpolation and regridding, and data assimilation. The interpolation from original model level to pressure level can introduce considerable error to the mass budget (Trenberth et al., 2002). Therefore we prevent interpolations onto the pressure levels and use data on the native model levels with a high temporal resolution. Trenberth (1991) provided a method to correct the mass budget through the use of the continuity equation. The method assumes that the mass imbalance mainly comes from the divergent wind fields and corrects the overall mass budget by adjusting the barotropic wind. The conservation of mass for a unit column of air can be represented as:

$$\frac{\partial p_s}{\partial t} + \nabla \int_{p_s}^{p_t} \mathbf{v} dp = g(E - P) \tag{4}$$

Where E stands for evaporation and P denotes precipitation. It has been noticed that big uncertainties reside in the evaporation and precipitation of global reanalyses (Graversen, 2006). Hence we use the moisture budget to derive the net moisture change in the air column, according to:

$$E - P = \frac{\partial}{\partial t}\left(\int_{p_s}^{p_t} q \frac{dp}{g}\right) + \nabla \int_{p_s}^{p_t} (\mathbf{v} \cdot q) \frac{dp}{g} \tag{5}$$

After determining the mass budget imbalance, we correct the barotropic wind fields (u_c, v_c)~~and calculate~~ , with u_c and v_c indicating the correction terms for zonal and meridional wind components as a result of barotropic mass budget correction, and then calculate AMET (Trenberth, 1991). Note that all the computations regarding baratropic mass budget correction were performed in the spectral domain via spherical harmonics. Figure 1 shows the mean AMET ~~. Figure ?? shows the total AMET~~ and each component in each month at 60°N estimated from ERA-Interim. ~~In addition, recently there are some improved formulations of energy budget equations proposed by Mayer et al. (2017) and Trenberth and Fasullo (2018). But they mainly target on the tropical and extratropical regions and are not so relevant to our target area.~~

2.3.2 Energy Budget in the Ocean

Unlike the atmosphere, energy transport in the ocean can be well represented by the internal energy itself. Consequently, the total energy transport in the ocean at a given latitude ϕ_i can be expressed in terms of the temperature transport (Hall and Bryden, 1982):

$$E = \oint_{\Phi=\Phi_i} \int_{z_b}^{z_0} \rho_0 c_{p_0} \theta \cdot v dz d\phi \tag{6}$$

where ρ_0 is the sea water density (kg/m^3), c_{p_0} is the specific heat capacity of sea water (~~$J/kg°C$~~ $J/(kg°C)$), θ is the potential temperature $(°C)$, v is the meridional current velocity (m/s), z_0 and z_b are sea surface and the depth till the bottom (m), respectively. A constant value of $c_{p_0} = 3987 J/kg°C$ $c_{p_0} = 3987 J/(kg°C)$ was used in all the calculations of OMET. Ocean heat content (OHC, with unit J) is another variable that plays a role in the ocean heat budget. The total OHC at a certain latitude between certain latitudes can be calculated by:

$$OHC = \int_{\Phi_i}^{\Phi_0} \int_{z_b}^{z_0} \rho_0 c_{p_0} \theta dz d\phi \tag{7}$$

As a general problem known by oceanographers, there are sinks and sources in oceanreanalyses as wellOur computation of OMET suffers from a small mass imbalance (e.g. mass imbalance coming from the residual between precipitation and evaporation (Mayer et al., 2017)). In the ocean, with its strong boundary circulations even the smallest imbalance can lead to large errors in the heat flux. However, the barotropic correction method adopted by the atmosphere is not feasible here, as a consequence of a varying sea surface height. So far there is no practical way to deal with the mass imbalance in the ocean. Moreover, the definition of OMET in this way cannot account for the recirculation (Zheng and Giese, 2009), which indicates the northward flow passing the Arctic acting as southward flow afterwards. To deal with this issue, we In oceanographic literature it is common to use a reference temperature when calculating OMET in both observations and model diagnostics (Bryan, 1962; Hall and Bryden, 1982; Zheng and Giese, 2009). Here, we also take a reference temperature θ_r (°C). C). Note that the influence from taking a reference temperature on a zonally integrated transport is smaller than that on a single strait (Schauer and Beszczynska-Möller, 2009). Then the quantification of OMET becomes:

$$E = \oint_{\Phi=\Phi_i} \int_{z_b}^{z_0} \rho_0 c_{p_0} (\theta - \theta_r) \cdot v dz d\phi \tag{8}$$

Here, we take θ_r equal to 0. Finally, operations in the “zonal” direction are different from their conventional meaning. As the three ocean reanalyses products used here are all built on a curvilinear grid, the zonal direction on the native model grid is curvilinear as well. Similar to the considerations made in Section 2.1, regridding from the native curvilinear grid to a uniform geographical grid will introduce large errors. So, we work on the original multi-pole grid and follow the native zonal directions when performing numerical operations. After applying this method the resulting OMET values are comparable to those in earlier publications (Trenberth and Caron, 2001; Wunsch, 2005; Trenberth and Fasullo, 2008). Note that since we only have access to sub-monthly data for SODA3, the computation of OMET using monthly data in ORAS4 and GLORYS2V3 could miss part of the heat transport by eddies.

2.4 Statistical Analysis

In order to understand the connection between MET and changes in the Arctic and compare to the results from numerical climate models or single reanalyses reanalysis dataset (Graversen, 2006; Van der Swaluw et al., 2007; Graversen et al., 2008; Jungclaus and Koenigk, 2010; Kapsch et al., 2013), in the following section we performed linear regressions on multiple fields with AMET and OMET. To test the significance of the regressions, we simply use student's t-test. ~~Due to the slow response time of the ocean, the~~ We decorrelate the monthly mean OMET anomalies ~~show a large autocorrelation. For a threshold of 0.6, we find a correlation time of 3 months. This effectively reduces the number of independent data points in the regression by a factor of 3. As a result, those regressions effectively influenced by the autocorrelation of OMET were performed after reducing the degree of freedom by 3. Another issue about autocorrelation is the~~ after the implementation of low pass filter. ~~Since a running mean of multiple years will increase the correlation, we only show the significance at monthly time scales.~~ This means the relevant significance tests are performed with ~~raw time series before applying the low pass filter~~time series after removing the autocorrelation.

Note that all the reanalyses ~~datasets~~ data sets included in this study have short time series at monthly ~~scale~~ time scales (no more than 456 months, see Table 1). Therefore the analysis based on these ~~datasets~~ data sets is not statistically significant compared with those using the output data from numerical simulations with a large time span, since the relatively short records of reanalyses do not have many samples at interannual time scales. Nevertheless, the reanalyses products are better representations of the real world. So the statistical analysis with ~~reanalyses~~ reanalysis data is still useful to answer the questions about connections in climate system.

3 Results

Unless specifically noted, the results shown in this section are all based on monthly mean fields with low pass filter from 1 to 5 years.

3.1 Overview of AMET and OMET

Globally, MET is driven by the unequal distribution of net solar radiation and thermal radiation. The atmosphere and oceans transport energy from regions receiving more radiation to the regions receiving less. Figure 2 gives the mean of AMET and OMET over the entire time series of every product at each latitude in the Northern Hemisphere. For the atmosphere, all three datasets agree very well. The results differ a bit in amplitude but capture similar variations along each latitude. The peak of AMET is around 41°N, after which it starts to decrease towards the north pole. In ERA-Interim and JRA55 AMET peaks at ~~5.1~~ 4.45 PW at 41°N, while in MERRA2 AMET peaks at ~~4.8 PW at 40°Nand in JRA55 AMET peaks at 4.8 PW at 40°N after smoothing the signals with a spatial lowpass filter~~4.5 PW at 41.5°N. These findings are consistent with previous work (e.g. Trenberth and Caron (2001); Fasullo and Trenberth (2008); Mayer and Haimberger (2012) and many others). ~~The mean MET from MERRA2 and JRA55 show more latitudinal variations than those obtained from ERA-interim, which is due to the difference in the spatial resolution of each atmospheric product.~~

Apart from the climatology of MET, we are particularly interested in the variations across different time scales from midlatitudes towards the Arctic. The time series of AMET, integrated zonally over 60°N, are shown in Figure 3a. ~~Again, we include "ERA-Interim res" only for reference.~~ The seasonal cycle is dominant in each component as expected and the phase is very similar, but differences in the amplitudes are noted. The mean AMET provided by the chosen three atmospheric reanalyses agrees well. However, their variations differ from each other. In ERA-Interim, the standard deviation (std) of AMET is ~~0.88~~ 0.92 PW, while MERRA2 has a relatively ~~small std of 0.67 PW but~~ large std of 0.97 PW and in JRA55 the std is ~~1.21~~ 0.91 PW. Hence it can be concluded that the seasonal cycles of AMET presented by the chosen atmospheric reanalyses are ~~different~~similar. After removing the seasonal cycle and applying a low pass filter, neither the amplitude nor the trend of the signals agree between the data sets (see Figure 3b). The std of the AMET anomaly in ERA-Interim is ~~0.07~~ 0.02 PW, while in MERRA2 it is ~~0.12~~ 0.04 PW and in JRA55 it is ~~0.04~~ 0.03 PW. This implies that the variation of AMET anomalies are different in the chosen data sets. We further assess the sources of the difference in the next section.

For the ocean, all the reanalyses ~~datasets~~ data sets agree well at almost all the latitudes except for the OMET between 30°N and 40°N, where the Gulf Stream resides. The difference can be explained by the models. GLORYS2V3 and SODA3 both have been generated with eddy-permitting models while ORAS4 has not. ~~The~~ In ORAS4, an eddy parameterization scheme from Gent and Mcwilliams (1990) is implemented. The implementation of this eddy parameterization scheme can lead to a big difference in volume transport and heat transport, compared to eddy-permitted models (Stepanov and Haines, 2014). However, in this case the computation of OMET with ORAS4 does not include the contribution from eddy-induced velocity as the fields related to the use of eddy advection schemes were not saved. The eddy-permitting reanalyses with higher resolution, like GLORYS2V3 and SODA3, are capable of addressing the large scale turbulence. It has been shown that their eddy-permitting capacity can account for the large scale eddy variability and represent the eddy energy associated with both the Gulf Stream and the Kuroshio pathways well (Masina et al., 2017). ~~Whereas, in ORAS4 the large scale eddies can not be resolved due to its relatively low resolution. To illustrate the differences, the spatial distributions of heat transport are shown in Figure **??**. The plots show the monthly mean OMET at the Atlantic basin in January, 1996. At the~~ Consequently, at the latitude of the Gulf Stream (between 30°N and 40°N), a higher spatial variability, which represents more realistic patterns of the large scale eddy variability, is apparent in all datasets but ORAS4.

Similarly, we show the zonal integral of the OMET at 60°N in Figure 4. Differences in amplitude and trends can be observed in the unfiltered time series. The mean OMET and the std of all the OMET time series are similar (see Figure 4a). The mean OMET in ORAS4 is 0.47 PW, in GLORYS2V3 is 0.44 PW and in SODA3 is 0.46 PW. The ~~NEMO~~ OGCM hindcast gives a similar mean OMET of 0.47 PW. For the std of OMET, ORAS4 and the ~~NEMO~~ OGCM hindcast give 0.06 PW, while GLORYS2V3 and SODA3 give 0.07 PW. In terms of the difference in the OMET time series between the chosen products, it is not surprising that large differences appear after we take a running mean of 5 years when computing the OMET anomalies. However, the large variation of OMET anomalies in Figure 4b is not noticeable from their std. Given the time series of all the chosen reanalyses, ORAS4 resembles SODA3, especially after 1998. Whereas, GLORYS2V3 is clearly different from ORAS4 and SODA3 from 1998 to 2006. The differences can be tracked in the time series, which reveals that the initial years of GLORYS2V3 might experience some problems. The first 10 years in GLORYS2V3 are quite suspicious because of its large deviation from the other products. Such large differences should be noticeable in the heat content changes or surface fluxes. Nevertheless, after 2007 all the reanalyses time series agree well and the ~~NEMO~~ OGCM hindcast deviates from the reanalyses. It is noteworthy that the observations improve considerably around that period due to an increasing number of Argo floats in use

(Riser et al., 2016). The reanalyses products used here are greatly influenced by the number of available in-situ observations. We further assess the sources of differences in the next section.

3.2 Source of Disparity

In order to further understand the difference between the AMET estimated from each atmosphere reanalyses product, we compare each component of AMET separately. Figure ?? gives We investigate the difference between each component of AMET at 60°N estimated from ERA-Interim against those from MERRA2 (Figure ??a) and JRA55(Figure ??b). It can be . It is noticed that the differences mainly originate from meridional temperature transport(vc_pT) and geopotential energy transport (vgz). A simple linear regression shows the correlation between the difference of total energy transport and the difference of meridional temperature transport, taking ERA-interim and MERRA2, is 0.950.55, while for ERA-Interim and JRA55 that is 0.48very small. In addition, the correlation between the difference of total energy transport and the difference of geopotential energy transport (vgz), for ERA-interim ERA-Interim and MERRA2 is 0.60 0.56 and for ERA-Interim and JRA55 that is 0.070.60. For the other components, the correlations between them and the total difference are all smaller than 0.05neglectable. The results are all obtained with a confidence interval over 9995%. This is generally the case as large differences in temperature transport between reanalyses products are found at all latitudes (not shown). Such differences are consistent with the fact that the temperature transport has the biggest and geopotential energy transport have larger contribution to the total AMET (see Figure ??1). Note that the differences of each AMET component between every two products are of the same order of magnitude as the absolute values of that component. Besides, the latent heat transport agrees well between all the chosen atmospheric products, in terms of the mean and anomalies (not shown). A similar result was found by Dufour et al. (2016) in their study using more reanalyses datasetsdata sets.

In order to know the relative contribution of each field to the difference of the total AMET among the chosen reanalyses, a direct comparison of the vertical profile of temperature and meridional velocity fields between ERA-Interim and MERRA2 is presented in Figure 5, as an example. We take the monthly mean temperature and velocity fields of ERA-Interim and MERRA2 from 1994 to 1998, in which the biggest difference was observed (Figure 3, taking into account the running mean of 5 years). For the sake of a point-wise comparison, the fields from MERRA2 are interpolated onto the vertical grid of ERA-Interim. This shows that these two reanalyses products differ substantially regarding each variable field (Figure 5a and b). By taking the product of the mean temperature (meridional wind velocity) and the difference between meridional wind velocity (temperature), we can qualitatively identify the relative contribution from the difference between each variable field (Figure 5c and d). This shows that the difference in meridional wind velocity between MERRA2 and ERA-Interim is Big differences in temperature reside mostly at the tropopause, while large differences in meridional wind component are distributed over the entire vertical column of the tropopause. Such differences in both fields are expected to be responsible for the difference in temperature transport (vc_pT). Large differences are found in geopotential height fields too (not shown). It should be noted that this comparison is carried out on pressure levels and the mass conservation is not ensured. Therefore it can only provide insight qualitatively and a quantitative contribution of the difference in each single field to the temperature transport can not be identified here.

Differences between every two chosen atmospheric products are found at nearly each pressure level. Given the data available, this analysis is not sufficient to explain conclusively where the uncertainty mainly comes from in terms of the dynamics and physics in the atmosphere model and data assimilation system. We do find that uncertainties as indicated by the spread between the datasets, in both the temperature and meridional velocity fields, are too large to constrain the AMET. Hence studies on low frequency variability of energy transports and associated variables, should be interpreted with care as the reanalyses products differ substantially and we cannot make a priori judge how close they are to actual energy transports since independent direct observations are not available.

For the ocean, fortunately independent observations of OMET in the Atlantic Ocean are available. First, OMET estimated from ORAS4, GLORYS2V3, SODA3 and the ~~NEMO ORCA~~ OGCM hindcast is evaluated against OMET measured at 26.5°N. Given in Figure 6, the inter-comparison shows that the reanalyses products capture roughly the mean amplitude of the OMET. Some large events are captured as well, such as the strong weakening in 2009. Statistically, the mean OMET provided by RAPID ARRAY is $1.21 \pm 0.27 PW$. It is higher than all the chosen products here. The mean OMET in ORAS4 is $0.66 \pm 0.27 PW$, in GLORYS2V3 it is $0.89 \pm 0.52 PW$, in SODA3 it is $0.81 \pm 0.52 PW$ and in ~~NEMO~~ OGCM hindcast is $1.05 \pm 0.21 PW$. This means that all chosen products underestimate the mean OMET at 26.5°N in the Atlantic basin. Of all products, ORAS4 has the largest bias. The std of OMET given by ORAS4 is the same as that from RAPID ARRAY, while both in GLORYS2V3 and SODA3 we find a higher std of OMET. The ~~NEMO~~ OGCM hindcast has a relatively small OMET std of 0.21 PW. In terms of the correlation and standard deviation, ORAS4 and the ~~NEMO~~ OGCM hindcast agree well with observations. It is noteworthy that NEMO does not assimilate ocean data. The simulation is only constrained by the surface fluxes. To conclude, the heat transport at 26.5°N is too low in these products.

Moreover, the comparison of time series in the chosen reanalyses and OSNAP observations is given in Figure 7. Due to the limited length of the OMET time series, only ORAS4 and SODA3 are included in the comparison. It can be noticed that the OMET given by ORAS4 is quite comparable to that in OSNAP in terms of the amplitude and variations. For most of the time within the observation period, OMET in ORAS4 falls into the range of the OSNAP observation including the uncertainty margins. The mean of OMET in ORAS4 is $0.39 \pm 0.11 PW$, which is quite similar to the mean OMET $0.45 \pm 0.07 PW$ of OSNAP. However, OMET in SODA3 has a larger mean and standard deviation than the OMET in OSNAP and thus deviates from the observation.

Just as in the atmosphere we would like to study the temperature and meridional current velocity contributions to the ocean heat transport to identify the sources of the difference between products. However, due to the nature of curvilinear grid, the comparison of local fields after interpolation is not trustworthy. To get further insight, we calculate the ocean heat content (OHC), since the convergence of the heat transports are likely related to OHC change. A full budget analysis was not feasible as most datasets did not include the surface fluxes. Figure 8 illustrates the OHC (Figure 8a) and the OHC anomalies (Figure 8b) quantified from ORAS4, GLORYS2V3, SODA3 and the ~~NEMO ORCA~~ OGCM hindcast. It depicts the OHC integrated in the polar cap (from 60°N to ~~70°N~~ 90°N) over all depths. The mean OHC in ORAS4 is ~~$6.85 \pm 0.45 * 10^{22} J$~~ $4.48 \pm 0.78 * 10^{22} J$, in GLORYS2V3 is ~~$6.19 \pm 0.40 * 10^{22} J$ and in the NEMO hindcast is $6.89 \pm 0.39 * 10^{22} J$, while SODA3~~ $4.23 \pm 0.59 * 10^{22} J$ and in SODA3 is $3.79 \pm 0.93 * 10^{22} J$, while the OGCM hindcast shows a much ~~smaller~~ larger mean OHC of ~~$4.51 \pm 0.40 * 10^{22} J$~~ $7.85 \pm 0.58 * 10^{2}$

The variations are ~~very~~ similar between chosen products. Regarding the OHC anomalies in Figure 8b, a positive trend of OHC anomalies in the polar cap is captured by each product. However, the variations are different and these are reflected in the standard deviation of OHC anomalies time series. Qualitatively, the variations of OHC in the chosen reanalyses at polar cap can be taken as a sign of AA but a quantitative evaluation of AA is not possible due to large differences between products. To conclude, for the OHC there are large difference between chosen products while their variations agree very well. Since OHC is a function of temperature fields only, this can imply that temperature profiles are different among all the chosen ocean reanalyses ~~datasets. ORAS4 and the NEMO hindcast~~ data sets. The chosen reanalyses data sets agree well. The differences of OHC between chosen products are partially consistent with the differences that we found for OMET. However, the OHC anomalies agree better with each other than the absolute OHC, which indicates that the trend of OHC is captured in a similar way among all the ocean reanalyses products.

3.3 MET and the Arctic

In previous sections it is found that MET of different reanalyses products at subpolar and subtropical latitudes differ substantially from each other. In order to further evaluate AMET and OMET given by different reanalyses and provide more insight, we investigate the links between MET and remote regions. We focus on the Arctic because previous studies indicate a strong role for subpolar MET in low frequency variability in the Arctic region. Given the complexity of the interaction between MET and the Arctic and the short time series available, determining cause-effect relations is out of scope for this paper. That is, we aim to compare the relation between MET and the Arctic within each reanalysis product to investigate the physical plausibility and compare it with previous studies that use data from one reanalysis product or from coupled climate models (e.g. Graversen (2006); Van der Swaluw et al. (2007); Graversen et al. (2008); Jungclaus and Koenigk (2010); Kapsch et al. (2013)).

Many of these studies perform linear regressions between a time series of MET and gridpoint values of other physical variables. Here we follow the same procedure and perform linear regressions of ~~multiple fields~~ sea level pressure (SLP), 2 meter temperature (T2M) and sea ice concentration (SIC) anomalies on AMET and OMET anomalies at 60°N for all the chosen products. We show linear regressions ~~including all calendar months in order to compare directly to previous studies with models and reanalysis data~~in summer and winter separately in order to account for the seasonal variability. We do note that correlations ~~can be~~ are higher when focusing on a particular season ~~.~~ than a whole year. It should also be noted that there are strong trends in OMET, T2M and SIC. We removed them by applying a polynomial fit to the time series on each grid point. We find that the second order polynomial fit is able to capture the trend without losing variations at interannual time scales. Hereafter we only address detrended OMET, T2M and SIC. For the sake of consistency, the regressions are carried out on the surface fields included in each respective reanalyses product. For instance, the regression of SLP on AMET estimated from ERA-Interim, involves SLP fields from ERA-Interim itself. For the ocean reanalyses, as they all apply forcing derived from ERA-Interim, the regressions are performed on the fields from ERA-Interim. Note that there is a known issue with the quality of sea ice field close to the north pole in ERA-Interim, which can be inferred from an evaluation of reanalyses data sets concerning near surface fields in Lindsay et al. (2014). Following the regressions performed ~~on SLP~~ by Van der Swaluw et al. (2007) and Jungclaus and Koenigk (2010), we repeated the same procedure here with AMET at ~~annual scale~~interannual scales.

The regression of SLP on AMET First we investigate the links between MET and the Arctic in winter. The regressions of anomalies of multiple fields on AMET anomalies at 60°N in each atmospheric product is in winter are shown in Figure ??. 9. The regression coefficients reach maximum when the regressions are instantaneous with given fields. In ERA-Interim and JRA55, AMET is anticorrelated correlated with SLP over the Greenland, the North Atlantic, the Barents Sea, the Kara Sea and the northern part of Eurasian continent. It suggests that an increase in subpolar AMET is linked to a northward advection over the North Atlantic Greenland which can bring relatively warm and humid air into the Arctic. Such pattern is patterns are consistent with the relatively warm air over the Greenland Seas and part of the Central Arctic close to the Eurasian side shown in Figure ??a. This figure shows the regression of 2 meter temperature (T2M) on AMET in ERA-Interim9d and f. Using ERA-40, Graversen (2006) found similar correlation between AMET and surface air temperature (SAT) at the Greenland Sea and Barents Sea as Figure 9d and f, without time lag. This is also consistent with a model study by Jungclaus and Koenigk (2010). The reducing of sea ice concentration with increasing AMET at the Baffin Bay and the northern part of Barents Sea given by Figure 9g and i is consistent with the relations between AMET and T2M. A further eddy decomposition of AMET following the method from Peixoto and Oort (1992) indicates that heat transported by standing eddies has the biggest contribution to the total AMET (no not shown), which is consistent with Graversen and Burtu (2016).

These patterns are found only in ERA-Interim and JRA55, but not in MERRA2. Given the difference in AMET amongst products, MERRA2 and JRA55 provide provides an entirely different story about AMET and the statistical relation with subpolar and Arctic atmospheric circulation. Hence, there is also large uncertainty in the assertion that heat and humidity transport by stationary eddies contribute to the changes in the subpolar and Arctic regions at annual to interannual scale. interannual time scales.

Using ERA-40, Graversen (2006) found similar correlation between AMET and surface air temperature (SAT) at the Greenland Sea and Barents Sea as Figure ??a, without time lag. This is also consistent with a model study by Jungclaus and Koenigk (2010) . Nevertheless, these patterns are found only in ERA-Interim, but not in the other reanalysis.

Moreover, similar to Van der Swaluw et al. (2007) and Jungclaus and Koenigk (2010), we investigate the link links between the variability of OMET and variations of sea ice multiple fields at interannual (∼ 5 year) time scales. Unlike atmospheric fields, there are strong trends in OMET and Sea Ice Concentration (SIC). We removed them by applying a polynomial fit to the time series on each grid point. We find that the second order polynomial fit is able to capture the trend without losing variations at annual scale, for both the OMET and SIC. Hereafter we only address detrended OMET and SIC. The regressions of detrended SIC anomalies anomalies of multiple fields on detrended OMET anomalies at 60°N for all seasons in winter are shown in Figure ??. The anticorrelation between SIC and OMET can be identified in the Greenland Sea, the Barents Sea, the Kara Sea and the East Siberian Sea within ORAS4 (Figure ??a) and 10 with OMET leading by 1 month. The regression coefficients are maximal when the OMET leads by 1 month. In ORAS4 and SODA3(Figure ??c), increasing OMET can lead to a decrease in SLP in the Arctic, while in ORAS4 this polar-low is much stronger. This indicates that an increase in OMET is related to warm and humid air transport over the North Atlantic. Such patterns explain the correlation between OMET and T2M at the Greenland Sea and Barents Sea in Figure 10d and f, as well as the anticorrelation between OMET and SIC in the same regions in Figure 10g and i. Meanwhile, GLORYS2V3 tells an entirely different story. This is mainly due to the difference between OMET in this dataset compared to the other ocean ~~datasets~~ data sets during the 1990s as shown in Figure 4.

In general, reduction of OMET leads to an increase in the growth rate of SIC, which is consistent with studies performed with global climate models at decadal to inter-decadal time scales (e.g. Van der Swaluw et al. (2007); Jungclaus and Koenigk (2010); van der Linden et al. (2016)). Studies with observations of sea ice at the Barents Sea and OMET across Barents Sea Opening (BSO) also confirm the strong correlation between the OMET and sea ice variation over the Barents Sea (Årthun et al., 2012; Onarheim et al., 2015). ~~Note~~ However, note that some discussed regions are below the significance of 95%.

In summer, the situation becomes more intricate and unclear. The instantaneous regressions of anomalies of multiple fields on AMET anomalies at 60°N in each atmospheric product in summer are shown in Figure 11. A high pressure center in the central Arctic is linked to an increase in AMET in all products. However, large differences are found in the relations between AMET and T2M and SIC. Strong positive correlations between AMET and T2M are found over the Greenland in both ERA-Interim and JRA55, but not in MERRA2. However, anticorrelations between AMET and T2M are observed at the Barents Sea and the Kara Sea in ERA-Interim and MERRA2, but not in JRA55. Links between AMET and SIC differ much between chosen products, they are consistent with relations between AMET and T2M in each individual product, through. Consequently, the consistency between surface fields and AMET between chosen products in summer is even worse compared to winter. Given the differences between chosen reanalyses and relatively low statistical significance, it is quite difficult to make inference about the relation between AMET and T2M and SIC in summer.

It can be noticed that the consistency of associations between AMET and multiple fields is better in winter than that in summer within the chosen products. Atmospheric dynamical processes are more dominant in winter, which is also reflected in large scale patterns of variability such as the AO and NAO which are more pronounced in winter than in summer (e.g. Lian and Cess (1977); Curry et al. (1995); Goosse et al. (2018)). Therefore the regressions of SLP, T2M and SIC on AMET in winter are easier to understand than those in summer.

Similar issues are found in the regressions of the same fields on OMET at 60°N in each oceanic reanalysis product in summer, which are shown in Figure 12 with OMET leads by 1 month. Regarding the relations between OMET and SLP, a dipole pattern is observed in each oceanic reanalysis dataset, but the patterns are different in ORAS4 and SODA3 compared to those in GLORYS2V3. Different relations between OMET and T2M are found among all the products. In all the chosen oceanic reanalyses data sets, SLP and T2M are weakly correlated with OMET compared to those in winter. Although strong correlations between SIC and OMET are found in each oceanic reanalysis product (Figure 12g, h and i), the patterns are not consistent among them. Note that the statistical significance in these regressions are very low.

In this section we compared the reanalysis data with findings from previous studies. We found that ERA-Interim ~~is~~ and JRA55 are most consistent with the results given by coupled numerical models in winter, while MERRA2 ~~and JRA55 do~~ does not corroborate model studies. For the ocean, results from ORAS4 and SODA3 are more consistent with literature ~~.~~ in winter. The regressions of anomalies from multiple fields on AMET and OMET anomalies in winter are easier to understand than those in summer. However, given the low statistical significance and the difference among chosen products, it is still hard to determine which atmospheric product provides a more convincing plausible interannual ~~to decadal~~ variations in AMET.

4 Discussion

In this study we found substantial differences between reanalyses products. In order to improve the accuracy of variability of AMET and OMET estimated from reanalyses, one needs more observations to constrain the models. Vertical profiles differ substantially between products and surface and top of the atmosphere radiation budget are too uncertain to constrain variability in the different products. Climate models already provide information on the interaction between atmosphere and ocean and connections provided by the energy transport from mid to high latitudes (Shaffrey and Sutton, 2006; Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010). This can potentially sketch the mechanism of the interaction between energy transport and the Arctic climate change. Moreover, some studies point out that the latent heat is more influential on the Arctic sea ice rather than the dry static energy (Kapsch et al., 2013; Graversen and Burtu, 2016). With improved reanalyses products and independent observations, such as ocean mooring arrays and atmospheric in-situ and remote observations, to validate the reanalyses, the validity of these mechanisms can be further studied.

The regression of SIC on OMET suggests that sea ice variation is sensitive to changes of meridional energy transport at subpolar latitudes, which is noticed by other studies on SIC and MET as well (Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010; van der Linden et al., 2016). ORAS4 and SODA3 show a large anticorrelation between SIC and OMET in winter around Greenland Sea and Barents Sea. However, GLORYS2V3 does not show this relation. ~~From the time series it seems that this product may have unrealistic heat transports in the first decade of the analysis~~The differences in OMET are reflected in the regressions on sea ice. The strong connection between OMET from mid-to-high latitudes and the Arctic sea ice indicates ~~a~~ an indirect link between midlatitudes and the Arctic. Many studies that explored these remote links found large scale "horseshoe" and dipole patterns over the Atlantic (Czaja and Frankignoul, 2002; Gastineau and Frankignoul, 2015; Delworth et al., 2017). However, the physical mechanism remains disputable. Overland et al. (2015) and Overland (2016) propose that the multiple linkages between the Arctic and midlatitudes are based on the amplification of existing jet stream wave patterns, which might also be driven by ~~the~~ tropical and midlatitudes SST anomalies (Screen and Francis, 2016; Svendsen et al., 2018). Cohen et al. (2014) lists possible pathways for the teleconnection between the Arctic and midlatitudes, including changes in storm tracks, the jet stream, and planetary waves and their associated energy propagation. However, due to the shortness of time series, a small signal-to-noise ratio, uncertain external forcing, and the internal atmospheric variability (Overland, 2016; Barnes and Screen, 2015), this question has no easy answer.

Previous studies have shown that the variations of total OMET are very sensitive to the changes of its overturning component (e.g. McCarthy et al. (2015); Lozier et al. (2019)). Hence, AMOC can serve as a indicator of the changes of OMET. In our case, a quantitative estimation of the difference in AMOC among the chosen datasets is beyond our scope. However, the downward trend of AMOC, which has been reported by several studies (Smeed et al., 2014; McCarthy et al., 2015; Oltmanns et al., 2018), is consistent the downward trend observed in OMET at 60°N in our chosen oceanic reanalyses (see Figure 4). After visiting six oceanic reanalyses ~~datasets~~data sets, Karspeck et al. (2017) find the reanalyses products are ~~less~~ not consistent in their year-to-year AMOC variations. The discrepancy between AMOC represented by each reanalyses product may explain the difference in OMET in each ~~reanalyses~~ reanalysis dataset.

5 Conclusions

This study aimed to quantify and inter-compare AMET and OMET variability from 3 atmospheric and 3 oceanic reanalyses datasets data sets at subpolar latitudes. It also serves to illustrate the relation between AMET and OMET with high latitude climate characteristics. The study is motivated by previous studies with coupled models that show a strong relation between meridional energy transport and sea ice. It is also motivated by previous studies with reanalyses reanalysis data, where generally only one reanalyses reanalysis data set is considered, and which includes mostly only oceanic or atmospheric analysis.

All selected datasets data sets agree on the mean AMET and OMET in the Northern Hemisphere. The results are consistent with those achieved over the previous 20 years (Trenberth and Caron, 2001; Fasullo and Trenberth, 2008; Mayer and Haimberger, 2012). However, when it comes to anomalies at annual and interannual time scales they differ from each other, both spatially and temporally. Although there is overlap of observational data assimilated by different reanalyses products, large deviations still exist in main fields, especially for the vertical profiles of temperature and velocity in atmospheric reanalyses. Some reanalyses quality reports (Simmons et al., 2014, 2017; Uotila et al., 2018) have raised warnings for the use of certain variables from reanalyses. A further investigation of the relations between multiple fields in the Arctic and meridional energy transport shows that the Arctic climate is sensitive to the variations of AMET and OMET in winter. The patterns in ERA-Interim and JRA55 are more consistent in winter. For the ocean, ORAS4 and SODA3 provide similar patterns in winter. Based on our results, it seems that AMET and OMET cannot be constrained by the available observations. The reanalyses datasets data sets are not designed for the studies on energy transport, specifically. The existence of sources and sinks at each grid point, which is the mass residual of the entire column of air or water due to the data assimilation scheme or regridding, cannot be avoided and in reanalyses data sets introduces large uncertainties in the computations computation of energy transport (Trenberth, 1991; Trenberth and Solomon, 1994). As a consequence, much care should be taken when adopting the reanalyses for investigations on energy balance and energy transport related issues, especially for the ones aiming at relatively large time scales.

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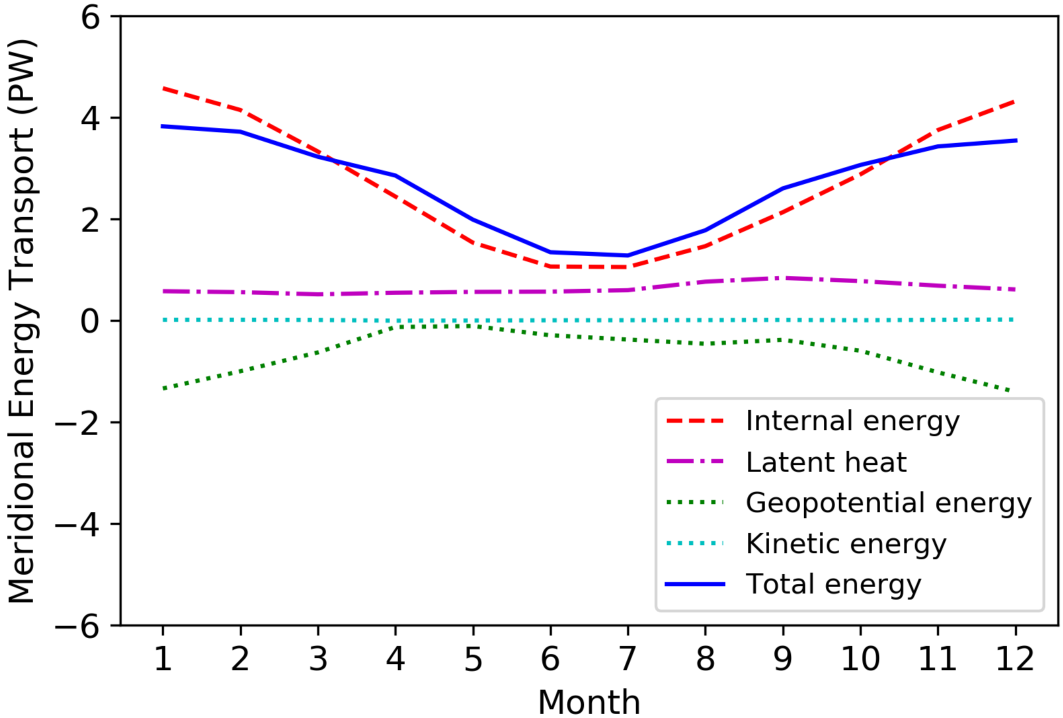

Figure 1. Estimation of mean AMET and each component in each month at 60°N with ERA-Interim from 1979 to ~~2016.~~ 2017. The unit is Peta Watt (PW).

Table 1. Basic specification of reanalyses products included in this study

Type	Product Name	Producer	Period	Temporal Resolution	Spatial Resolution / Grid
	ERA-Interim	ECMWF	1979 - ~~2016~~ 2017	6-hourly	TL255, L60 up to 0.1 hPa
Atmosphere	MERRA2	NASA	1980 - ~~2016~~ 2017	3-hourly	0.5° x 0.625°, L72 up to 0.01 hPa
	JRA55	JMA	1979 - ~~2015~~ 2016	6-hourly	TL319, L60 up to 0.1hPa
	ORAS4	ECMWF	1979 - ~~2014~~ 2016	Monthly	ORCA1
Ocean	GLORYS2V3	Mercator-Ocean	1993 - 2014	Monthly	ORCA025
	SODA3	Univ. of Maryland	1980 - 2014	5-daily	MOM5

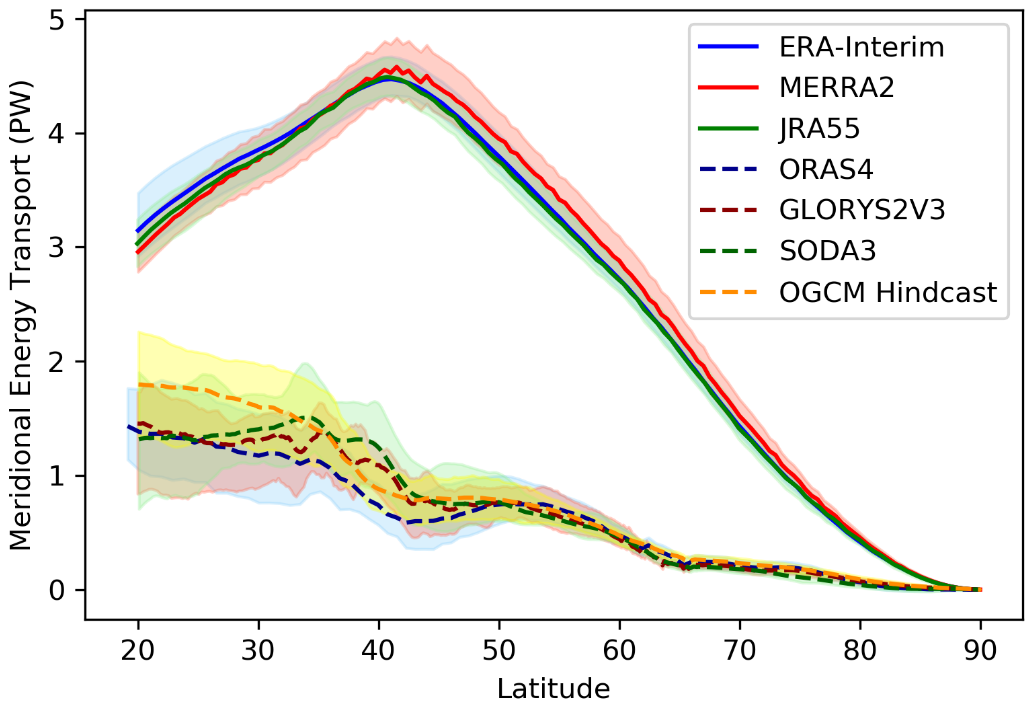

Figure 2. Mean AMET and OMET over the entire time span of each product as function of latitude in the Northern Hemisphere. AMET are illustrated with solid lines while OMET with dash lines. The ~~shaded regions~~ shades represent the full range of MET across the entire time series at each latitude. The time span of each product used in this study is given in Table 1.

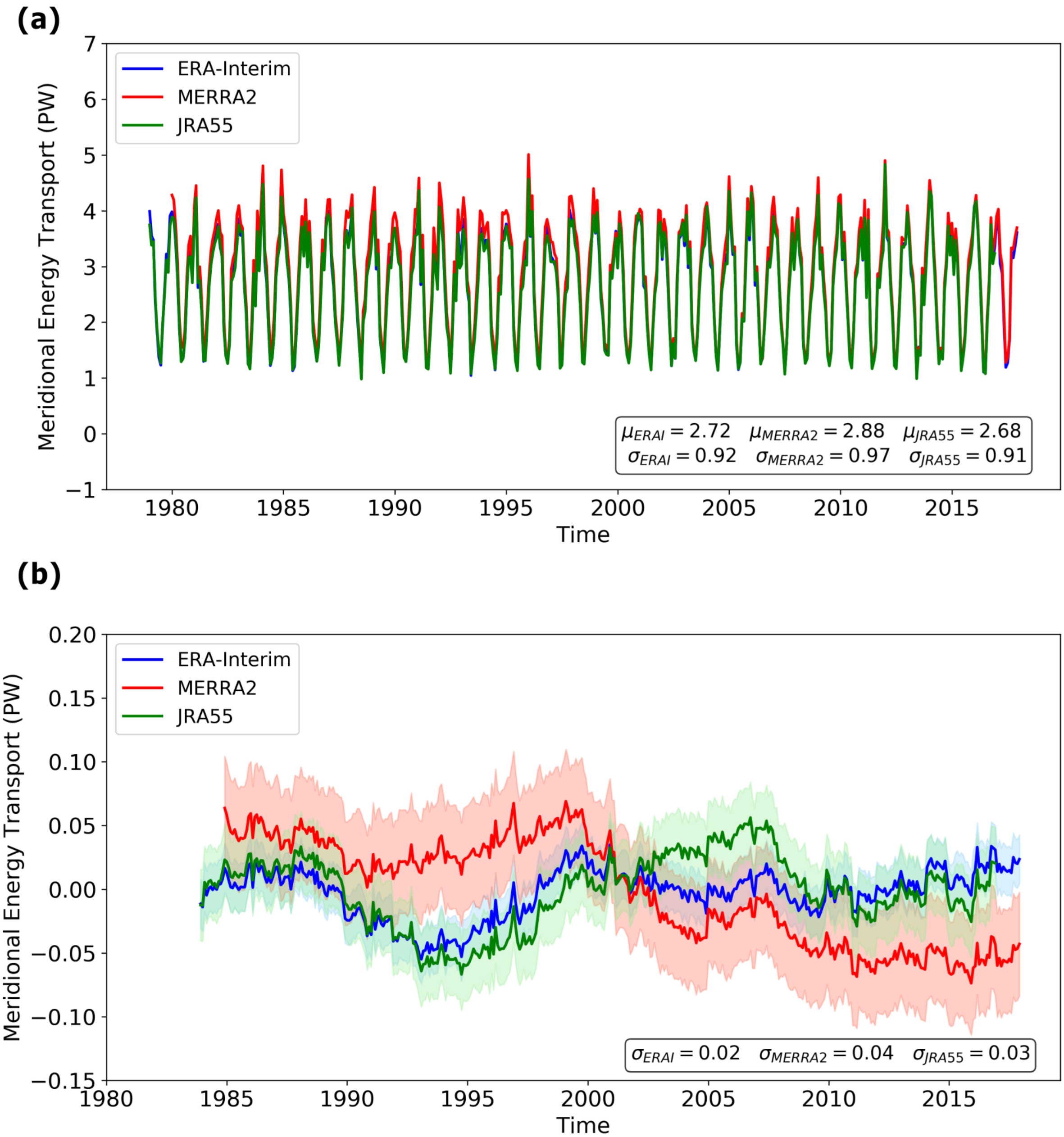

Figure 3. Time series of zonal integral of AMET at 60°N without/with low pass filter. (a) The original time series ~~(top)~~ and (b) the ones with low pass filter ~~(bottom)~~ include signals from ERA-Interim (blue), MERRA2 (red) and JRA55 (green). For the low pass filtered ones, we take a running mean of 5 years. The shades represent the confidence intervals with one standard deviation. σ is the standard deviation and μ is the mean of the entire time series. ~~"ERA-Interim res" refers to the AMET calculated as the residual between net radiation flux at top of the atmosphere and net surface flux, which is only for reference.~~

~~Monthly mean of OMET in January 1996 from three ocean reanalyses products (a) ORAS4 (b) GLORYS2V3 and (c) SODA3.~~

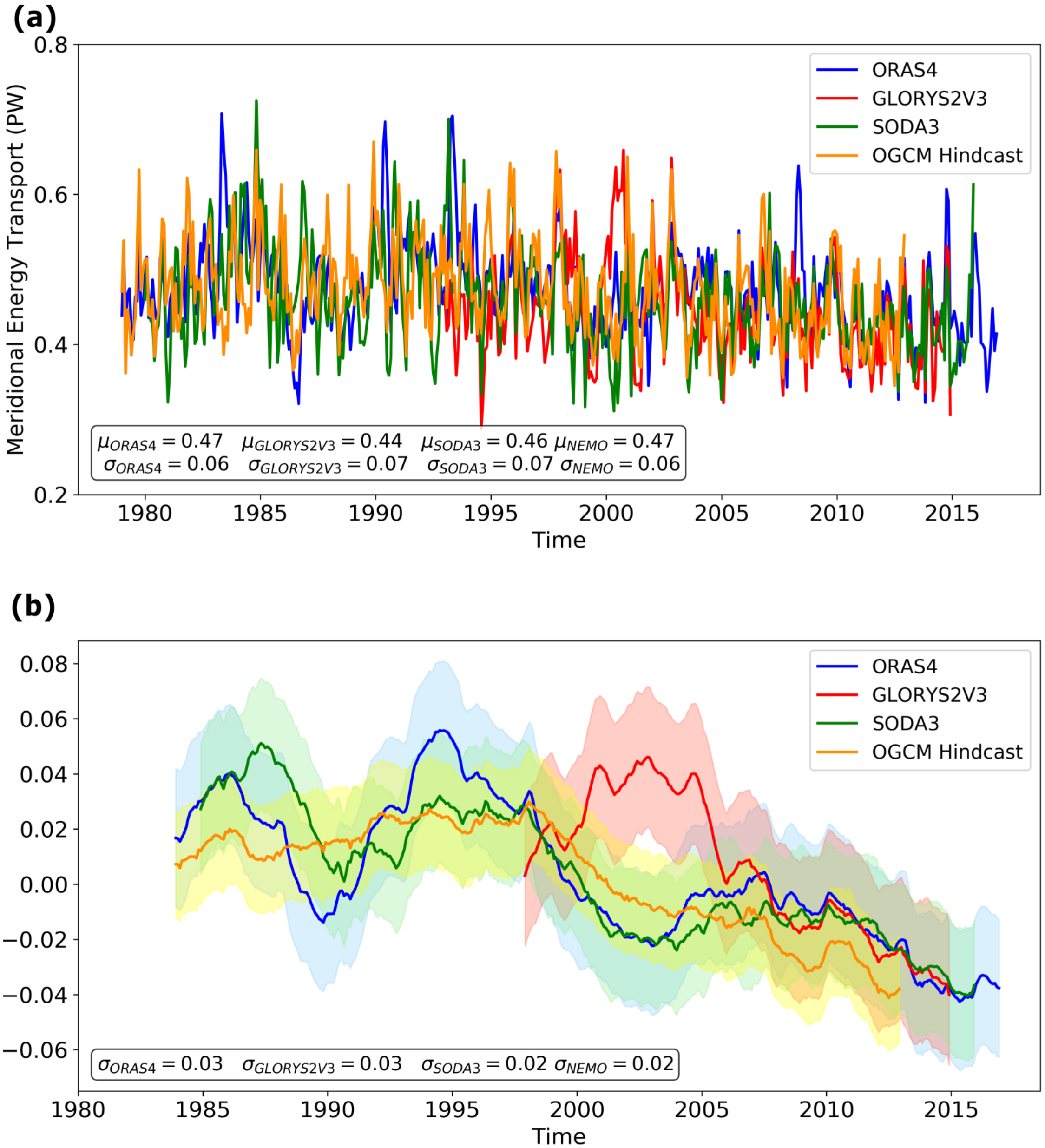

Figure 4. Time series of zonal integral of OMET at 60°N without/with low pass filter. (a) The original time series ~~(top)~~ and (b) the ones with low pass filter ~~(bottom)~~ include signals from ORAS4 (blue), GLORYS2v3 (red)~~and~~ , SODA3 (green) and the OGCM hindcast (yellow). For the low pass filtered ones, we take a running mean of 5 years. The shades represent the confidence intervals with one standard deviation. σ is the standard deviation and μ is the mean of the entire time series.

Difference in total AMET and each component between ERA-Interim, MERRA2 and JRA55 at 60°N in the same period. (a) The deviation between ERA-Interim and MERRA2, as well as (b) the deviation between ERA-Interim and JRA55, are defined as the component-wise subtraction. The unit is Peta Watt (PW).

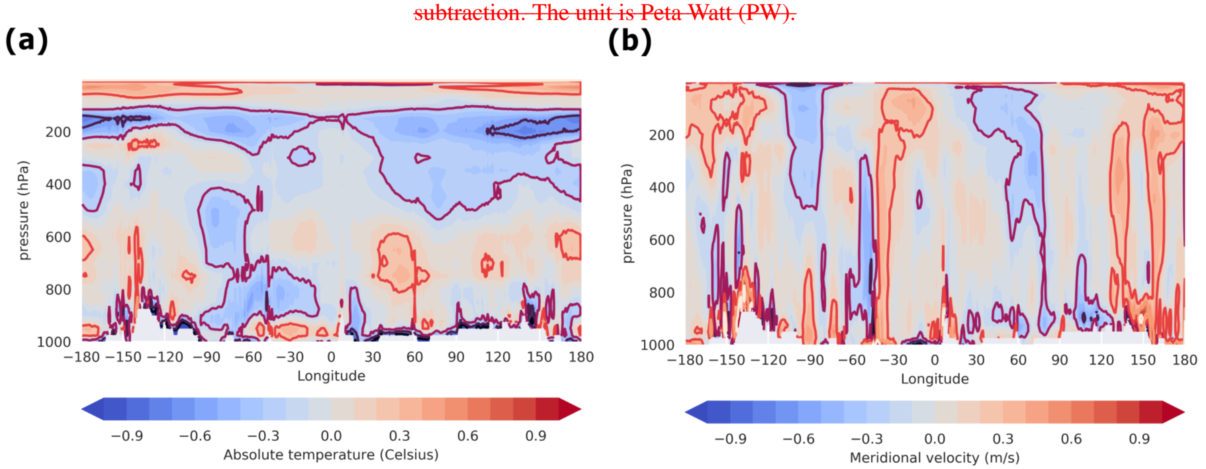

Figure 5. Difference in temperature, meridional wind velocity and temperature transport between MERRA2 and ERA-Interim at 60°N. The vertical profile of (a) temperature difference and (b) meridional wind velocity difference are calculated from the climatology of each fields from 1994 to 1998, respectively.The contributions to the total difference in temperature transport by the difference in (c) meridional wind velocity and (d) temperature between MERRA2 and ERA-Interim, are calculated as $T_{mean} \cdot (v_{erai} - v_{merra2})$ and $v_{mean} \cdot (T_{erai} - T_{merra2})$.

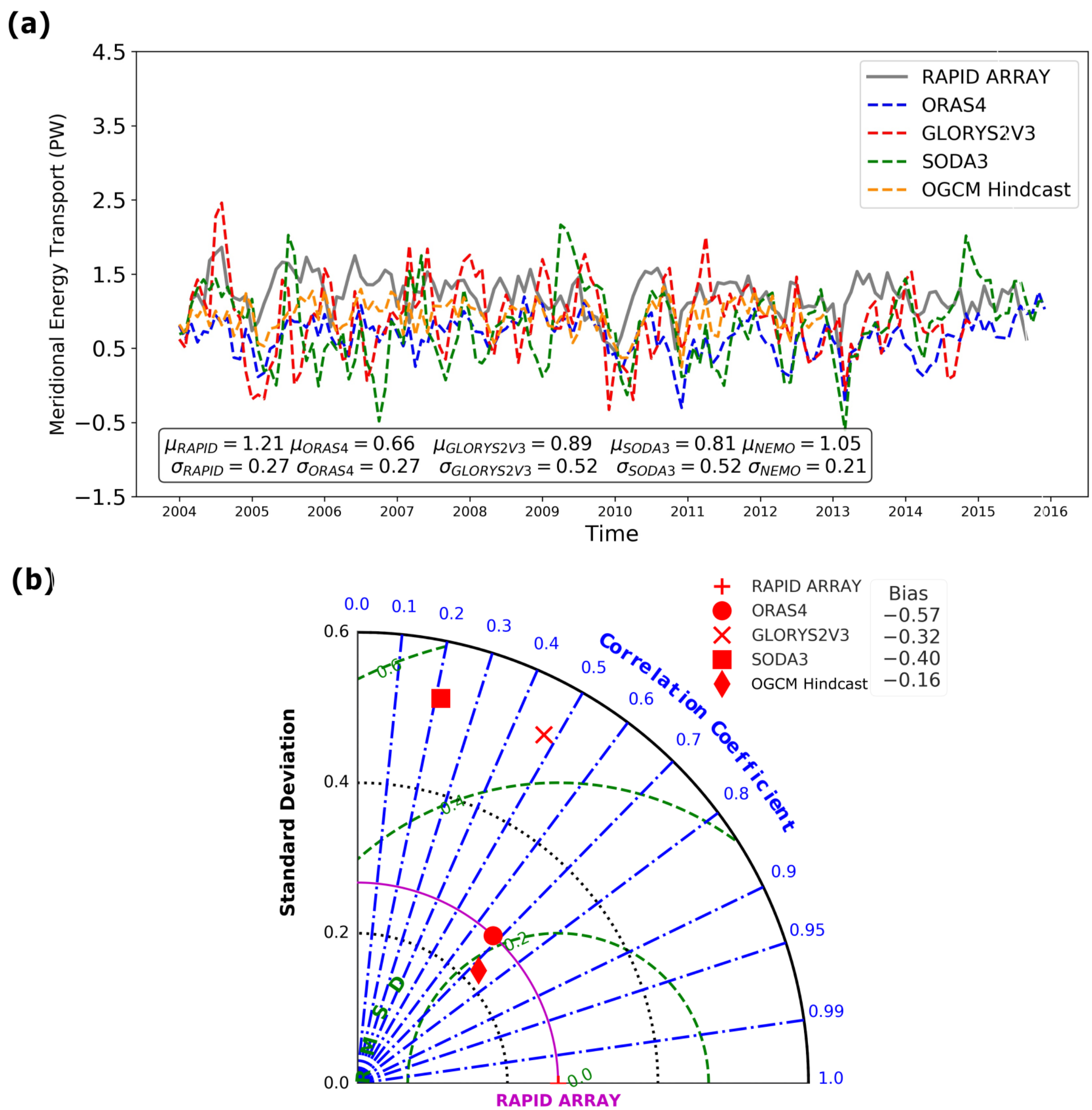

Figure 6. OMET estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the ~~NEMO ORCA0083~~ OGCM hindcast (orange) compared to the RAPID ARRAY observation (gray) at 26.5°N across the Atlantic basin. The time series of OMET is presented in (a). The statistical properties are shown in (b) Taylor Diagram, including bias, correlation (blue), standard deviation (black) and root mean square deviation (green). σ is the standard deviation and μ is the mean of the entire time series.

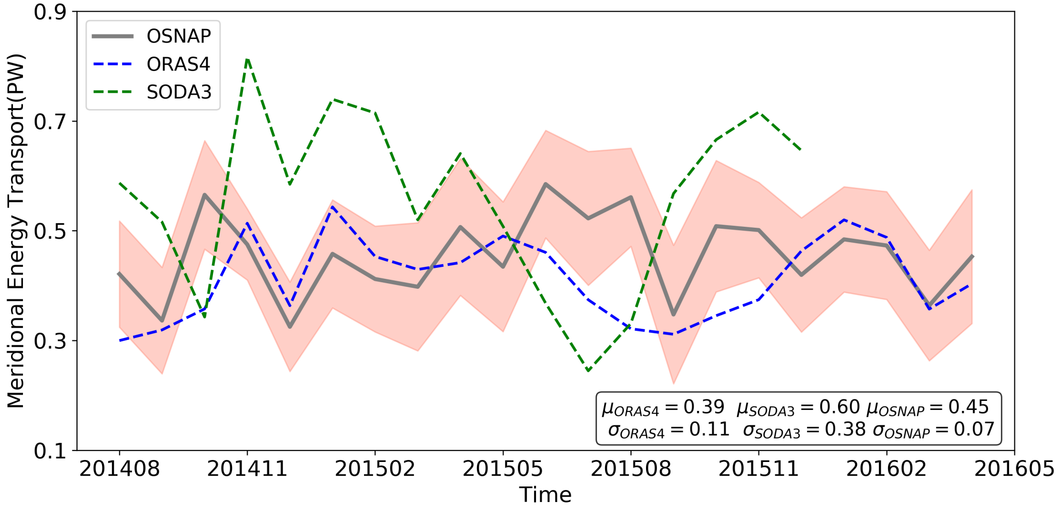

Figure 7. OMET estimated from ORAS4 (blue), SODA3 (green) and compared to the OSNAP observation (gray) at subpolar Atlantic basin. The range of uncertainty from OSNAP observation is marked by the red shade. σ is the standard deviation and μ is the mean of the entire time series.

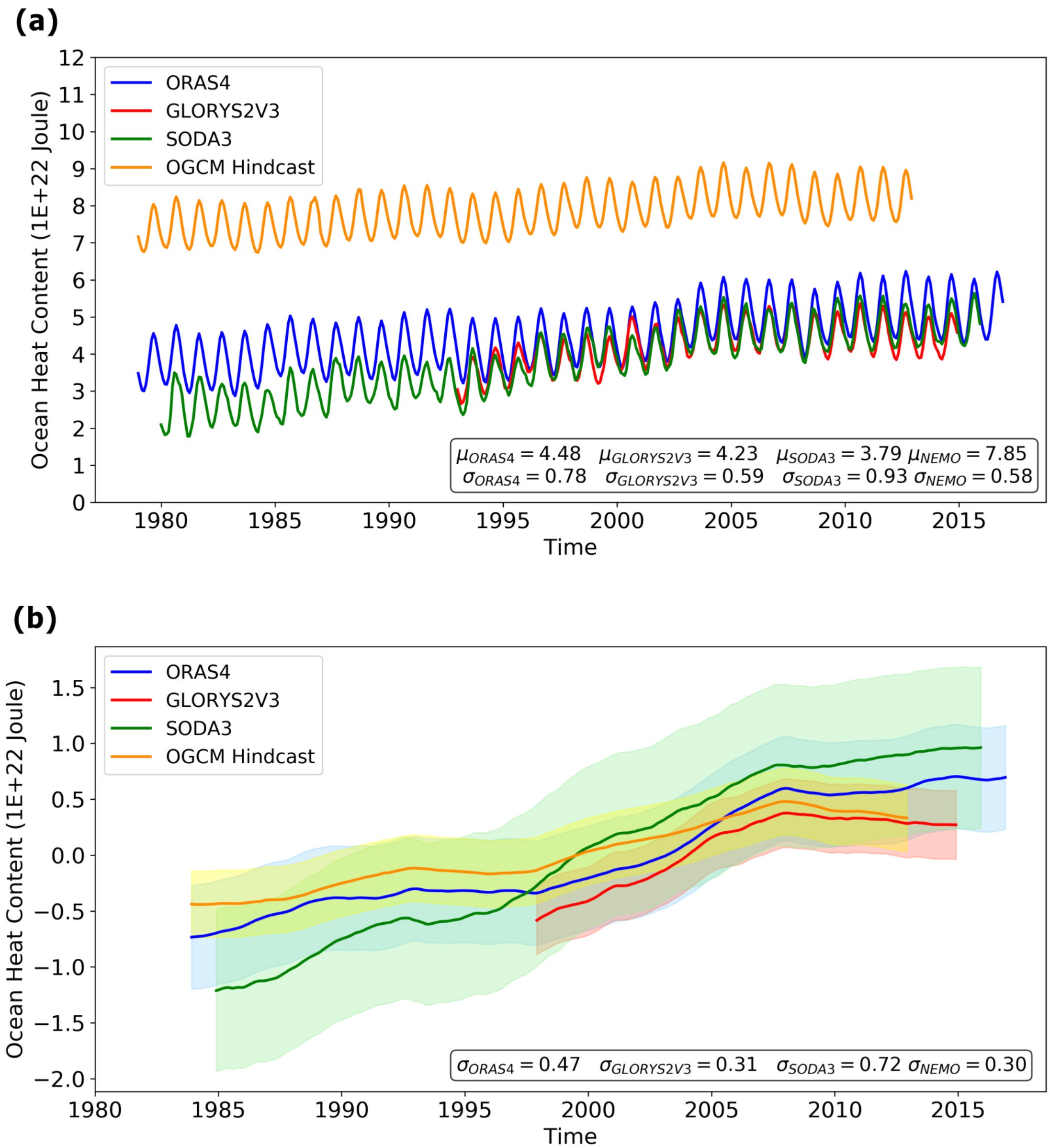

Figure 8. Time series of (a) ocean heat content (OHC) and (b) OHC anomalies with a low pass filter at ~~60°N~~the polar cap. The OHC is ~~the integral~~ integrated from surface to the bottom between 60°N and ~~70°~~90°N. It is estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the ~~NEMO ORCA~~ OGCM hindcast (yellow). The shades represent the confidence intervals with one standard deviation. σ is the standard deviation and μ is the mean of the entire time series.

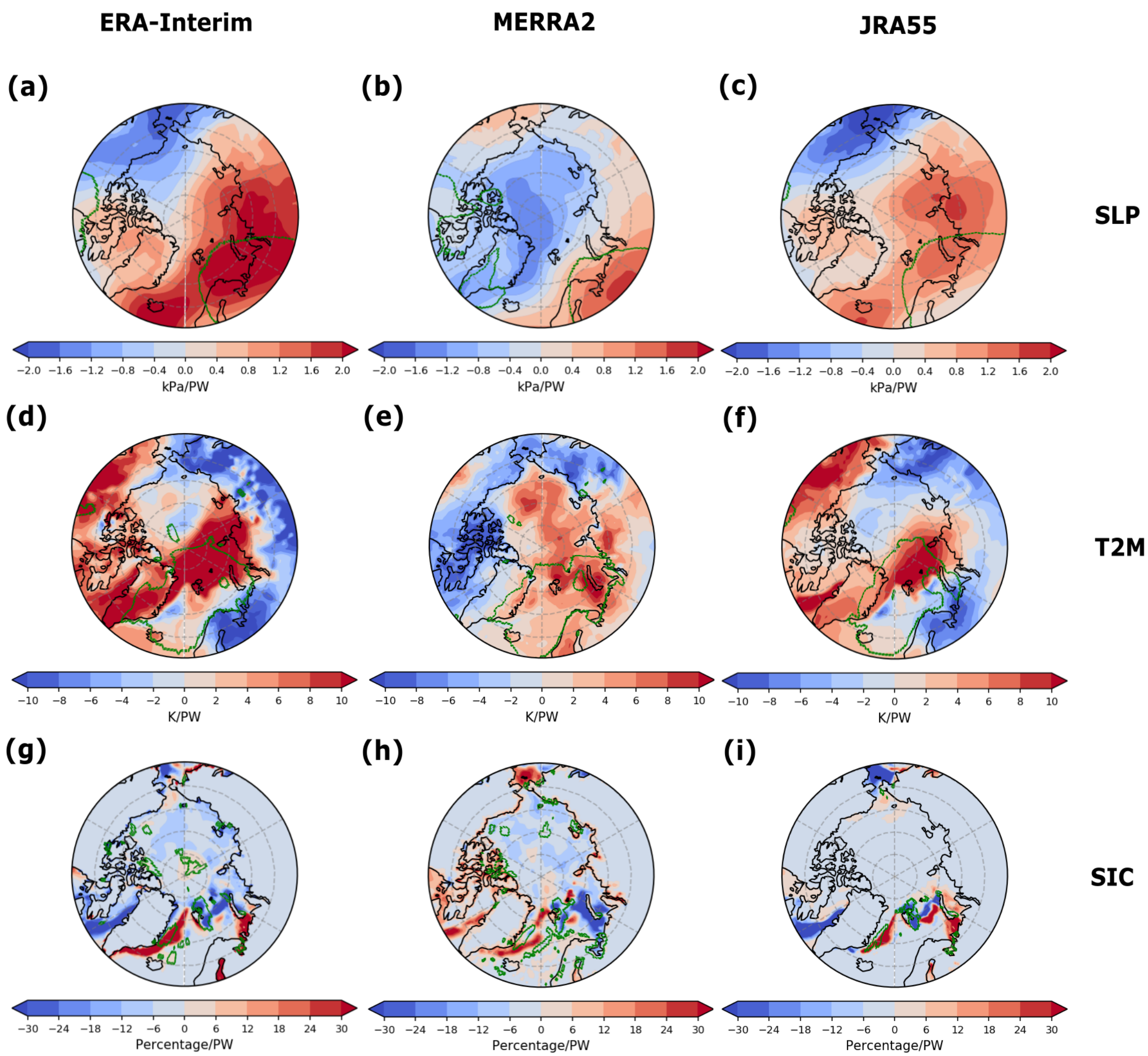

Figure 9. ~~Regression~~ Regressions of sea level pressure~~(SLP)~~ , 2 meter temperature and sea ice concentration anomalies on AMET anomalies at 60°N in winter (DJF) at ~~annual scale~~ interannual time scales with no time lag. ~~All seasons are included.~~ The monthly mean fields are used here after taking a running mean of ~~1~~ 5 year. Both the 2 meter temperature and sea ice concentration are detrended. From left to right, they are the ~~regression of SLP~~ regressions on AMET of (a, d, g) ERA-Interim, (b, e, h) MERRA2 and (c, f, i) JRA55. The green ~~shades~~ contour lines indicate a significance level of 95%.

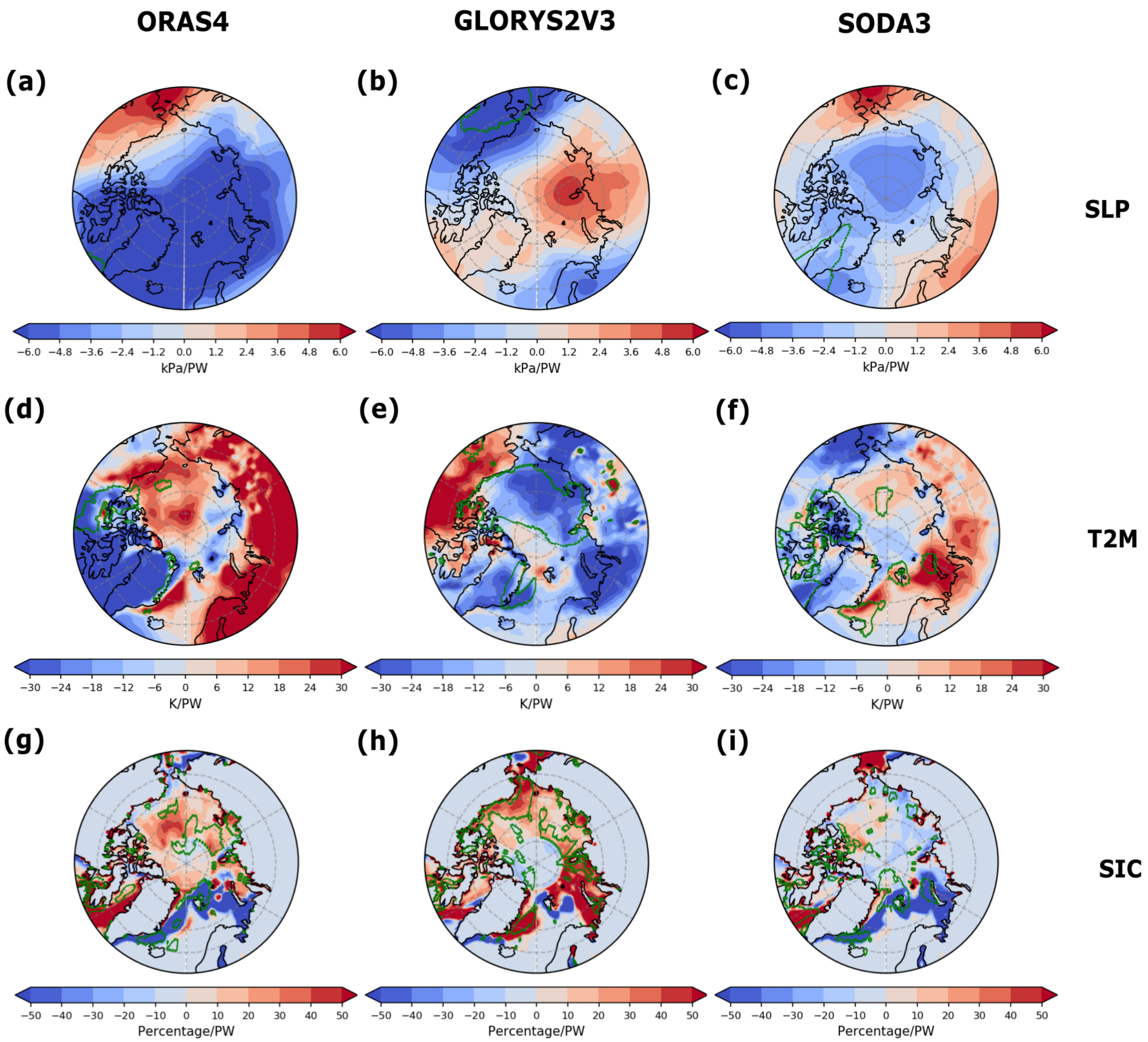

Figure 10. ~~Regression~~ Regressions of sea level pressure, 2 meter temperature ~~(T2M)~~ and sea ice concentration anomalies on ~~AMET~~ OMET anomalies at 60°N in winter (DJF) at interannual ~~scale with no~~ time ~~lag~~scales. ~~All seasons are included~~OMET leads the fields by one month. The ~~monthly mean fields~~ 2 meter temperature, sea ice concentration and OMET are ~~used here after taking a running mean of 5 years~~detrended. From left to right, they are the ~~regression of T2M~~ regressions on ~~AMET~~ OMET of (a, d, g) ~~ERA-Interim~~ORAS4, (b, e, h) ~~MERRA2~~ GLORYS2V3 and (c, f, i) ~~JRA55~~SODA3. The green ~~shades~~ contour lines indicate a significance level of 95%.

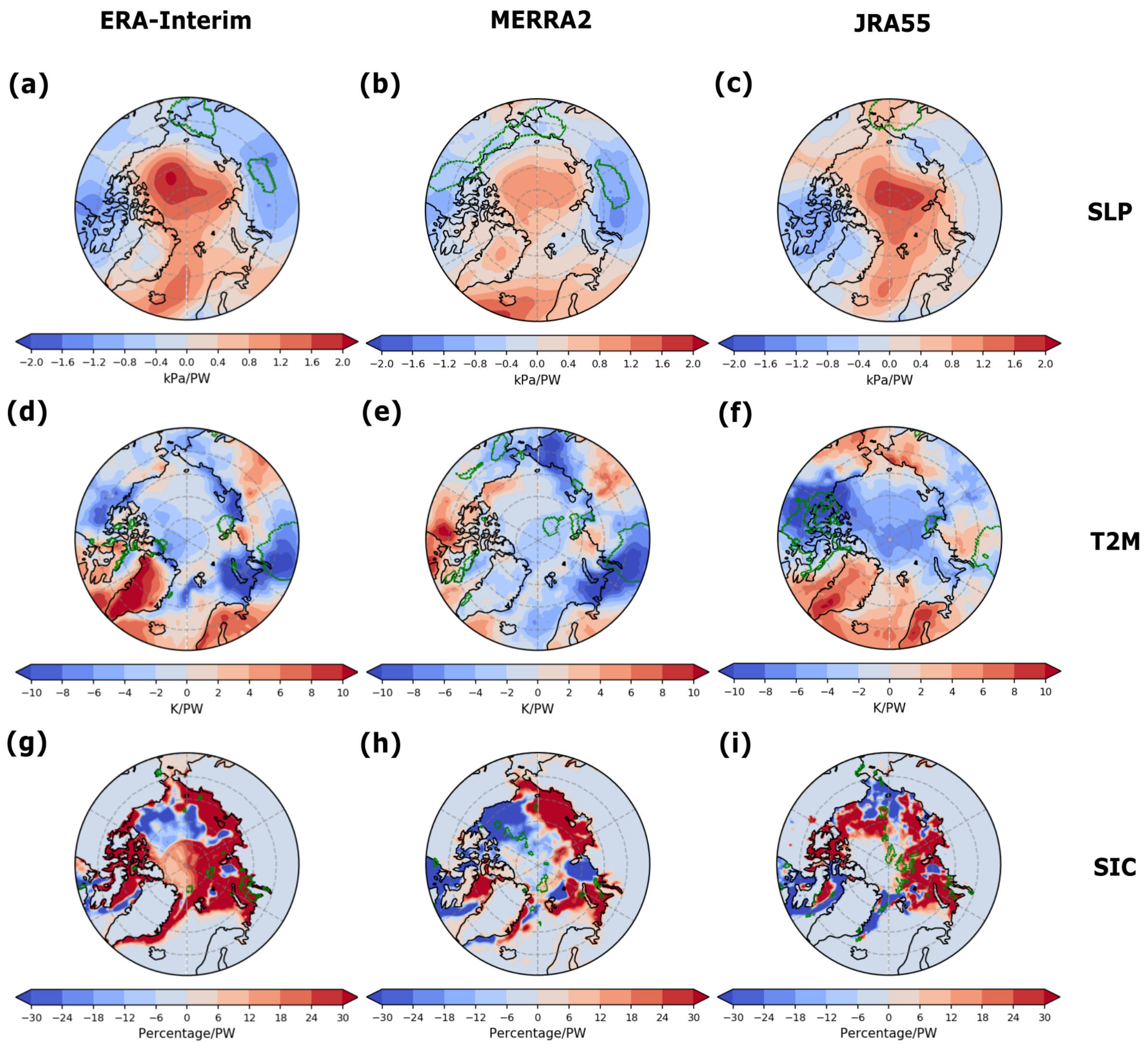

Figure 11. ~~Regression~~ Regressions of sea level pressure, 2 meter temperature and sea ice concentration ~~(SIC)~~ anomalies on ~~OMET~~ AMET anomalies at 60°N ~~for all seasons~~ in summer (JJA) at interannual ~~scale~~time scales with no time lag. ~~OMET leads the SIC by one month~~The monthly mean fields are used here after taking a running mean of 5 year. Both the ~~SIC~~ 2 meter temperature and ~~OMET~~ sea ice concentration are detrended. From left to right, they are the ~~regression of SIC~~ regressions on ~~OMET~~ AMET of (a, d, g) ~~ORAS4~~ERA-Interim, (b, e, h) ~~GLORYS2V3~~ MERRA2 and (c, f, i) ~~SODA3~~JRA55. The green ~~shades~~ contour lines indicate a significance level of 95%.

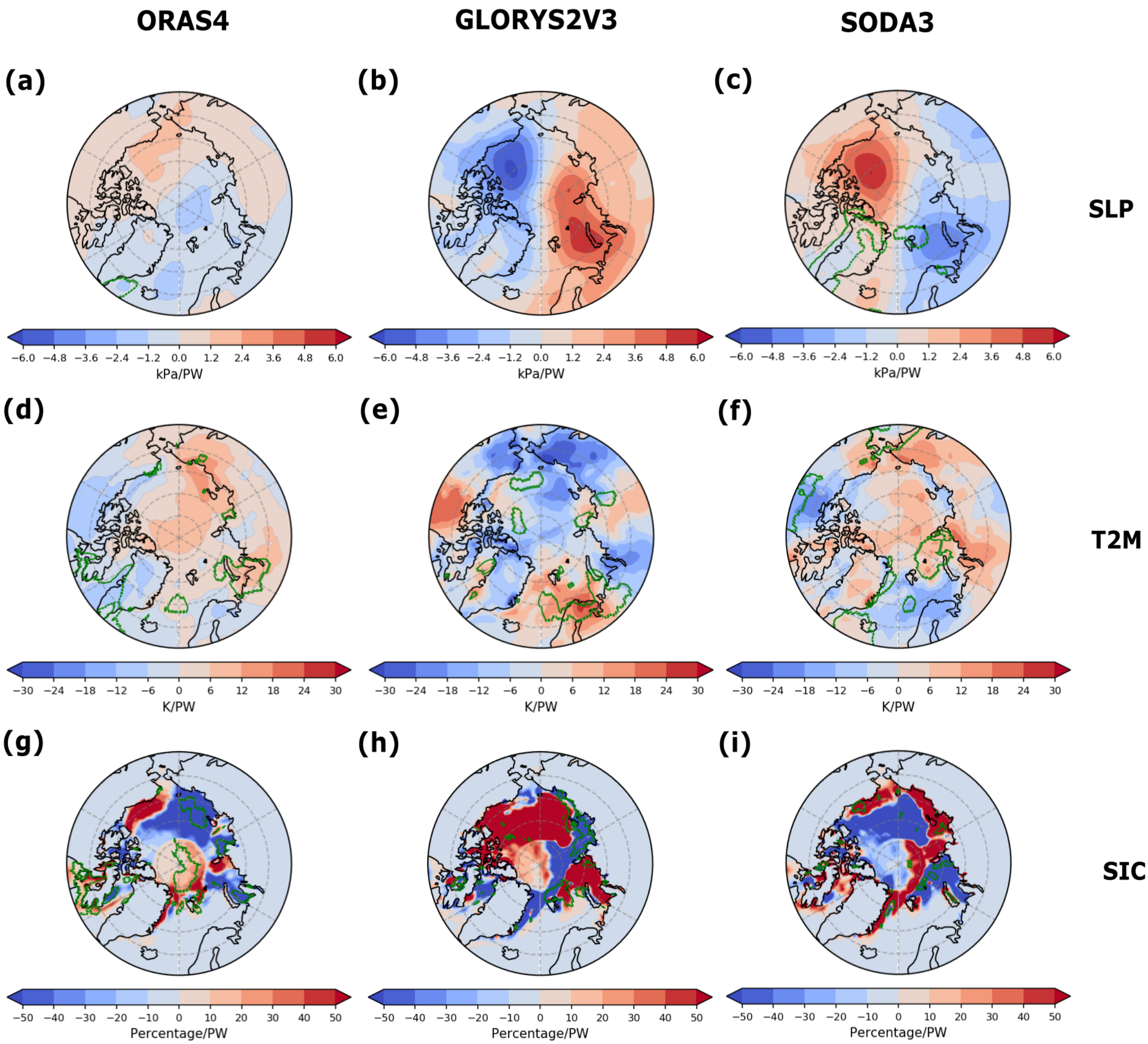

Figure 12. Regressions of sea level pressure, 2 meter temperature and sea ice concentration anomalies on OMET anomalies at 60°N in summer (JJA) at interannual time scales. OMET leads the fields by one month. The 2 meter temperature, sea ice concentration and OMET are detrended. From left to right, they are the regression on OMET of (a, d, g) ORAS4, (b, e, h) GLORYS2V3 and (c, f, i) SODA3. The green contour lines indicate a significance level of 95%.