

Dear Editor Prof. Dr. Lohmann,

Many thanks for the time and the effort you put on processing and reviewing our paper. We have revised our manuscript based on the remarks from two anonymous reviewers. The main changes are to add more details based on the major comments in the manuscript and to edit the whole manuscript for language.

Again, we would like to thank you for reviewing our work and contacting 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

Response to reviewer #1,

We would like to thank the reviewer for reviewing our manuscript and providing many constructive comments. Similar as in previous review, we address the comments point-by-point and our response is given below. The main changes are to add more details based on the major comments in the manuscript and to edit the whole manuscript for language.

(the *original comments* are given by *Italic gray text*, and each follows our response in plain text. The page and line numbers of changes made to the text are listed below each response.)

Response to the major comments

In the conclusions, the authors recommend not using reanalyses for energy transports diagnostics. I think this statement is too general. While I agree that data assimilation systems used in reanalyses do not explicitly conserve energy, energy budget diagnostics still are a very useful method to assess the quality of the products. And indeed, some diagnostics show quite good agreement, e.g. the mean annual cycle of the atmospheric energy transports, as shown by the authors. Moreover, other studies found quite good agreement also for oceanic transports (Uotila et al. 2019; Mayer et al. 2019) or seasonal trends in the budgets (Mayer et al. 2016). For the decadal variability, it should be kept in mind that relative changes on these timescales are really small (a few percent of the total transport), which is very hard to get right given the permanently evolving observational system (in both atmosphere and ocean). So I suggest to soften the conclusions (and abstract) in that regard and say that care should be taken when doing this kind of evaluations and that robustness of results must be assessed through intercomparison (as the authors did).

We thank the reviewer for this comment and call for a more nuanced statement. We were not implying that these reanalyses were not recommended for evaluation of energy transports. We only would like to put a caveat on the low frequency signals of energy transport derived from the reanalysis data. But we do agree with the reviewer that this should be made clear in the texts.

We now updated both the abstract and the conclusion with a recommendation for using reanalyses to calculate energy transport and evaluate products, and an alert on energy transport diagnostics at large (e.g. decadal) time scales and the robustness of results.

Page 1, lines 17-22 and page 19, lines 4-9

P6L15: Attributing differences between these very different ocean products to resolution will be difficult as there are many other differences, such as in the forcing and data assimilation.

We thank the reviewer for the comment. We agree that the NEMO ORCA hindcast is different in many aspects. We didn't aim to emphasize the difference in resolution. Therefore, in this paragraph more details are provided about the NEMO ORCA hindcast. To avoid confusion, we reformulate it without saying "high resolution".

Page 6, lines 27

Section 2.3.1: The authors nicely discuss mass imbalances and how they can be corrected for. However, the authors do not describe which fields they use in practice. While earlier studies have detailed this for ERA-Interim (and JRA55 is very similar structure-wise), I am not aware of a detailed description of the

mass adjustment for MERRA2. This would certainly be of interest, given that MERRA2 is very different from the ECMWF reanalyses in many regards. Also, suboptimal implementation of the correction for MERRA2 may also explain why ERA-Interim and JRA55 results are quite similar, while MERRA2 results look different.

We would like to thank the reviewer for the comment. The fields used in practice are shown in equation (4) and (5), which are surface pressure, meridional and zonal winds, and specific humidity. We will stress this in the text.

In terms of the discretization and grid incorporated by the dynamical core, MERRA2 is very different from ERA-Interim and JRA55. The dynamical core for MERRA2 is the GEOS-5 model and it computes all fields on a cubed-sphere grid with a resolution of 50kmx50km (see their official file specification: <https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich785.pdf>). However, the data collections are saved only on the latitude-longitude grid after interpolation (source of data via GES DISC: https://disc.gsfc.nasa.gov/datasets/M2T3NVASM_5.12.4/summary?keywords=MERRA-2). Because of the interpolation, the data cannot be transferred back to the cubed-sphere grid without loss of information. Besides, vector field computations on the cubed-sphere grid are not divergence free due to the implementation of finite volume discretization methods (Putman and Lin, 2007). Therefore, we transferred MERRA2 fields to the spectral domain and performed vector field computations via spherical harmonics to minimize the loss. This might explain the difference between the results from MERRA2, ERA-Interim and JRA55. However, due to the difference in resolutions, dynamical cores and data assimilation methods, a causality cannot be determined.

Even if we would have MERRA2 data on cubed-sphere grid, there is no proper tool to perform the computation of divergence, gradient and inverse Laplacian, which are required by mass budget correction.

We added this discussion to our paper.

Page 9, lines 3-11

Reference

Putman, W. M., & Lin, S. J. (2007). Finite-volume transport on various cubed-sphere grids. *Journal of Computational Physics*, 227(1), 55-78.

P9L9: the varying sea surface height is not a strong argument against doing a barotropic mass adjustment in the ocean: most of the local sea level change is due to steric changes, rather than ocean mass changes. So ocean bottom pressure would be the appropriate quantity. Also, as I wrote in my first review, we tested these things in our own work and I can say that mass imbalances are not present in the NEMO model, i.e. the divergence of ocean currents is consistent with bottom pressure changes up to very high accuracy (see also the NEMO documentation). What you could say instead is that there is a mass imbalance (in the sense of non-vanishing lateral divergence) in the stemming from P-E and small hard-to-diagnose budget terms.

We thank the reviewer for the suggestion. We now explain it with P-E and small, but hard to diagnose budget terms.

Page 9, lines 26-27

P9L21: It is unclear to me how you do the calculation. You are writing about “integrals along the zonal direction of the native grid”. Instead, one has to perform “zig-zag” line integrals (including zonal and meridional transports to close the line) on the native grid in order to get transports across a circle of latitude. Can you clarify how you do these computations?

Sorry for the unclear description. Indeed, we followed a zig-zag setup to take the zonal integrals on curvilinear grid. The method is explained by Outten et al., (2018) in their Figure 2. We updated the text and include this reference.

Page 10, lines 8-10

Reference

Outten, S., I. Esau, and O. H. Ottera°, 2018: Bjerknes compensation in the cmip5 climate models. *Journal of Climate*, 31 (21), 8745–8760.

P9L23: Use of monthly ocean data for computation of transports is particularly problematic in regions with eddy activity. The authors could use SODA3 data (from which they do have daily data) to estimate the error of neglecting sub-monthly variability as a function of latitude.

We would like to thank the reviewer for the comment. We agree with the reviewer that monthly data is problematic for eddies. In this case, ORAS4 and GLORYS2V3 are monthly data, while SODA3 is 5 daily averaged. This combination already provides some insight into the contribution from eddy transports. It would be nice to have either daily data or monthly data with SODA3 to gain more knowledge about the contribution from eddies. However, for SODA3, only 5 daily data is available on model (original) grid. Daily data is not available. Monthly data has been interpolated to latitude-longitude grid, thus it cannot be used for comparison. (see the link here for the access to SODA3 data with surface forcing coming from ERA-Interim https://www.atmos.umd.edu/~ocean/index_files/soda3.4.1_mn_download.htm). Therefore, we cannot check the sub-monthly variability of energy transport within the same reanalysis dataset.

Section 3.3: Many results in this section obviously are not robust at all. While it is of value to point this out, I do not think it makes sense to discuss them too much in detail. There is too much discussion of things that may be spurious. Also, I am unsure whether it is meaningful to regress pan-arctic atmospheric fields onto OMET, where OMET leads by one month. How would OMET impact SLP one month later? It may make more sense to, e.g., regress OMET with SLP at zero lag, as surface winds drive ocean surface currents. The reverse impact of OMET on SLP is probably much weaker.

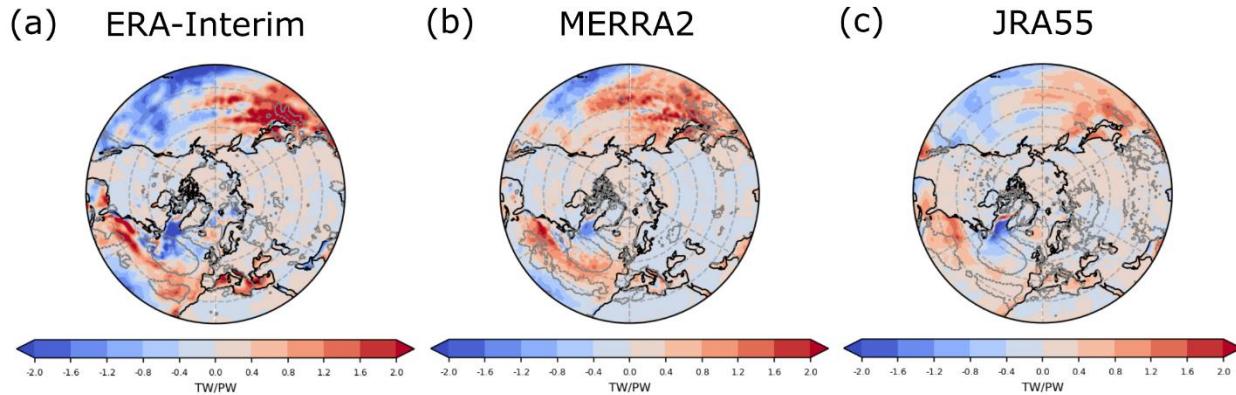
We thank the reviewer for the comment. The extended analysis in section 3.3 is requested by reviewer #2. It helps to investigate the physical plausibility by comparing the relation between MET and the Arctic within each reanalysis product. But we do agree with the reviewer that most of the results are not robust. Therefore we emphasized that we aim to study physical plausibility of fields associated with OMET variations. Indeed, numerical model studies indicate such relationships.

We now move the summer regressions to the supplementary material and reduce the length of the discussion.

Regarding the reviewers' questions about regressions of SLP on OMET, those are not entirely about the wind-driven effect. It seems that the ocean could affect atmospheric fields thermodynamically via OMET

convergence \rightarrow net surface flux \rightarrow SLP (no causality proved), which could explain the time lag. We noticed that the regression coefficients peak when the ocean leads by one month, for both the regressions of net surface fluxes (see figures below) and SLP on OMET.

Section 3.3 from page 14-17

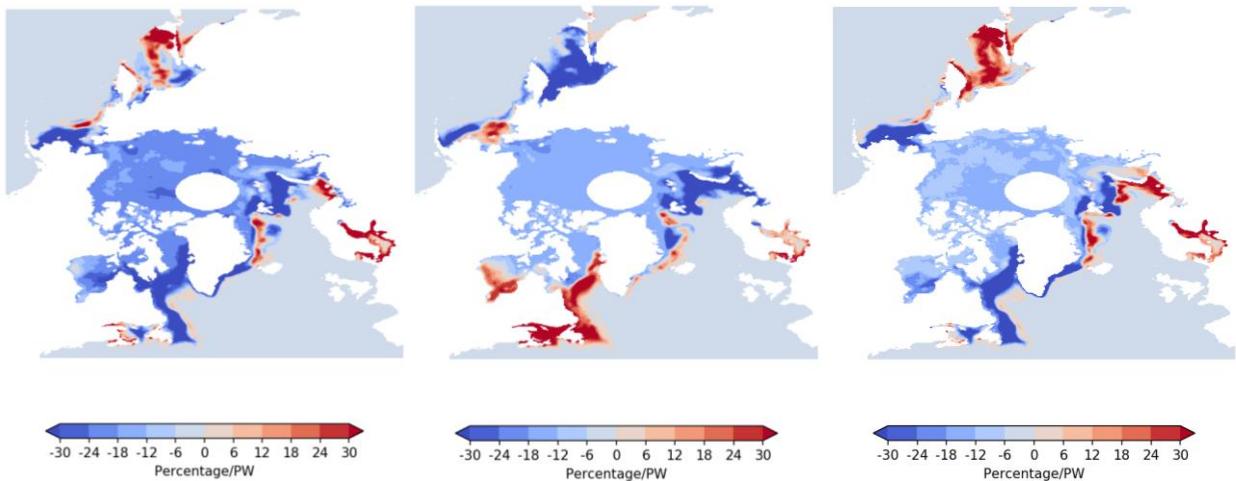


Regression of net surface fluxes on OMET at 60N at interannual scale in winter with ocean leading by 1 month.

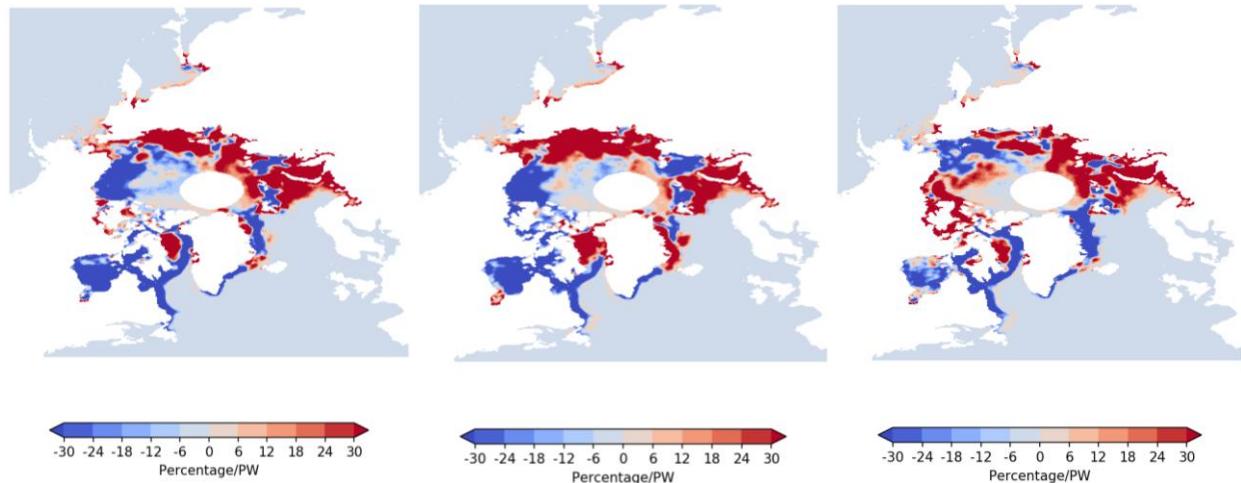
I also have to come back to the use of sea ice data. I would at least recommend to perform all computations against an “independent” satellite products, to check how robust the results are. It is not necessary to show extra figures, but it should be checked.

We thank the reviewer for the comment. We performed the same regressions with AMET and OMET at 60N on NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (Version 3, <https://nsidc.org/data/G02202/versions/3>). The results are very similar to our results with sea ice from reanalyses. For consistency, the regressions on AMET are shown below.

From left to right (ERA-Interim, MERRA2 and JRA55)



Regression of NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration on AMET in winter (DJF).



Regression of NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration on AMET in summer (JJA).

Response to the minor comments

P1L6: 2010 is inconsistent with Fig 4b and P11L32, which indicates good agreement from ~2007 onward
Corrected.

Page 1, line 6

P1L11: “among all the chosen” sounds a bit bold given that you only use 3 atmospheric reanalyses.
Better to remove “all”.

Deleted.

Page 1, line 9-10

P2L27: remove “of” before “OHC”

Corrected.

Page 3, line 5

P2L30: insert “the” before “understanding”

Corrected.

Page 3, line 9

P3L8: Why “ARRAY” in capital letters? It is not an acronym, so I would recommend “array”.

Corrected.

P4L3: "higher" (than what?) -> "high"

It is "high" here.

Page 4, line 13

P4L3: *I disagree with "due to the need". Budget diagnostics are certainly not the main reason for having reanalyses with high resolution. In fact it is the other way round: they have high resolution and thus "enable" energy budget diagnostics*

Sorry for the confusion. Here we mean "due to our needs for energy budget diagnostics". We now reformulate it.

Page 4, line 13-14

P4L4: "It is preferable..." This statement is obvious and can be removed.

Deleted.

P4L16: "generates data using 4D-Var assimilation" -> "generates atmospheric state estimates using 4D-Var data assimilation"

Updated.

Page 4, line 26

P4L20: Could add that this data comes on a 256x512 gaussian grid

We added it.

Page 5, line 1

P4L26: add "Incremental Analysis Update (IAU)" before "assimilation"

We added it.

Page 6, line 8

P4L27: preceding -> predecessor

We think the reviewer mean Line 17. Corrected.

Page 4, line 27

P5L2: insert „the“ before „Japan“

Corrected.

Page 5, line 13

P5L4: "assimilated observations" -> "assimilated upper air observations"

It is "assimilated upper air observations" here.

Page 5, lines 15-16

P5L5: "level" -> "grid"

Corrected.

Page 5, line 17

P5L15: "at" -> "in the"

Corrected.

Page 5, line 27

P5L16: The last sentence contradicts the statement above that high temporal resolution is needed for the presented diagnostics

ORAS4 has only monthly resolution but it is good in many other aspects. We think our description is ok.

P5L21: approximate -> approximately

Corrected.

Page 5, line 2

P5L27: What does "mainly" mean here?

Because part of their work was done in TAMU, and many other joint organizations (e.g. NOAA/GFDL, NOAA/NESDIS, etc.). See <https://www.atmos.umd.edu/~ocean/>

P6L9: remove "of" after "comprises"

Corrected. Sorry for the typo.

Page 6, line 21

P6L18: remove "climatological"

This is the description from paper Moat et al., (2016). It is better to keep it.

Reference

Moat, B. I., Josey, S. A., Sinha, B., Blaker, A. T., Smeed, D. A., McCarthy, G. D., ... & Duchez, A. (2016). Major variations in subtropical North Atlantic heat transport at short (5 day) timescales and their causes. *Journal of Geophysical Research: Oceans*, 121(5), 3237-3249.

P7 equation 1: "internal energy" is $c_v T$, NOT $c_p T$

C_p and C_v are Specific heat capacity for constant pressure and volume, respectively. We now use c_v for the internal energy then.

Page 7, line 13

P7L9: Lv should be higher, something like $2.5e6$

We thank the reviewer for the comment. We took the value from Datt 2014.

Reference

Datt, P. (2011). Latent heat of vaporization/condensation. *Encyclopedia of snow, ice and glaciers*, 703-703.

P8 equations 4 and 5: add a dot after the nabla operator

Corrected.

Equation 4 and 5

P9L1: I would prefer to have K instead of °C in the units

°C is used by oceanographers in many literature (e.g. Warren, 1999). The chosen reanalyses also provide potential temperature fields (°C) rather than absolute temperature (K). To be consistent, we think it is better to use °C.

Reference

Warren, B. A. (1999). Approximating the energy transport across oceanic sections. *Journal of Geophysical Research: Oceans*, 104(C4), 7915-7919.

P9L6: maybe better "difference" instead of "residual"

Corrected.

Page 9, line 23

P9L14: I presume this is because recirculation is cancelled out?

Agree, quite likely to be, but not proved.

P9L26: insert "to" before "compare"

Corrected

Page 10, line 16

P10L1: delete "simply"

Deleted.

Page 10, line 20.

P10L7: Is this just a convoluted way of saying that autocorrelation is taken into account?

We changed it.

Page 10, line 20-25

P10L8: I suggest adding "relatively" before short

Corrected.

Page 10, line 23

P10L15: What is meant by "from 1 to 5"? Is it 1 or 5 or something in between?

Sorry for the confusion. It is exactly 5 years running after revision. We corrected it.

Page 10, line 30

P10L19: This is still inaccurate. There is a transport from regions with positive net TOA radiation to regions with negative net TOA radiation.

Sorry for the confusion. It is corrected now.

Page 11, lines 3-4

P11L4: ERA-Interim and JRA55 agree quite well, actually. How about the correlation coefficient?

The correlation coefficient is 0.82 (while between ERA-Interim and MERRA2 is -0.53). We will add it to the text.

Page 11, lines 18-21

P11L13: Shouldn't the ocean currents be implicitly affected by this?

Yes, they should. This is requested by Reviewer #2.

P11L20: This is just a suspicion. How can you be sure about this statement?

We only know that the other two models are eddy-permitting with high spatial resolution. But we don't know if they can produce realistic patterns. We agree with the reviewer and we reformulated the sentence "...which might represent more realistic patterns....".

Page 12, lines 1-2

P12L6: I think you mean "correlation"

Yes, we do. We reformulate it to make it clear.

Page 12, lines 24-27

P12L7: please provide the value

It is 0.21 and the value is given there.

Page 12, line 27

P12L11: neglectable -> small

Corrected.

Page 12, line 29

P12L11: over -> of

Corrected.

Page 12, line 30

P12L11: rest of the paragraph is hard to understand, e.g. what is meant by "This is generally the case"?

Sorry for the confusion. We add more details this paragraph.

Page 12, lines 30-35 and page 13, lines 1-3

P13L4: "make a priori judge" -> cannot judge a-priori

Corrected.

Page 13, line 24

P13L16: NEMO -> OGCM

Corrected.

Page 14, line 1

P13L34: can you provide these values also as a column-average temperature?

We thank the reviewer for the comment. The column-integrated OHC already implies column-averaged temperature. Since most of the oceanography literatures show OHC in Joule, for consistency, we think it suffices to just show OHC here.

P14L37 vs P14L5: aren't the statements about agreement among the products contradictory?

Sorry for the confusion. This is an editing error. We revised it again.

Page 14, lines 25-29

P23L35: I think you mean issue 2 of the ocean state report, which appeared in 2018.

We thank the reviewer for the comment. It is corrected.

Page 24, line 33

Figs 9-12: Maybe better to stipple statistically significant values. Also, have fields like SIC been detrended before performing regression?

We thank the reviewer for the suggestion. We tried stippling but it masks the color underneath. So, we switched to contour lines. All the fields have been detrended before performing regression, as mentioned in the beginning of section 3.3.

Response to the general comments

I would strongly recommend to let the manuscript check for language. There are several sentences that sound very sloppy and/or are hard to understand (e.g. P2L12, P10L10). I am not an English native speaker – so I will refrain from making suggestions.

We went over the manuscript very carefully and now the paper has been edited with great care (One of our authors is a native speaker).

There still seems to be some confusion about the spelling of reanalysis/reanalyses. In my opinion, "reanalyses" should only be used when standing alone and when plural is meant. In combination with

“dataset”, it should always be “reanalysis”, i.e. “reanalysis data set” for singular and “reanalysis data sets” for plural. Please modify accordingly.

Thanks for the explanation. We correct it.

Again, we would like to express our gratitude to the time and effort that the reviewer spent on our manuscript. We feel the manuscript has improved again!

With best regards

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

Response to reviewer #2,

We would like to thank the reviewer for reviewing our manuscript again. Similar as in previous review round, we address the comments point-by-point. The main changes are to add more details based on the major comments and to edit the whole manuscript for language. Our responses are given below:

(the *original comments* are given by *Italic gray text*, and each follows our response in plain text. The page and line numbers of changes made to the text are listed below each response.)

Response to minor comments

A list of specific comments follows, but more generally the paper needs to be edited to improve the English: it is barely understandable in places. Examples are page 11, lines 7–10, or page 10, lines 26–29.

We thank the reviewer for the check. We edited the manuscript and reformulated the sentences which would cause confusion.

– ERA-I and JRA-55 now seem very close to each other in most respects (mean, variations, regressions with surface variables...). This should be highlighted in the conclusion / abstract? Merra 2 behaves very differently, and seems still noisy: a problem remaining in the computation?

We thank the reviewer for this good question. In terms of the discretization and grid incorporated by the dynamical core, MERRA2 is very different from ERA-Interim and JRA55. The dynamical core for MERRA2 is GEOS-5 model and it computes all fields on a cubed-sphere grid with an resolution of 50kmx50km (see their official file specification:

<https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich785.pdf>). However, the data collections are saved only on the latitude-longitude grid after interpolation (source of data via GES DISC:

https://disc.gsfc.nasa.gov/datasets/M2T3NVASM_5.12.4/summary?keywords=MERRA-2). Because of the interpolation, the data cannot be transferred back to the cubed-sphere grid without loss of information. Besides, vector field computations on the cubed-sphere grid are not divergence free due to the implementation of finite volume discretization methods (Putman and Lin, 2007). Therefore, we transferred MERRA2 fields to spectral domain and performed vector field computations via spherical harmonics to minimize the loss. This might explain the difference between the results from MERRA2, ERA-Interim and JRA55. However, due to the difference in resolutions, dynamical cores and data assimilation methods, a causality cannot be determined.

Even if we would have used MERRA2 data on cubed-sphere grid, there is no proper tool to perform the computation of divergence, gradient and inverse Laplacian, which are required by mass budget correction.

We now add this explanation to our paper and highlight the similarity between ERA-I and JRA55, and the difference with MERRA2 in the abstract and conclusion.

Page 9, lines 3-11

Reference

Putman, W. M., & Lin, S. J. (2007). Finite-volume transport on various cubed-sphere grids. *Journal of Computational Physics*, 227(1), 55-78.

– page 6, line 24: the moist static energy is $H + I + gz$, not H .

Corrected.

– page 7, l9 (advection schemes): this should come later (as a potential source of errors)

We thank the reviewer for the comment. We moved this part to the section 3.2 “Source of Disparity”, to further explain the potential source of the differences.

Page 13, line 11-12

– page 9, line 7: the sentence should be “note that we have access to sub-monthly data only for SODA3. The computation of OMET in GLORYS using monthly data could miss part... eddies, while ORAS4 does not have explicit eddies (insert missing GM comment here). There is no causality between having data for SODA3 and the smoothing in GLORYS.”

We thank the reviewer for the comment. We updated the text based on your suggestion.

Page 10, line 11-14

– Figure 1/2: it would be useful to see a decomposition into components (at least dry static / latent) as a function of latitude.

We thank the reviewer for the comment. We agree with the reviewer that a decomposition into components can provide more insight into the energy transport diagnostics. But it is a bit too messy to include it in figure 2. In order to be complete, we added it in the figure 1.

– fig 3b : ERA-I and JRA55 look similar to me (at least compared to MERRA). The text should reflect that.

We thank the reviewer for the comment. It is mentioned in the result section and conclusion section. We further emphasized it now.

Page 1, lines 10-11 and Page 11, lines 22-24

– page 10, lines 10–20: it would be useful to have a figure of OMET as a function of latitude, to support the discussion in this paragraph. Also, presumably the GM transport in ORAS4 would compensate?

We thank the reviewer for the comment. OMET as a function of latitude is shown in Figure 2. We put a note there to guide our readers to figure 2. The eddy-induced velocity field was not saved by ORAS4 and therefore it misses the heat transport by parameterized by the GM parameterization.

– page 10, line 15: eddy-induced velocity contributes to the heat transport, not to the volume transport. (works like en overturning streamfunction).

We thank the reviewer for the comment. It is corrected.

Page 11, lines 29-30

– page 11, lines 20–30, and figure 5 : This discussion assumes that the differences in AMET are due to differences in the climatological–mean v or T (not knowing which), but why would this be true when the

total transport is dominated by transients ? This figure seems unnecessary as not much can be concluded from it.

We thank the reviewer for the comment. The idea originates from Figure 2, which illustrates the difference of annual mean AMET as a function of latitude between ERA-Interim and MERRA2. We would like to understand the source of the differences. We agree with the reviewer that at mid-latitudes the total energy transport is mainly eddy driven. However, given the differences in annual mean AMET, it is instructive to show the difference in mean v & T fields. So, we think this figure is informative.

– page 12, line 30– (OHC): why would polar cap OHC be a sign of Arctic Amplification (not just Arctic warming)? Note that the observed increasing trend of OHC can also be due to surface heat fluxes, indeed there is a downward trend of OMET at 60° over the same period...

We thank the reviewer for the comment. Increases in surface temperature and OHC are often taken as a sign of AA in many peer reviewed papers (e.g. Serreze and Barry 2011). But we do agree with the reviewer that it might be just Arctic warming and not necessarily a higher warming rate than the global mean temperature change. Moreover, we do not aim to identify a causality here. Therefore, we reformulated it "...could be taken as a sign of AA.....".

The downward trend of OMET at 60N is likely related to the AMOC or the energy compensation between the atmosphere and ocean or a combination thereof (Smeed et al., 2014; McCarthy et al., 2015; Oltmanns et al., 2018).

Page 14, lines 20-24

Reference

McCarthy, G. D., Smeed, D. A., Johns, W. E., Frajka-Williams, E., Moat, B. I., Rayner, D., ... & Bryden, H. L. (2015). Measuring the Atlantic meridional overturning circulation at 26 N. *Progress in Oceanography*, 130, 91-111.

Oltmanns, M., Karstensen, J., & Fischer, J. (2018). Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers. *Nature Climate Change*, 8(4), 300.

Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and planetary change*, 77(1-2), 85-96.

Smeed, D. A., McCarthy, G., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., ... & Bryden, H. L. (2014). Observed decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean Science*, 10(1), 29-38.

– Section 3: the use of "interannual" is usually year-to-year variability. To use it for a 5-yr smoothing (intending ~ decadal signals) is a bit misleading.

We thank the reviewer for the comment. We agree that 'interannual' is a bit unclear. Thus, we will put a note at the beginning of section 3 "...with a low pass filter of 5 years, which is now referred to as interannual time scales for the rest of the paper".

Page 10, line 30.

– section 3 (bis): a striking point in these results is the similarity between ERA-I and JRA, and ORAS4/SODA3. For the latter, it would be good to know if it could be due to similar surface fluxes used, or to the model / data assimilation.

We thank the reviewer for the comment. Actually, for these reanalysis products, the dynamical core, data assimilation method and the data assimilated are all very different and it is very difficult to disentangle them and find causal relations. We have underlined their dynamical core, data assimilations method and surface forcing in the section 2 “Data and methodology”. It was emphasized in the text that the chosen oceanic reanalyses systems all use surface fluxes from ERA-Interim and ERA-40.

Section 2.1, pages 4-6

– page 14, lines 10–15 : Why "an increase in OMET is related to warm and humid air transport over the North Atlantic" ?? My impression on figure 10 is that an increase in OMET leads to sea-ice melt and increase in T2m around the Nordic seas. In addition, there is an AO/NAO-like SLP anomaly (that can be cause or consequence) with the associated large-scale temperature pattern (North AM–Greeland / Siberia dipole).

We thank the reviewer for the comment. Since a causal relationship was not identified, we cannot put a solid conclusion here, thus only one suggested mechanism similar to this one. We do agree with the reviewer that it is likely to be an increase in OMET and OMET convergence that leads to sea-ice melt and increase in T2m around the Nordic seas, and there is an AO/NAO-like SLP anomaly with the associated large-scale temperature pattern.

We now reformulated it carefully and only describe the patterns following the reviewer's suggestion.

Page 16, lines 7-16

Reference

Graversen, R. G.: Do changes in the midlatitude circulation have any impact on the Arctic surface air temperature trend?, *Journal of climate*, 19, 5422–5438, 2006.

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.

Graversen, R. G., & Burtu, M. (2016). Arctic amplification enhanced by latent energy transport of atmospheric planetary waves. *Quarterly Journal of the Royal Meteorological Society*, 142(698), 2046–2054.

– figure 11 : this seems broadly consistent with a colder Arctic : colder temp, more ice, high pressure. Is this causing the increase in AMET?

This could be the case. Since identifying causal relationships is not the aim of this analysis, we cannot say this for sure.

– figure 12 : In the sea ice regressions, it looks like there are sea ice trends in areas with no ice in summer... Also, values are very large, may be a scale of % per 0.01 PW would be more adapted?

We checked the regressions of sea ice, especially for the marginal sea ice covered area which could be ice free in summer. Most of the ice free regions in recent decades have sea ice in early 1990s. As the

anomalies were taken by removing the climatology and detrended, the sea ice concentration in these regions are not strictly zero.

We rescaled it by per 0.1PW. Now they look very reasonable.

Figure 10 and S2

Again, we would like to express our gratitude to the time and effort that the reviewer spent on our manuscript. We thank the reviewer for contributing to the improvement of our paper!

With best regards

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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~~reanalysis data sets. We investigate the differences between the ~~datasets~~data sets and we check the coherence between MET and the Arctic climate variability at interannual time scales. The results indicate that, although the mean ~~transport~~transports in all 5 data sets agree well, the spatial ~~distribution~~distributions and temporal variations of AMET and OMET differ substantially among the ~~reanalyses~~reanalysis data sets. For the ocean, only after ~~2010~~2007 the low frequency signals ~~for all~~in ~~reanalyses~~all ~~reanalysis~~ 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~~confirms that the OMET estimated from ~~reanalyses~~the ~~reanalysis~~ data 10 sets are consistent with ~~independent~~the observations. For the atmosphere, the ~~variations among~~reanalyses ~~data sets are large~~. ~~This can be attributed to differences in temperature transport and geopotential energy transport. A further differences between ERA-Interim and JRA55 are small, while MERRA2 differs from them. An extended~~ analysis of linkages between ~~the~~ Arctic 15 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 those from~~ coupled climate models. For the ocean, ORAS4 and SODA3 agree well on the relation between OMET and sea ice concentration 20 (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~~transports at subpolar latitudes in winter. ~~Our study suggests, since the reanalyses products are not designed for the quantification of energy transport, Given the good agreements on the diagnostics among assessed reanalysis products, our study suggests that the reanalysis products are useful for the evaluation of energy transports. However, assessments of products with the AMET and OMET estimated from reanalyses should be used~~ reanalysis data sets beyond interannual time scales should be conducted with great care and the robustness of results should be evaluated through intercomparison, especially when studying variability and interactions between the Arctic and midlatitudes~~beyond 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 the changes of weather and climate at different latitudes. The quantification quantifications of AMET and OMET has have been studied extensively. Dating back to 1970s In the 1980s, 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, 1973; Oort and Vonder Haar, 1976). After entering the satellite era, further much progress has been made in particular during the recent two data-rich decades. Using the radiation at the top of the atmosphere and the reanalyses from satellite data and the reanalysis 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) (Trenberth, 1991; Trenberth and Solomon, 1994). Fortunately, recent improvements in numerical weather prediction and ocean models, and increased data coverage of observations provide a basis to improve estimates the estimation of AMET and OMET. There is As a result of an increase of available reanalyses products, reanalysis products, an increase in resolution and length of the time span that is covered and covered time span, and an 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; It (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 reanalysis data sets. In this study, we will provide further insights into MET from midlatitudes towards the Arctic, with the state-of-the-art reanalysis products.

To support our elaboration on MET, we also study the examination of MET from midlatitudes towards the Arctic, it is worth investigating the AMET and OMET in relation to climate variability at interannual different 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) (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) (Miller et al., 2010; Serreze and Barry, 2011). In order to understand the warming, the processes processes 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) (Graversen et al., 2008; Kapsch et al., 2013; Zhang, 2015). There is a large volume of published studies describing the impact impacts 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 showed that poleward AMET is linked with the evolution of temperature in the free troposphere at decadal time scales. By separating the planetary and synoptic-scale waves, Graversen and Burtu (2016) show that the showed that 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 moisture

transport with reanalysis data and observation data, and show observations, and showed that the moisture sources for in the Arctic region is are linked with interannual fluctuations in the extent of Arctic sea ice. Nummelin et al. (2017) analyse analyzed the linkages between OMET, Ocean Heat Content (OHC) and AA through the climate model simulations within the Coupled Model Intercomparison Project Phase 5 (CMIP5). They report reported an enhancement of OMET as a result of heat loss in the 5 subpolar ocean and the contribution of OMET to the AA through the increasing of increasing OHC in the Arctic ocean. Also by analyzing CMIP5 simulations, Sandø et al. (2014) show showed a large impact of heat transport in the Barents Sea on sea ice loss. However, ocean reanalyses don't do not show a clear sign of AA in the Arctic OHC increases (Mayer et al., 2016;?) (Mayer et al., 2016; von Schuckmann et al., 2018). Consequently, increasing knowledge on poleward AMET and OMET at subpolar and polar latitudes will aid in the understanding of AA.

10 Global climate models indicate a compensation show compensations 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, 2014; some 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 transports and variations of the Arctic climate. However, these results 15 are mostly based on numerical model simulations and they tend to differ among the these models. In contrast to numerical modeling studies, here we intend to study AMET, examine AMET and OMET variability and the their relation with the Arctic in using reanalysis data sets, which are regarded as the best estimates of the historical variability.

In this paper, we quantify AMET and OMET using multiple state-of-the-art reanalyses reanalysis products. These are representations of the historical state of the atmosphere and ocean optimally combining available observations and numerical simulations 20 using data assimilation techniques. Emphasis is placed on the variation of AMET and OMET from midlatitudes to the Arctic at interannual time scales. In contrast with (~5 yr). Different from earlier studies, we will compare the different reanalyses data sets include multiple reanalysis data sets for intercomparison. Independent observations in the Atlantic from the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID ARRAY array) and the Overturning in the Subpolar North Atlantic Program (OSNAP) are included in the comparison. The RAPID ARRAY array is a trans-basin observing 25 array along 26.5° N in the Atlantic (Johns et al., 2011; McCarthy et al., 2015) (Johns et al., 2011; McCarthy et al., 2015). It operates since 2004 and provides the volume and heat transport in the Atlantic basin. OSNAP 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) (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 30 (Moat et al., 2016) is also included employed in the comparison. It will be referred as Oceanic General Circulation Model (OGCM) hindcast in this paper. Based on the intercomparison of reanalysis data, especially with the independent observation data, we will be able to identify the 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 35 studies that explain those connections with only numerical models or a single reanalysis dataset to explain those connections.

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 reanalysis data and an intercomparison of them. The correlation between the 5 variability of AMET and OMET, and the Arctic climate is elaborated upon in detail. Finally, remarks ~~constitute~~are given in Section 4 and conclusions are provided in Section 5.

2 Data and Methodology

The ~~reanalyses~~reanalysis data sets used in this study are introduced in this section. Moreover, the methodology for the quantification of AMET and OMET ~~are~~is also included in this section. The statistical tests performed in this study are elucidated 10 in detail.

2.1 Reanalyses

In order to make use of observations and advanced numerical models, six state-of-the-art ~~reanalyses~~reanalysis data sets are used in this study. The chosen ~~reanalyses~~products ~~have~~are ~~reanalysis~~products ~~have~~are a high temporal and spatial resolution~~due to the need~~thus are suitable for the computation of energy transport (see section 2.3). ~~It is preferable that they incorporate the latest numerical models and data assimilation schemes.~~ As a result, we chose three atmosphere ~~reanalyses~~reanalysis data sets: ERA-Interim, MERRA2, and JRA55 (references below) and three ocean ~~reanalyses~~reanalysis 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). 15 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~~reanalysis products contained in this study.

20

2.1.1 ERA-Interim

ERA-Interim is a global reanalysis dataset produced by the European Center for Medium Range Weather Forecasts (ECMWF) 25 (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~~atmospheric state estimates using 4D-Var ~~data~~ assimilation with a T255 (~ 79 km) horizontal resolution on 60 vertical levels (Berrisford et al., 2009). Compared with its ~~preceding~~reanalyses~~predecessor~~, 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 30 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~~ that is provided on a 256×512 Gaussian grid, with a $0.75^\circ \times 0.75^\circ$ 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, 5 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 atmospheric state estimates are~~ produced by a 3D- 10 Var [Incremental Analysis Update \(IAU\)](#) assimilation scheme and ~~has-a have~~ coverage from 1980 ~~till until~~ present. Unlike most of the ~~reanalyses reanalysis~~ products, the GEOS atmospheric model includes a finite-volume dynamical core ~~which that~~ uses a cube-sphere horizontal-discretization (Gelaro et al., 2017). The model grid has a resolution of $0.5^\circ \times 0.625^\circ$ 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 reanalysis~~ product made by [the](#) Japan Meteorological Agency (JMA) (Kobayashi et al., 2015; Harada et al., 2016). JRA55 applies 4D-Var assimilation and it is 15 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 grid~~, which has a horizontal resolution of $0.5625^\circ \times 0.5625^\circ$ with 60 hybrid model levels.

2.1.4 ORAS4

Serving as the historical reconstruction of the ocean's climate, the Ocean reanalyses System 4, in short ORAS4, is the replacement 20 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 analyses with a 3D-Var FGAT assimilation scheme and spans from 1958 to [the](#) present. ORAS4 runs on the ORCA1 grid, which is associated with a horizontal resolution of 1° in the 25 extratropics and a refined meridional resolution up to 0.3° in the tropics. It has 42 vertical levels, 18 of which are located ~~at in the~~ 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, ~~which is~~ short for GLobal Ocean reanalyses and Simulations version 3, is a global ocean and sea-ice eddy 30 permitting ~~reanalyses reanalysis system that~~ yielded from the collaboration between the Mercator Ocean, the Drakkar consor-

tium 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 approximately $0.25^\circ \times 0.25^\circ$ with 75 vertical levels). The model is forced by a combination of ERA-Interim fluxes (e.g., shortwave radiation) and turbulent fluxes obtained with bulk formulae using ERA-Interim near-surface parameters. The data is generated by a 3D-Var assimilation scheme with 5 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 10 0.25° (latitude) $\times 0.25^\circ$ (longitude) $\times 50$ levels resolution (Carton et al., 2018). To be consistent with the other two reanalyses reanalysis 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. Reanalysis data from this period on the original MOM5 grid is used in this case.

15 2.2 Oceanic Observations and OGCM Hindcast

For the purpose of independent examination of the OMET calculated from reanalyses reanalysis data sets, 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 the RAPID array, employs a transbasin 20 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 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 too short to provide a good estimate of the 25 interannual variability of OMET, we include it anyway still include it 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 NEMO ORCA hindcast is also included here to provide more insights to the analysis since two of the chosen reanalyses reanalysis products are also built on NEMO the NEMO ocean circulation model (Moat et al., 2016; 30 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 the ORCA0083 grid, which has a nominal resolution of $1/12^\circ$, on 75 vertical levels. The climatological 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).

It is forced by the surface fields ~~coming from the the procuded by the~~ Drakkar project, 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 5 from 1979 to 2012. For clarity, this hindcast will be referred to as the Oceanic General Circulation Model (OGCM) simulation in this paper.

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.

10 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:

$$\begin{aligned} I &= c_v T \\ H &= L_v q \\ \Phi &= gz \\ k &= \frac{1}{2} \mathbf{v} \cdot \mathbf{v} \end{aligned} \quad (1)$$

with c_p the specific heat capacity of dry air ~~at a constant pressure for constant volume~~ ($J/(kgK)$), T the absolute temperature (K), L_v the specific heat of condensation (J/kg), q the specific humidity kg/kg , g the gravitational acceleration ($kg/(ms^2)$), z the altitude (m) and v the zonal/meridional wind velocity (m/s). The northward propagation is positive. In addition, these 15 four quantities can be divided into three groups: the dry static energy $I + \phi$, the moist static energy ~~$H + I + \phi + H$~~ and the kinetic energy k . A constant value of $c_p = 1004.64 J/(kgK)$ and $L_v = 2264.67 KJ/kg$ ~~were was~~ used to compute the AMET with ~~all the atmosphere reanalyses the atmosphere reanalysis~~ data sets. In addition, recently ~~there are some~~ improved formulations 20 of energy budget equations proposed by Mayer et al. (2017) and Trenberth and Fasullo (2018) ~~are addressed here~~. 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):

$$25 E = \oint_{\Phi=\Phi_i p_s}^{p_t} \int [(1-q)c_p T + L_v q + gz + \frac{1}{2} \mathbf{v} \cdot \mathbf{v}] v \frac{dp}{g} dx \quad (2)$$

with c_p the specific heat capacity of dry air at constant pressure, p_t the pressure level at the top of the atmosphere (Pa) and p_s the pressure at the surface (Pa). A constant value of $c_p = 1004.64 \text{ J/(kgK)}$ was used. Since we work on the native hybrid model coordinate with each atmosphere reanalyses reanalysis product, the equation can be adjusted as follows (see Graversen (2006)):

$$5 \quad E = \oint_{\Phi=\Phi_i} \frac{1}{g} \int_0^1 [(1-q)c_p T + L_v q + gz + \frac{1}{2} \mathbf{v} \cdot \mathbf{v}] v \frac{\partial p}{\partial \eta} d\eta dx \quad (3)$$

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 meaningful energy transports obtained from reanalysis data. It has been widely reported that reanalyses reanalysis products 10 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 the original model level to pressure level can introduce considerable error errors 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 15 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:

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

Where E stands for evaporation and P denotes precipitation. It has been noticed that big uncertainties reside in the evaporation 20 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:

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

The related fields for the mass budget correction are surface pressure (p_s), meridional and zonal winds (u, v), and specific 25 humidity (q). After determining the mass budget imbalance, we correct the barotropic wind fields (u_c, v_c), with u_c and v_c indicating the correction terms for zonal and meridional wind components as a result of the barotropic mass budget correction, and then calculate AMET (Trenberth, 1991). Note that all the computations regarding barotropic barotropic mass budget correction

were performed in the spectral domain via spherical harmonics. Figure 1 shows the mean AMET and each component in each month at 60°N estimated from ERA-Interim.

It is worth mentioning that MERRA2 is very different from ERA-Interim and JRA55, in terms of the discretization method and grid incorporated by the dynamical core. The dynamical core for MERRA2 is the GEOS-5 model and it computes all fields on a cubed-sphere grid with a resolution of $50 \times 50 \text{ km}$ (Gelaro et al., 2017), while in ERA-Interim and JRA55 the computations were performed in the spectral domain. However, the data collections are saved only on the latitude-longitude grid after interpolation. Thus the data cannot be transferred back to the cubed-sphere grid without loss of information. Moreover, the vector field computations on the cubed-sphere grid are not divergence-free due to the implementation of finite volume discretization methods (Putman and Lin, 2007). Consequently, we transferred MERRA2 fields to the spectral domain and performed vector field computations via spherical harmonics to minimize the numerical errors, the same treatment as ERA-Interim and JRA55.

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):

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

where ρ_0 is the ~~sea-water~~ ~~seawater~~ density (kg/m^3), c_{p_0} is the specific heat capacity of ~~sea-water~~ ~~seawater~~ ($\text{J}/(\text{kg}^\circ\text{C})$), θ is the potential temperature ($^\circ\text{C}$), 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 $c_{p_0} = 3987 \text{ J}/(\text{kg}^\circ\text{C})$ 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 between certain latitudes can be calculated by:

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

Our computation of OMET suffers from a small mass imbalance (e.g., mass imbalance coming from the ~~residual difference~~ 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 due to the mass imbalance coming from the residual between precipitation and evaporation, and some budget terms that are hard to diagnose~~. 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). Note that the influence ~~from~~^{of} 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:

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

5 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~~^{reanalysis} 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~~^{worked} on the original multi-pole grid and ~~follow the native zonal directions when performing numerical operations, followed a zig-zag setup when taking zonal integrals. The method~~
10 ~~is illustrated by Outten et al. (2018) in their Figure 2.~~ 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~~^{The} computation of OMET using monthly data in ~~ORAS4~~ and GLORYS2V3 could miss part of ~~the~~ heat transport by eddies, ~~while ORAS4 does not include the heat transport from the eddy parameterization scheme (Gent and Mcwilliams, 1990) as the related eddy-induced velocity field was not archived.~~

15 2.4 Statistical Analysis

In order to understand the connection between MET and changes in the Arctic ~~and, and to~~ compare to the results from numerical climate models or single reanalysis dataset (~~Graversen, 2006; Van der Swaluw et al., 2007; Graversen et al., 2008; Jungclaus and Koenigk, 2010; 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~~^{use the} student’s t-test. ~~We decorrelate the monthly mean OMET anomalies after the implementation of low pass filter. This means the relevant significance tests are performed with time series after removing the autocorrelation.~~

The autocorrelations are taken into account. Note that all the ~~reanalyses~~^{reanalysis} data sets included in this study have ~~relatively~~ short time series ~~at monthly time scales~~ (no more than 456 months, see Table 1). Therefore the analysis based on ~~these 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 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 30~~^{of} 5 years, ~~which will be referred to as interannual time scales for the rest of the paper.~~

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. There are transports from regions with positive net TOA radiation to regions with negative net TOA radiation.~~ Figure 2 gives the mean of ~~shows the mean~~ AMET

5 and OMET over the entire time series of every product at each latitude in the Northern Hemisphere. For the atmosphere, all three data sets agree very well. The results differ a bit in amplitude but capture similar variations ~~along~~ ~~at~~ 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 4.45 PW at 41°N, while in MERRA2 AMET peaks at 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 10 others). ~~(e.g. Trenberth and Caron, 2001; Fasullo and Trenberth, 2008; Mayer and Haimberger, 2012, and many others).~~

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. The seasonal cycle is dominant in each component ~~as expected~~, ~~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~~ ~~reanalysis data sets~~ agrees well. However, their 15 variations differ from each other. In ERA-Interim, the standard deviation (std) of AMET is 0.92 PW, while MERRA2 has a relatively large std of 0.97 PW, and in JRA55 the std is 0.91 PW. Hence, it can be concluded that the seasonal cycles of AMET presented by the chosen atmospheric ~~reanalyses~~ ~~reanalysis datasets~~ are similar. After removing the seasonal ~~cycle~~ ~~cycles~~ and applying a 5-year low pass filter, ~~neither the amplitude nor the trend of the signals agree between the data sets~~ ~~we obtain the~~ low frequency signals of AMET anomalies at interannual time scales (see Figure 3b). ERA-Interim and JRA55 agree well, and 20 the correlation coefficient between them is 0.82. MERRA2 provides a different result, and the correlation coefficient between ERA-Interim and MERRA2 is -0.53. The std of ~~the~~ AMET anomaly in ERA-Interim is 0.02 PW, while in MERRA2 ~~it~~ ~~the~~ std is 0.04 PW and in JRA55 ~~it~~ ~~the~~ std is 0.03 PW. This implies that the ~~variations~~ ~~variations~~ of AMET anomalies ~~are different in the chosen data sets~~ ~~at large time scales are similar in ERA-Interim and JRA55, but not in MERRA2~~. We further assess the sources of the difference in the next section.

25 For the ocean, all the ~~reanalyses~~ ~~reanalysis~~ data sets agree well at almost all the latitudes, ~~except for the OMET between~~ 30°N and 40°N, where the Gulf Stream resides (Figure 2). The difference can be explained by the models. GLORYS2V3 and SODA3 both have been generated with eddy-permitting models while ORAS4 has not. 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). 30 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~~ ~~archived~~. The eddy-permitting ~~reanalyses with higher~~ ~~reanalysis data sets with high~~ resolution, like GLORYS2V3 and SODA3, are capable of addressing the large scale ~~geostrophic~~ 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). Consequently, at

the latitude of the Gulf Stream (between 30°N and 40°N), a ~~higher~~ ~~strong~~ spatial variability, which ~~represents~~ ~~might~~ represent more realistic patterns of the large scale eddy variability, is apparent in all data sets but ORAS4.

Similarly, we show the zonal integral of the OMET at 60°N in Figure 4. Differences in ~~amplitude~~ ~~amplitudes~~ and trends can be observed in the unfiltered time series. The mean ~~OMET~~ and the ~~and~~ std of all the OMET time series are similar (see 5 Figure 4a). The mean ~~of~~ OMET in ORAS4 is 0.47 PW, in GLORYS2V3 ~~it~~ is 0.44 PW and in SODA3 ~~it~~ is 0.46 PW. The OGCM hindcast gives a similar ~~mean~~ ~~OMET~~ ~~of~~ ~~result~~, which is also 0.47 PW. ~~For the~~ ~~The~~ std of OMET ~~in~~ ORAS4 and the OGCM hindcast ~~give~~ ~~is~~ 0.06 PW, while ~~in~~ GLORYS2V3 and SODA3 ~~give~~ ~~the~~ std ~~is~~ 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~~ The OMET anomalies 10 ~~with a 5-year low pass filter are shown~~ in Figure 4b ~~is not noticeable from their std. Given the time series of all the chosen reanalyses~~. OMET anomalies in ORAS4 ~~resembles~~ resemble that in SODA3, especially after 1998. ~~Whereas, While~~ OMET anomalies in GLORYS2V3 ~~is clearly different from~~ are very different from that in 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~~ ~~reveal that the~~ first 10 years in GLORYS2V3 are quite suspicious because of its large deviation from the other 15 products. Such large differences should be noticeable in the heat content changes or surface fluxes. Nevertheless, after 2007 all the ~~reanalyses~~ ~~time series~~ ~~oceanic~~ ~~reanalyses~~ agree well and the 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~~ ~~reanalysis~~ 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.

20 3.2 Source of Disparity

In order to further understand the difference between the AMET estimated from each atmosphere ~~reanalyses~~ ~~reanalysis~~ product, we compare each component of AMET separately. We investigate the difference between each component of AMET at 60°N estimated from ERA-Interim against those from MERRA2 and JRA55. It is noticed that the differences mainly originate from meridional temperature transport ($vc_p T$) and geopotential energy transport (vgz). ~~A simple linear regression shows~~ ~~With linear regression, we find that~~ the correlation between the difference ~~of~~ ~~in~~ total energy transport and the difference ~~of~~ ~~in~~ meridional temperature transport, ~~taking~~ ~~between~~ ERA-Interim and MERRA2, is 0.55, while ~~for~~ ~~between~~ ERA-Interim and JRA55 that is ~~very small~~ 0.21. In addition, the correlation between the difference ~~of~~ ~~in~~ total energy transport and the difference ~~of~~ ~~in~~ geopotential energy transport (vgz), ~~for~~ ~~between~~ ERA-Interim and MERRA2 is 0.56 and ~~for~~, ~~while~~ ~~between~~ ERA-Interim and JRA55 that is 0.60. For the other components, the correlations between them and the total difference are ~~neglectable~~ small. 25 30 The results are all obtained with a confidence interval ~~over~~ ~~of~~ 95%. ~~This is generally the case as large~~ Large differences in temperature transport ~~between~~ ~~reanalyses~~ ~~among~~ ~~reanalysis~~ products are found at ~~almost~~ all latitudes (not shown). Such differences are consistent with the fact that the temperature transport and geopotential energy transport have ~~larger~~ ~~a large~~ contribution to the total AMET (see Figure 1). Note that the differences ~~of~~ ~~in~~ each AMET component ~~between~~ ~~every~~ ~~two~~ ~~products~~ are of the same order of magnitude as ~~the absolute values of that component~~ AMET. Besides, the ~~mean~~ and ~~anomalous~~

latent heat transport ~~agrees well between all~~ ~~agree well between~~ 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~~ ~~reanalysis~~ data sets.

In order to know the relative contribution of each field to the difference of the ~~mean~~ 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. We compare~~ 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~~ ~~To accommodate~~ a point-wise comparison, the fields from MERRA2 are interpolated onto the vertical grid of ERA-Interim. ~~This~~ ~~It~~ shows that these two ~~reanalyses~~ ~~reanalysis~~ products differ substantially regarding each variable field (Figure 5a and b). Big differences in temperature reside mostly at the tropopause, ~~while large~~ ~~Large~~ differences in meridional wind ~~component~~ ~~components~~ 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~~ ~~mean temperature transports~~ (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~~ ~~every~~ single field to the ~~temperature transport~~ ~~mean temperature transports~~ can not be identified here.

Differences between every two chosen atmospheric products are found at nearly each pressure level. ~~Given the data available, this~~ ~~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 data sets, in both the temperature and meridional velocity fields, are too large to constrain the AMET. ~~Note that the difference in horizontal advection schemes can also influence the results. The chosen atmospheric reanalyses systems use Semi-Lagrangian advection schemes, but this is not the case for MERRA2.~~ Hence studies on low frequency variability of energy transports and associated variables ~~should be interpreted with care as the~~ ~~reanalyses~~ ~~reanalysis~~ products differ substantially, and we cannot ~~make a priori~~ ~~judge~~ ~~judge a priori~~ 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 OGCM hindcast is evaluated against OMET measured at 26.5°N. ~~Given in Figure 6, the inter-comparison~~ ~~The intercomparison~~ shows that the ~~reanalyses~~ ~~reanalysis~~ products capture roughly the mean amplitude of the OMET (Figure 6). Some large events are captured as well, such as the strong weakening in 2009. Statistically, the mean OMET provided by ~~RAPID ARRAY~~ ~~the RAPID array~~ is 1.21 ± 0.27 PW. It is higher than ~~all~~ the chosen products here. The mean OMET in ORAS4 is 0.66 ± 0.27 PW, in GLORYS2V3 it is 0.89 ± 0.52 PW, in SODA3 it is 0.81 ± 0.52 PW and in OGCM hindcast ~~it~~ is 1.05 ± 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 ~~the RAPID array~~, while in GLORYS2V3 and SODA3 we find a higher std of OMET. The OGCM hindcast has a relatively small OMET std ~~def~~, ~~which is~~ 0.21 PW. In terms of the correlation and standard deviation, ORAS4 and

the OGCM hindcast agree well with observations. It is noteworthy that ~~NEMO~~ the OGCM 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

5 the OMET given by ORAS4 is quite comparable to that in OSNAP in terms of the amplitude and ~~variations~~ ~~variability~~. 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 $0.39 \pm 0.11 \text{ PW}$, which is quite similar to the mean OMET $0.45 \pm 0.07 \text{ PW}$ of OSNAP. However, OMET in SODA3 has a larger mean and standard deviation than ~~the OMET~~ ~~that~~ in OSNAP and thus deviates from the ~~observation~~ ~~observations~~.

10 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 ~~the~~ 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~~ ~~is~~ likely related to OHC change. A full budget analysis was not feasible as most data sets did not include the surface fluxes. Figure 8 illustrates the OHC (Figure 8a) and ~~the~~ OHC anomalies (Figure 8b)

15 quantified from ORAS4, GLORYS2V3, SODA3 and the OGCM hindcast. It depicts the OHC integrated in the polar cap (from 60°N to 90°N) over all depths. The mean OHC in ORAS4 is $4.48 \pm 0.78 \times 10^{22} \text{ J}$, in GLORYS2V3 ~~it~~ is $4.23 \pm 0.59 \times 10^{22} \text{ J}$ and in SODA3 ~~it~~ is $3.79 \pm 0.93 \times 10^{22} \text{ J}$, while the OGCM hindcast shows a much larger mean OHC of $7.85 \pm 0.58 \times 10^{22} \text{ J}$. The variations are 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~~ ~~variability~~ ~~is~~ different and these are reflected in the

20 standard deviation of OHC anomalies time series. ~~Increases in surface temperature and OHC are often taken as a sign of AA in many papers (e.g. Serreze and Barry, 2011).~~ Qualitatively, the ~~variations~~ ~~trends~~ of OHC in the chosen reanalyses at ~~polar cap~~ ~~can~~ ~~the polar cap could~~ be taken as a sign of ~~AA~~ ~~but a~~ ~~the~~ AA, but it might be just Arctic warming and not necessarily

25 a higher warming rate than the global mean temperature change. A quantitative evaluation of ~~the~~ AA is not possible due to large differences between products. To conclude, ~~for the OHC~~ there are large ~~difference~~ ~~differences in OHC~~ between chosen products, while their variations agree ~~very~~ ~~relatively~~ well. Since OHC is a function of temperature fields only, this can imply that temperature profiles are different among all the chosen ocean ~~reanalyses~~ ~~reanalysis~~ 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~~ ~~among reanalysis products~~ than the absolute OHC, which indicates that the trend of OHC is captured in a similar way among all the ocean ~~reanalyses~~ ~~reanalysis~~ products.

30 3.3 MET and the Arctic

In previous sections, it is found that MET ~~of different reanalyses~~ ~~in different reanalysis~~ products at subpolar and subtropical latitudes differ substantially from each other. In order to further evaluate AMET and OMET given by different reanalyses and ~~to~~ 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 in-

teraction between MET and the Arctic, and the short time series available, determining cause-effect relations is out of the scope for this paper. ~~That is, we~~ 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); 5 Kapsch et al. (2013)). (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 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 10 show linear regressions in summer and winter separately in order to account for the seasonal variability. ~~We do note that correlations 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 15 fields included in each respective ~~reanalyses~~ reanalysis 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~~ reanalysis data sets concerning near surface fields in Lindsay et al. (2014). Following the regressions performed by Van der Swaluw et al. 20 (2007) and Jungclaus and Koenigk (2010), we repeated the same procedure here with AMET at interannual scales (~5 year).

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 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 correlated with SLP over the Greenland, the North Atlantic, the Barents Sea, the Kara Sea and the northern part of the Eurasian continent. 25 It suggests that an increase in subpolar AMET is linked to a northward advection over the Greenland which ~~can~~ could bring relatively warm and humid air into the Arctic. Such patterns are consistent with the relatively warm air over the Greenland and part of the Central Arctic close to the Eurasian side shown in Figure 9d 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~~ decrease of 30 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 (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 provides an entirely different story about AMET and the statistical relation with subpolar and Arctic atmospheric circulation.~~ Hence, there is also large uncertainty in 35

the assertion that heat and humidity transport by stationary eddies contribute to the changes in the subpolar and Arctic regions at interannual time scales.

Moreover, similar to Van der Swaluw et al. (2007) and Jungclaus and Koenigk (2010), we investigate the links between the variability of OMET and variations of multiple fields at interannual (~ 5 year) time scales. The regressions of anomalies of 5 multiple fields on detrended OMET anomalies at 60°N in winter are shown in Figure 10 with OMET leading by 1 month. The regression coefficients are maximal when the OMET leads by 1 month. In ORAS4 and SODA3, increasing OMET can lead to a decrease in SLP in the Arctic, while in ORAS4 this polar-low is much stronger. This ~~indicates~~ ~~seems to indicate~~ 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 sea ice melt and increase in 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 around the Nordic seas. There~~ 10 is an AO/NAO like SLP anomaly with the associated large scale temperature pattern. However, GLORYS2V3 tells an entirely different story. This is mainly due to the difference between OMET in this dataset compared to the other ocean data sets during the 1990s as shown in Figure 4.

In general, ~~reduction~~ ~~the decrease~~ of OMET leads to an increase in the growth rate of SIC, which is consistent with studies 15 performed with global climate models at decadal to inter-decadal time scales (e.g. Van der Swaluw et al. (2007); Jungclaus and Koenigk (2010); (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) (Årthun et al., 2012; Onarheim et al., 2015). However, note that some discussed regions are below the significance of 95%.

20 In summer, the situation becomes more intricate and unclear. The ~~instantaneous~~ ~~same~~ regressions of anomalies of multiple fields on AMET ~~and~~ OMET anomalies at 60°N in each ~~atmospheric~~ ~~reanalysis~~ product in summer ~~are shown in Figure ??.~~ ~~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.~~

25

30 It can be ~~is~~ included in the supplementary material. It is noticed that the consistency of associations between AMET, OMET 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)). (e.g. Lian and Cess, 1977; Curry et al., 1995; Goosse et al., 2018). Therefore the regressions of SLP, T2M and SIC on AMET 35 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 ?? 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 5 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 ??g, 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 and JRA55 are most consistent with the results given by coupled numerical models in winter, while MERRA2 does not corroborate model 10 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 variations in AMET.

4 Discussion

15 In this study, we found substantial differences between reanalyses products with aspect to MET. In order to improve the accuracy of the 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 20 (Shaffrey and Sutton, 2006; Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010) (Shaffrey and Sutton, 2006; Van der Swaluw et al.). 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 25 (Kapsch et al., 2013; Graversen and Burtu, 2016) (Kapsch et al., 2013; Graversen and Burtu, 2016). With improved reanalyses reanalysis products and independent observations, such as ocean mooring arrays and atmospheric in-situ and remote satellite 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 30 (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 the Greenland Sea and the Barents Sea. However, GLORYS2V3 does not show this relation. The differences in OMET are reflected in the regressions on sea ice. The strong connection 35 between OMET from mid-to-high latitudes and the Arctic sea ice indicates 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) (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 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, 5 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) (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 (e.g. McCarthy et al., 2015; Lozier et al., 2019) 10 . Hence, the AMOC may serve as an indicator of the changes of OMET. In our case, a quantitative estimation of the difference in the AMOC among the chosen data sets is beyond our scope the scope of this paper. 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 15 reanalyses analyzing six oceanic reanalysis data sets, Karspeck et al. (2017) find the reanalyses reanalysis products are not consistent in their year-to-year AMOC variations. The discrepancy between AMOC represented by each reanalyses reanalysis product may explain the difference differences in OMET in each reanalysis dataset.

5 Conclusions

This study aimed to quantify and inter-compare intercompare AMET and OMET variability from 3 atmospheric and 3 oceanic 20 reanalyses reanalysis 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 reanalysis data, where generally only one reanalysis data set is considered, and which includes mostly only oceanic or atmospheric analysis.

All selected 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) 25 (Trenberth and Caron, 2001; Fasullo and Trenberth, 2008; Mayer and Haimberger, 2012). However, when it comes to anomalies at interannual time scales, they differ from each other, both spatially and temporally. The variations between ERA-Interim and JRA55 are small, while MERRA2 is very different from them. Although there is an overlap of observational data assimilated by different reanalyses reanalysis products, large deviations still exist in main many 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) 30 reanalysis 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 data sets are not designed for the studies on energy transport, specifically. The~~ existence of sources and sinks in ~~reanalyses reanalysis~~ data sets introduces large uncertainties in the computation of energy transport (Trenberth, 1991; Trenberth and Solomon, 1994). ~~As a consequence, (Trenberth, 1991; Trenberth and Solomon, 1994). Although the reanalysis data sets are not specifically~~ 5 ~~designed for the studies on energy transport, given the good agreements on mean AMET and OMET and their annual cycles among assessed reanalysis products, we still recommend to use these reanalysis products for the energy transport diagnostics. However, much care should be taken when adopting the reanalyses for investigations on energy balance and energy transport related issues, especially for the ones aiming reanalyses for the examination of energy transport~~ at relatively large time scales. ~~The robustness of those results based on the AMET and OMET estimated from reanalyses should be further assessed.~~

10 *Author contributions.* Y. Liu, J. Attema and W. Hazeleger designed this study, performed computations using reanalyses and analyzed the results. B. Moat performed OGCM simulation and contributed to the analysis.

Competing interests. The authors declare no competing interests.

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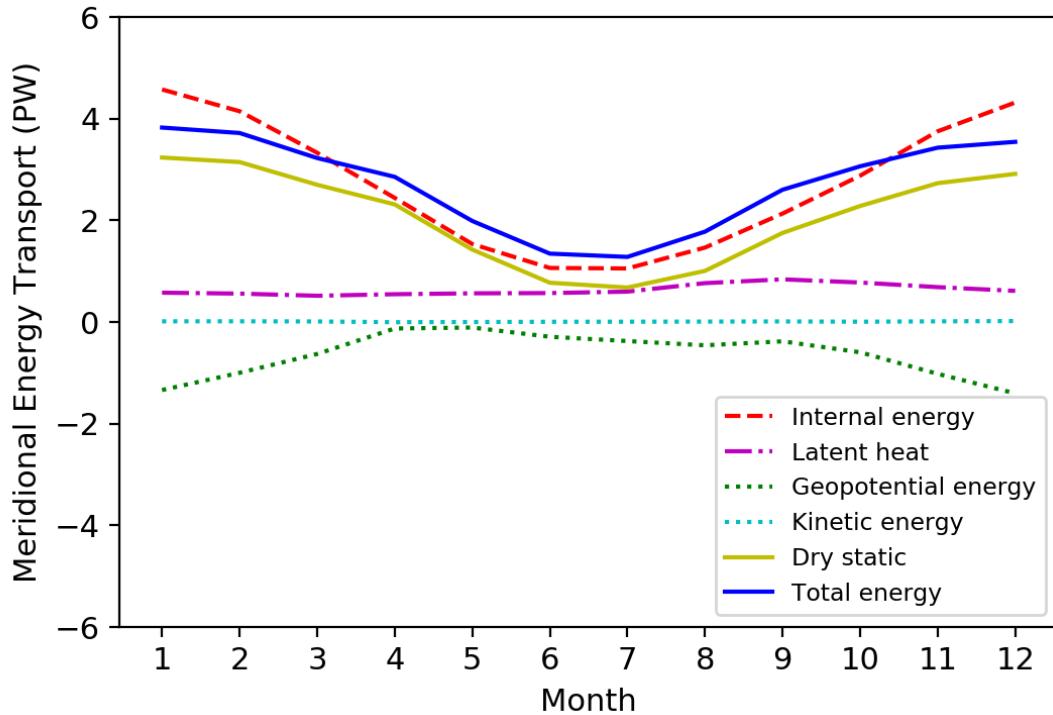


Figure 1. Estimation of mean AMET and each component in each month at 60°N with ERA-Interim from 1979 to 2017. The unit is Peta Watt (PW).

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

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%.

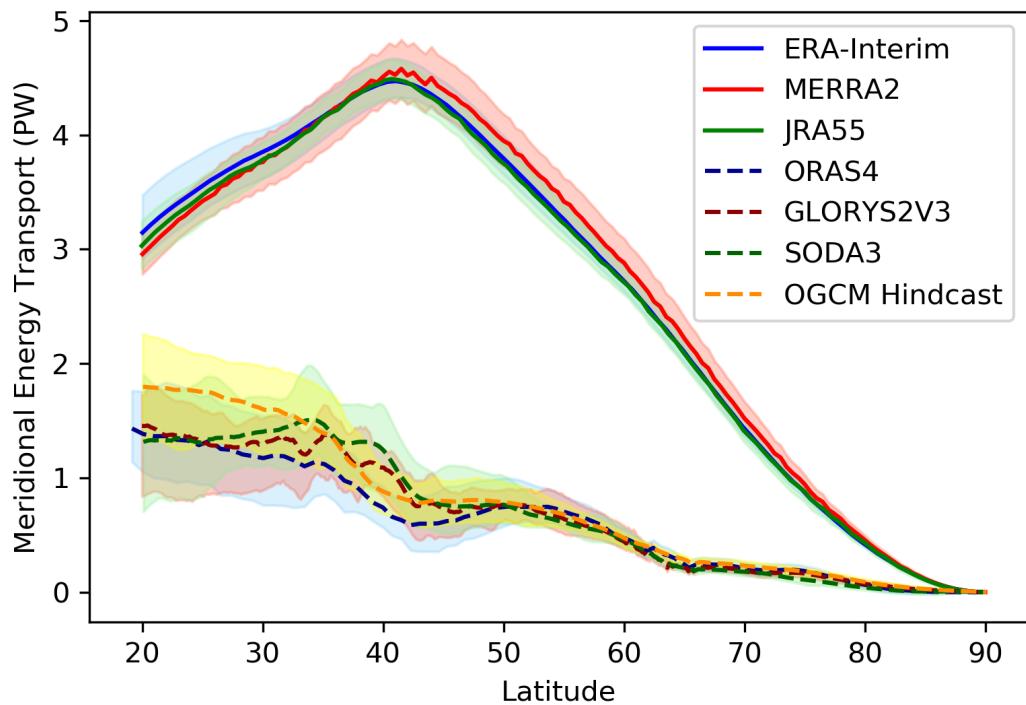


Figure 2. Mean AMET and OMET over the entire time span of each product as function of latitude in the Northern Hemisphere. AMET are illustrated with solid lines while OMET with dash lines. The shades represent the full range of MET across the entire time series at each latitude. The time span of each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

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

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

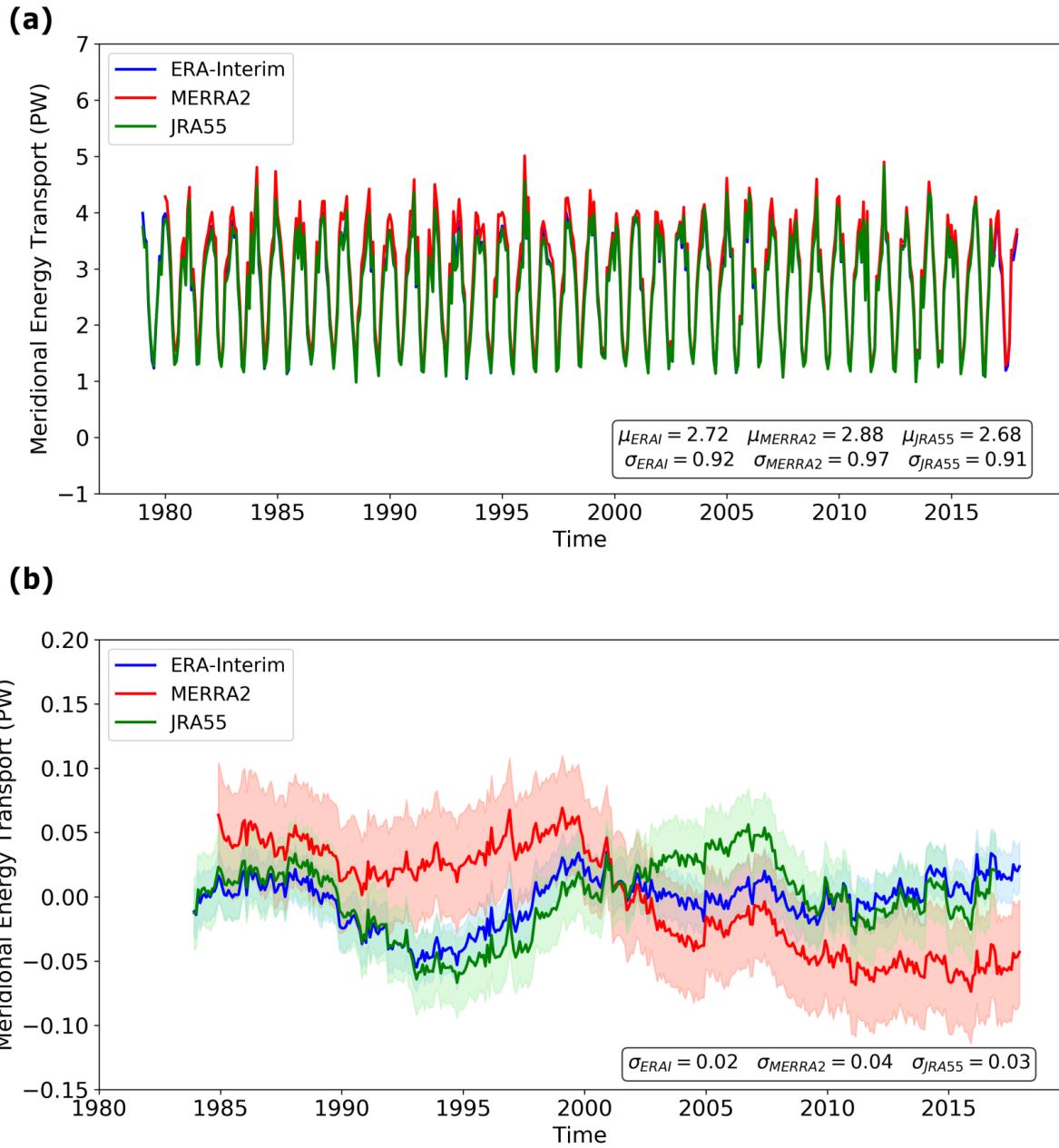


Figure 3. Time series of zonal integral of AMET at 60°N without/with low pass filter. (a) The original time series and (b) the ones with low pass filter include signals from ERA-Interim (blue), MERRA2 (red) and JRA55 (green). For the low pass filtered ones, we take a running mean of 5 years. The shades represent the confidence intervals with one standard deviation. σ is the standard deviation and μ is the mean of the entire time series.

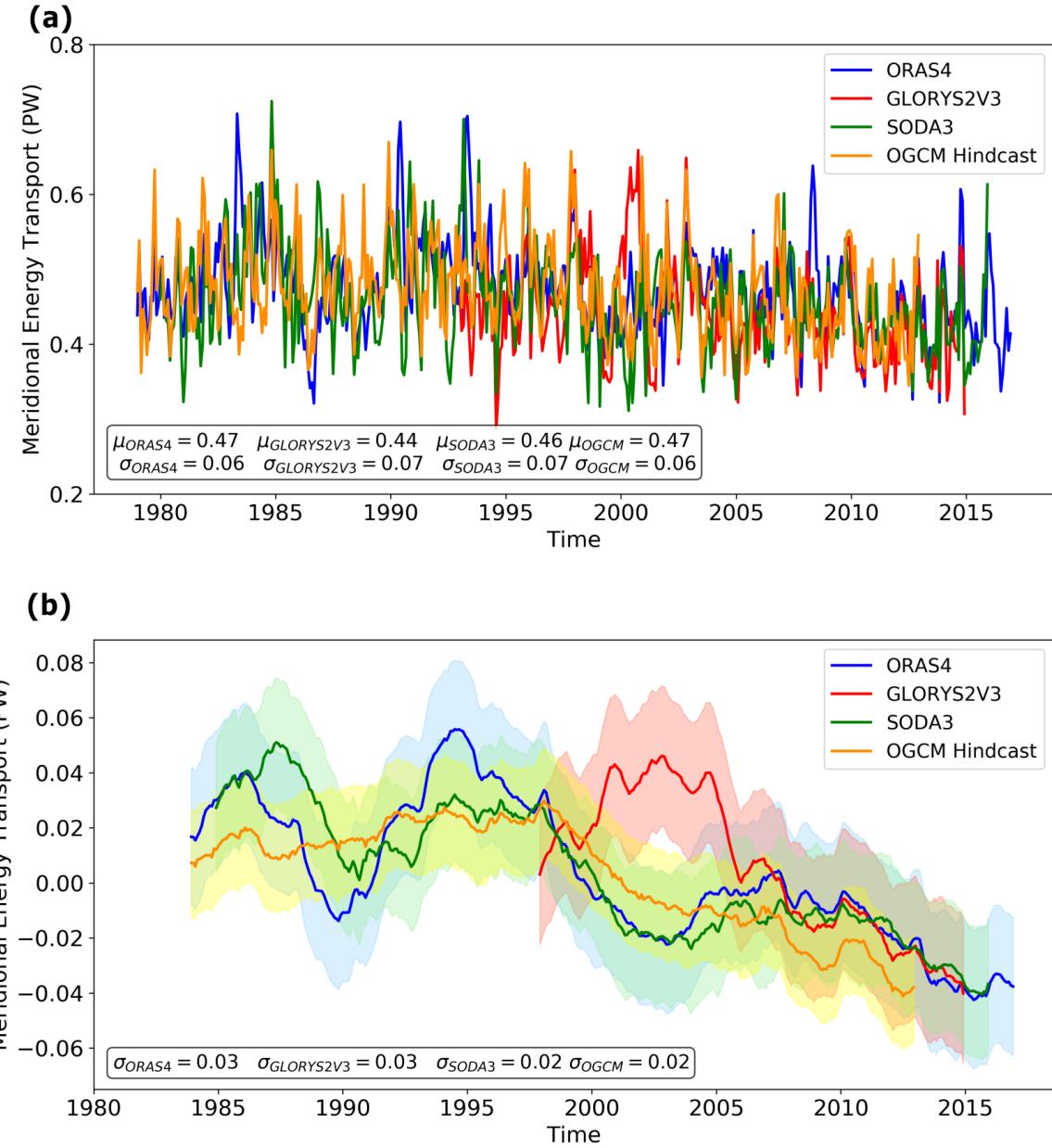


Figure 4. Time series of zonal integral of OMET at 60°N without/with low pass filter. (a) The original time series and (b) the ones with low pass filter include signals from ORAS4 (blue), GLORYS2v3 (red), SODA3 (green) and the OGCM hindcast (yellow). For the low pass filtered ones, we take a running 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.

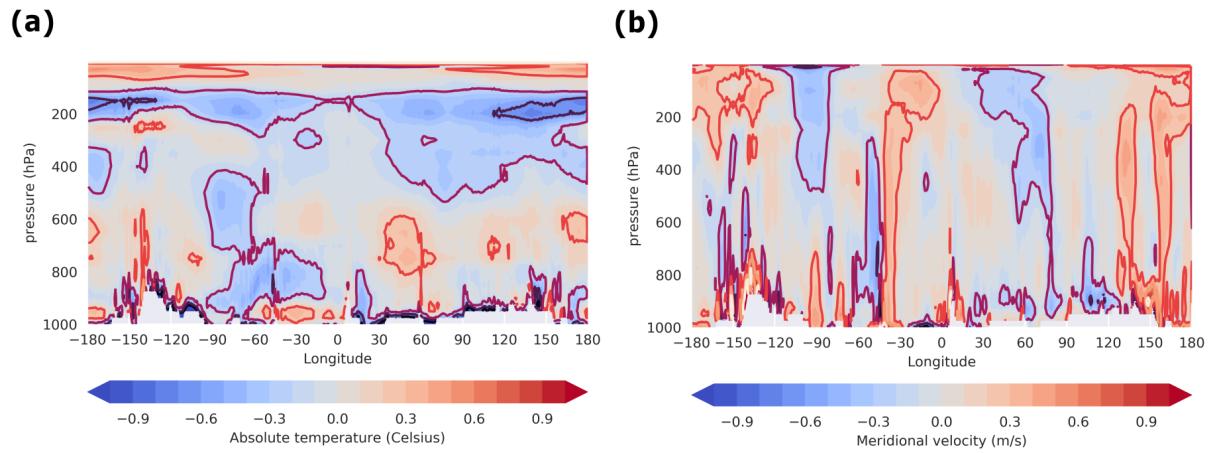


Figure 5. Difference in temperature, meridional wind velocity and temperature transport between MERRA2 and ERA-Interim at 60°N. The vertical profile of (a) temperature difference and (b) meridional wind velocity difference are calculated from the climatology of each fields from 1994 to 1998, respectively.

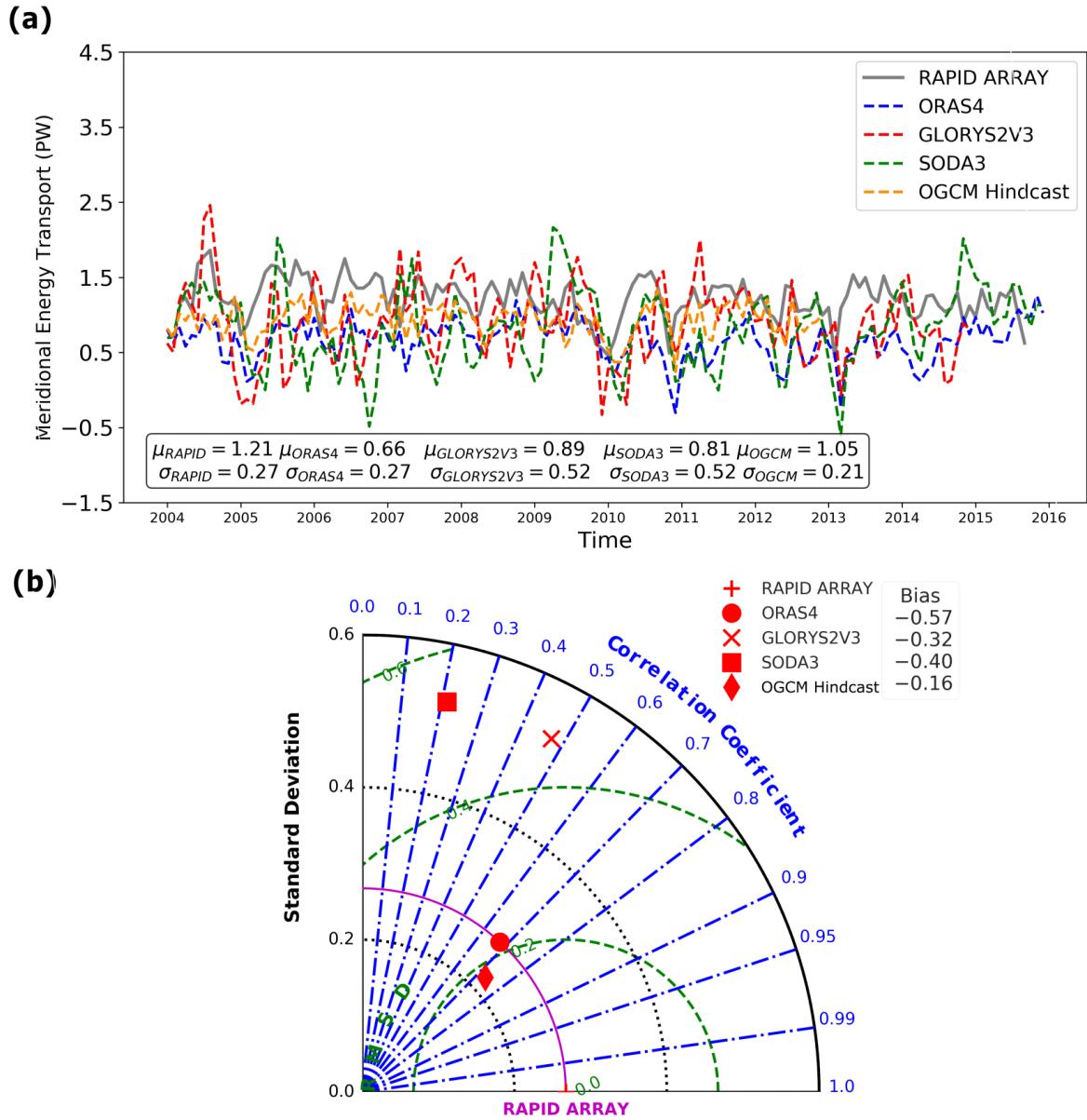


Figure 6. OMET estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the OGCM hindcast (orange) compared to the RAPID ARRAY observation (gray) at 26.5°N across the Atlantic basin. The time series of OMET is presented in (a). The statistical properties are shown in (b) Taylor Diagram, including 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.

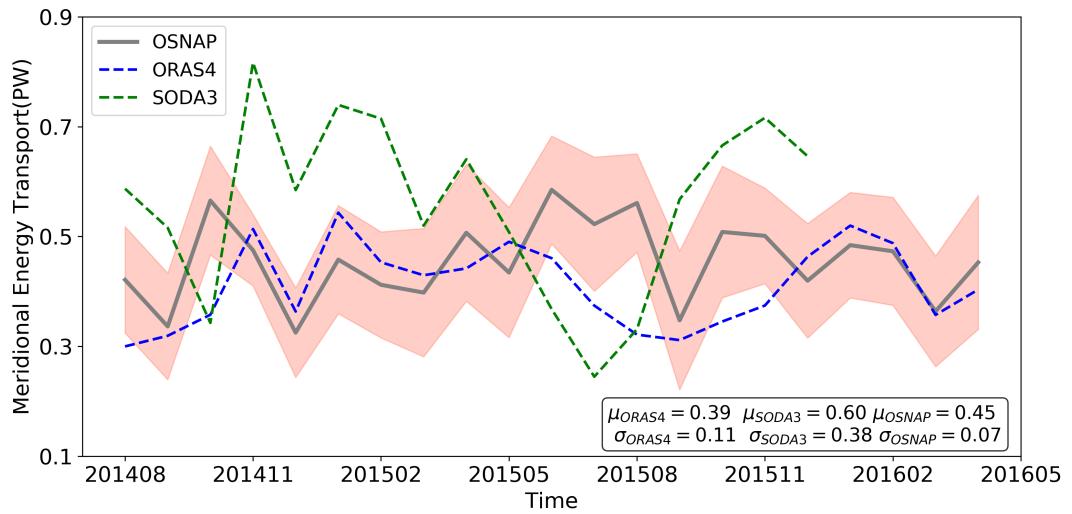


Figure 7. OMET estimated from ORAS4 (blue), SODA3 (green) and compared to the OSNAP observation (gray) at subpolar Atlantic basin. The range of uncertainty from OSNAP observation is marked by the red shade. σ is the standard deviation and μ is the mean of the entire time series.

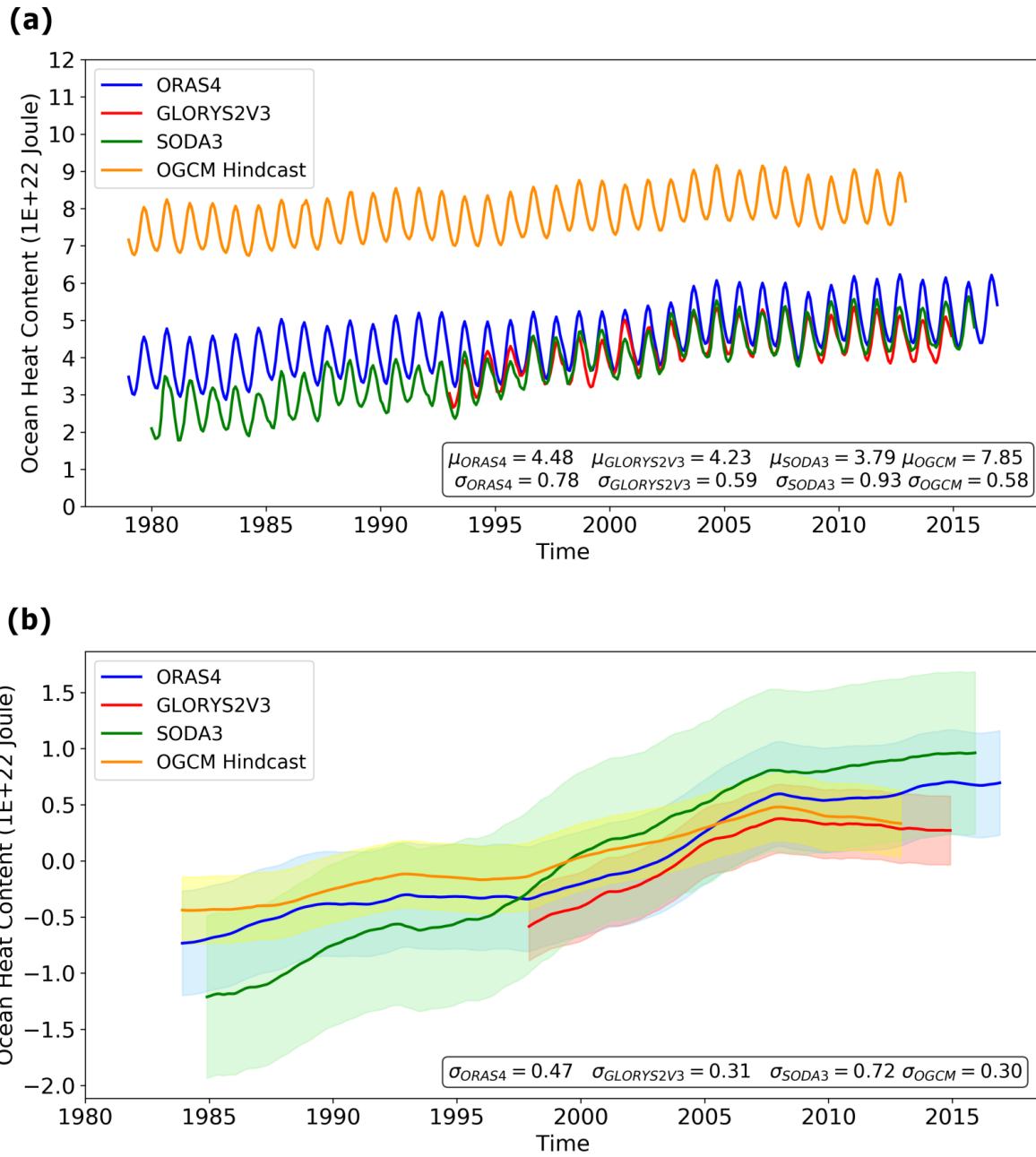


Figure 8. Time series of (a) ocean heat content (OHC) and (b) OHC anomalies with a low pass filter at the polar cap. The OHC is integrated from surface to the bottom between 60°N and 90°N . It is estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the OGCM hindcast (yellow). The shades represent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

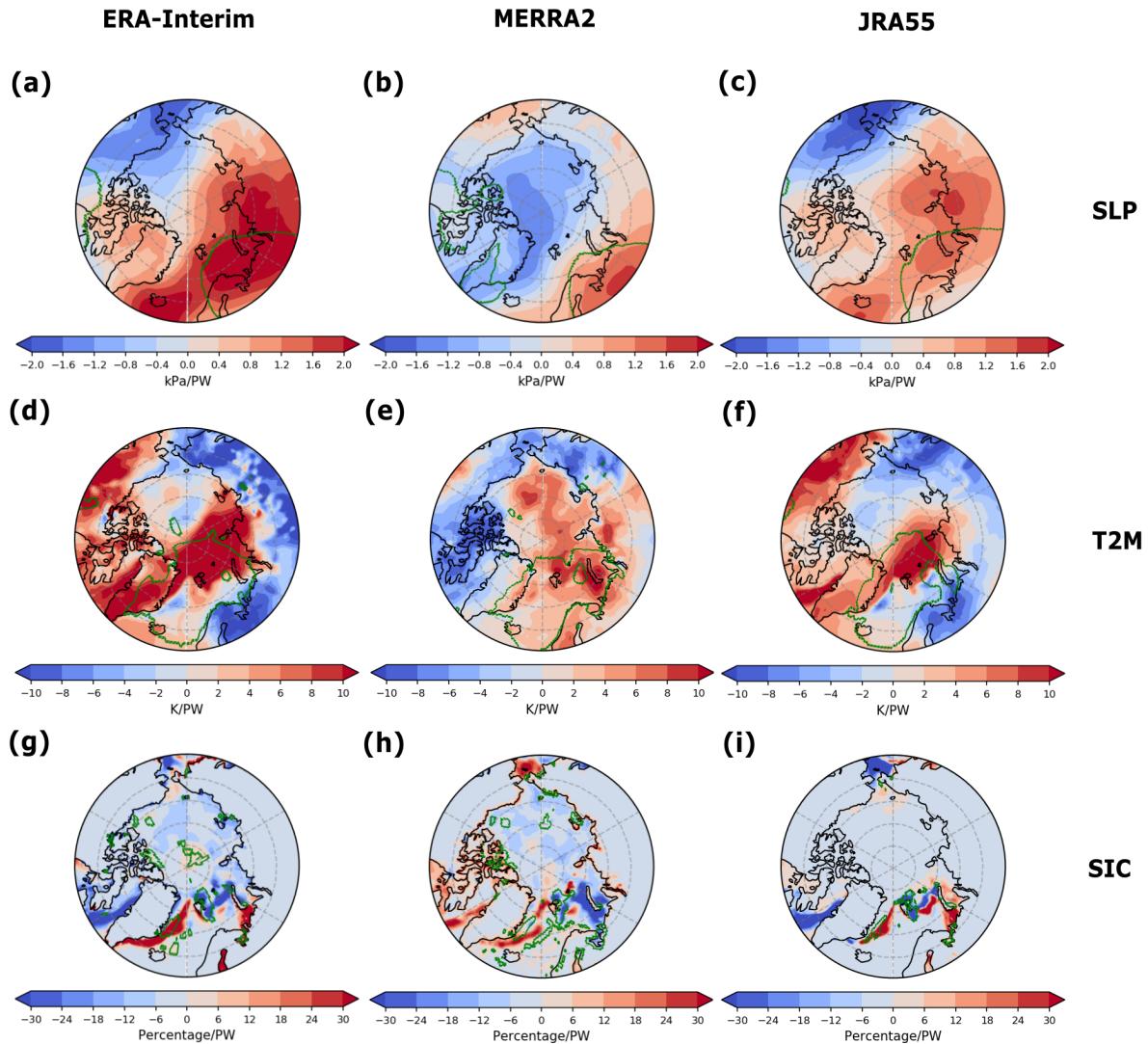


Figure 9. Regressions of sea level pressure, 2 meter temperature and sea ice concentration anomalies on AMET anomalies at 60°N in winter (DJF) at interannual time scales with no time lag. The monthly mean fields are used here after taking a running mean of 5 year. Both the 2 meter temperature and sea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

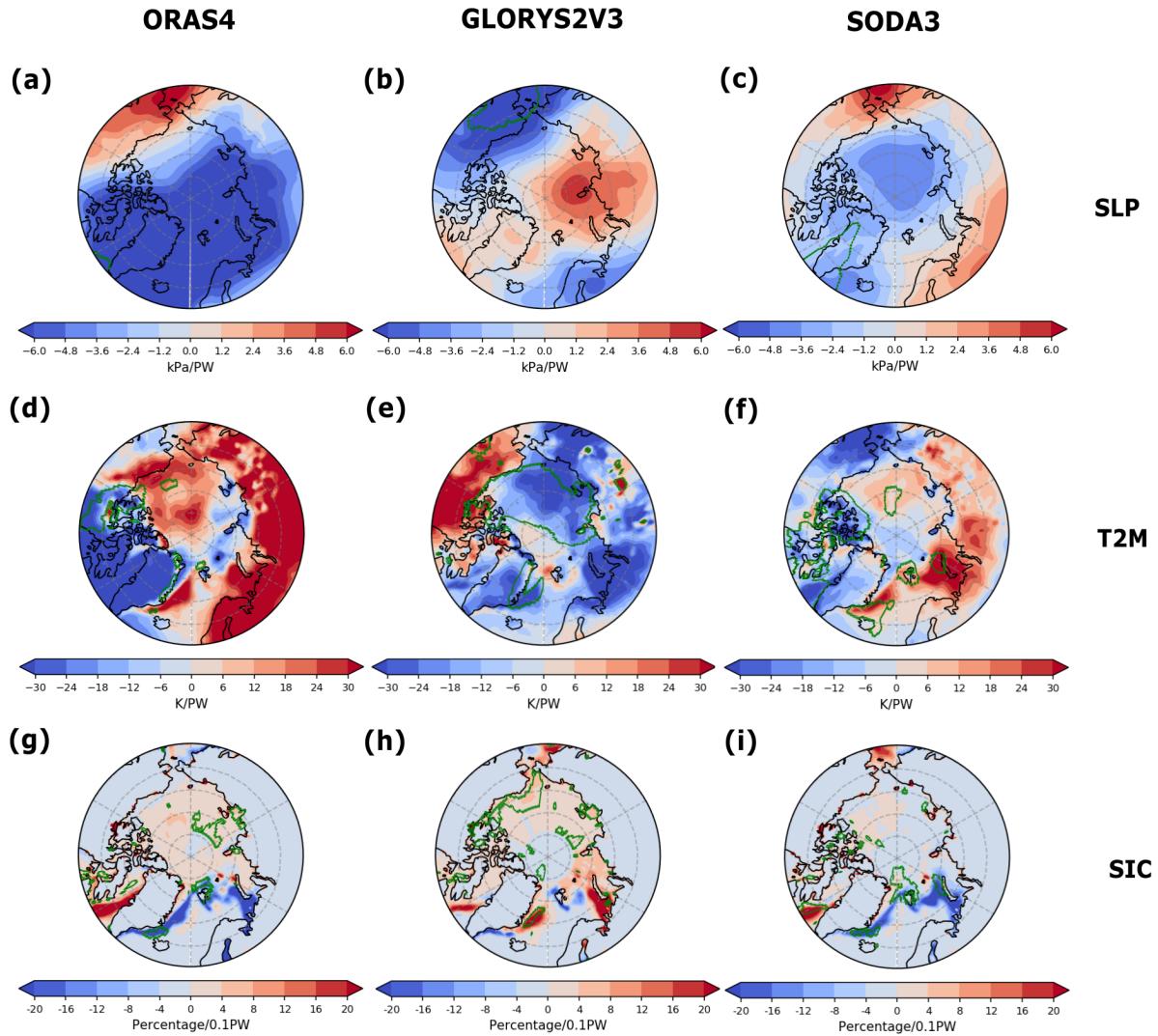


Figure 10. Regressions of sea level pressure, 2 meter temperature and sea ice concentration anomalies on OMET anomalies at 60°N in winter (DJF) at interannual time scales. OMET leads the fields by one month. The 2 meter temperature, sea ice concentration and OMET are detrended. From left to right, they are the regressions 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%.