



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

Yang Liu^{1,2}, Jisk Attema¹, Ben Moat³, and Wilco Hazeleger^{1,2}

¹Netherlands eScience Center, 1098 XG, Amsterdam, The Netherlands

²Wageningen University, 6708 PB, Wageningen, The Netherlands

³National Oceanography Center, SO14 3ZH, Southampton, United Kingdom

Correspondence: Yang Liu (y.liu@esciencecenter.nl)

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

1 Introduction

Poleward meridional energy transport, both in the atmosphere (AMET) and ocean (OMET), is one of the most fundamental aspects of the climate system. It is closely linked to changes of weather and climate at different latitudes. The quantification of AMET and OMET has been studied extensively. Dating back to 1970s, many efforts were made to reproduce the AMET and OMET with very limited observational data available (Vonder Haar and Oort, 1973; Oort and Vonder Haar, 1976). After entering the satellite era, further progress has been made during the recent two decades. Using the radiation at top of the atmosphere and the reanalyses data, a complete picture of AMET and OMET is given by Trenberth and Caron (2001). Following their work, rapid progress was made using similar methodologies and new data sets of observations (Ganachaud and Wunsch, 2000, 2003; Wunsch, 2005; Fasullo and Trenberth, 2008; Zheng and Giese, 2009; Mayer and Haimberger, 2012). Nevertheless, these



estimations still suffered from problems like mass imbalance, unrealistic moisture budget, coarse resolution, and sparseness of observations (Trenberth, 1991; Trenberth and Solomon, 1994). Fortunately, recent improvements in numerical weather and ocean models and increased data coverage of observations provide a basis to improve estimates of AMET and OMET. There is an increase of available reanalyses products, increase in resolution, length of the time span that is covered and increase of components of the Earth system that are included in the products (Dee et al., 2011; Gelaro et al., 2017; Harada et al., 2016; 5 Balmaseda et al., 2013; Ferry et al., 2012b; Carton et al., 2018). It is very promising to have better quantification of AMET and OMET using the latest reanalyses datasets.

To support our elaboration on MET, we also study AMET and OMET in relation to climate variability from annual to interannual time scales in the Arctic region. In recent decades, the Arctic is warming twice as fast as the global average 10 (Comiso and Hall, 2014; Francis et al., 2017). This phenomenon is known as Arctic Amplification (AA) and it has an impact far beyond the Arctic (Miller et al., 2010; Serreze and Barry, 2011). In order to understand the warming, the process behind the AA, its wider consequences and to make reliable predictions of the Arctic climate, it is crucial to understand the Arctic climate variability. Among all the factors responsible for the variability in the processes described above, meridional energy transport (MET), from midlatitudes toward the Arctic, plays a significant role (Graversen et al., 2008; Kapsch et al., 2013; Zhang, 2015). 15 There is a large volume of published studies describing the impact of AMET and OMET on the variation of sea ice and the warming in the Arctic. Yang et al. (2010) show that the poleward AMET is linked with the evolution of temperature in the free troposphere at a decadal scale. By separating the planetary and synoptic-scale waves, Graversen and Burtu (2016) show that the latent heat transport, as a component of AMET, influences the Arctic warming. Gimeno-Sotelo et al. (2019) studied the moisture transport for precipitation and show the moisture sources for the Arctic region is linked with inter-annual fluctuations 20 in the extent of Arctic sea ice. Nummelin et al. (2017) analyse the linkages between OMET, Ocean Heat Content (OHC) and AA through the simulations within the Coupled Model Intercomparison Project Phase 5 (CMIP5). They report enhancement of OMET as a result of heat loss in the subpolar ocean and the contribution of OMET to the AA through the increasing of OHC in the Arctic ocean. Also by analyzing CMIP5 simulations, Sandø et al. (2014) show a large impact of heat transport in the Barents Sea on sea ice loss. Consequently, increasing knowledge on poleward AMET and OMET at subpolar and polar 25 latitudes will aid in understanding of AA.

Global climate models indicate a compensation between variations in atmospheric and oceanic heat transports at subpolar and midlatitudes (Outten et al., 2018). This is indicative of positive feedbacks between the ocean and atmosphere and it has been associated with variations in sea ice by several studies (Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010; van der Linden et al., 2016). These studies all point out the connection between energy transport and the variations of the 30 Arctic climate. However, these results are mostly based on numerical model simulations and they tend to differ among the models. In contrast to numerical modeling studies, here we intend to study AMET, OMET variability and the relation with the Arctic in best estimates of the historical variability.

In this paper, we quantify AMET and OMET using multiple state-of-the-art reanalyses products. These are optimized representations of the historical state of the atmosphere and ocean based on available observations and numerical simulations. 35 Emphasis is placed on the variation of AMET and OMET from midlatitudes to the Arctic across annual to interannual time



scales. In contrast with earlier studies, we will compare the different reanalyses datasets. Independent observations in the Atlantic from RAPID ARRAY and OSNAP are included in the comparison. RAPID ARRAY, which is short for the RAPID-MOCHA-WBTS program, is a trans-basin observing array along 26.5° N in the Atlantic (Johns et al., 2011; McCarthy et al., 2015). It operates since 2004 and provides the volume and heat transport in the Atlantic basin. OSNAP, which is the abbreviation of Overturning in the Subpolar North Atlantic Program, is an ocean observation program designed to provide a continuous record of the trans-basin fluxes of heat, mass and freshwater in the subpolar North Atlantic (Susan Lozier et al., 2017; Lozier et al., 2019). Moreover, a state-of-the-art NEMO-LIM2 1/12° ocean circulation / sea ice model (Moat et al., 2016) is also included in the comparison. Based on the intercomparison of reanalyses data, especially with the independent observation data, we will be able to identify sources of uncertainty. To support our comparison of AMET and OMET, we also investigate the interactions between oceanic and atmospheric variations and remote responses. The correlations between the variability of AMET and OMET and the changes in the Arctic climate are compared to literature. This is motivated by previous studies with only numerical models or a single reanalysis dataset to explain those connections (Graversen, 2006; Van der Swaluw et al., 2007; Graversen et al., 2008; Jungclaus and Koenigk, 2010; Kapsch et al., 2013).

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

2 Data and Methodology

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

2.1 Reanalyses

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



2.1.1 ERA-Interim

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

10 2.1.2 MERRA2

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

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

25 2.1.4 ORAS4

Serving as the historical reconstruction of the oceans climate, the Ocean reanalyses System 4, in short ORAS4, is the replacement of the old reanalyses system ORAS3 used by the ECMWF (Balmaseda et al., 2013). It implements Nucleus for European Modelling of the Ocean (NEMO) as ocean model (Madec, 2008; Ferry et al., 2012a) and uses NEMOVAR as the data assimilation system (Mogensen et al., 2012). The model is forced by atmosphere-derived daily surface fluxes, from ERA-40 from 1957 to 1989 and ERA-Interim from 1989 onwards. ORAS4 produces data with 3D-Var assimilation and spans from 1958 to present. ORAS4 runs on the ORCA1 grid, which is associated with a horizontal resolution of 1° in the extratropics and a



refined meridional resolution up to 0.3° in the tropics. It has 42 vertical levels, 18 of which are located at upper 200m. Here we skip the first two decades and use the monthly data from 1979 to 2014 to avoid the uncertainties reported by Balmaseda et al. (2013). We will use the monthly mean fields on the native model grid.

2.1.5 GLORYS2V3

5 GLORYS2V3, short for GLobal Ocean reanalyses and Simulations version 3, is a global ocean and sea-ice eddy permitting reanalyses yielded from the collaboration between the Mercator Ocean, the Drakkar consortium and Coriolis Data center (Ferry et al., 2010, 2012b). It spans the altimeter and Argo eras, from 1993 till present. The NEMO ocean model is implemented on the ORCA025 grid (approximate $0.25^\circ \times 0.25^\circ$ with 75 vertical levels). The model is forced by surface fluxes using the ERA-Interim atmospheric near-surface parameters. The data is generated by a 3D-Var assimilation scheme with temperature and
10 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 Geo-
15 physical Fluid Dynamics Laboratory CM2.5 coupled model (Delworth et al., 2012) with a grid configuration of approximately $0.25^\circ \times 0.25^\circ \times 50$ levels resolution (Carton et al., 2018). To be consistent with the other two reanalyses datasets assessed in this study, the SODA 3.4.1 is chosen since it applies surface forcing from ERA-Interim. For this specific version, the 5-daily data is available from 1980 to 2015. reanalyses data from this period on original MOM5 grid is used in this case.

2.2 Oceanic Observations and NEMO ORCA Hindcast

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

30 Apart from the RAPID array and OSNAP observational data, a high resolution hindcast of the NEMO ORCA ocean circulation model is also included here to provide more insights to the analysis since two of the chosen reanalyses products are also



built on NEMO model (Moat et al., 2016; Marzocchi et al., 2015). This simulation implements the NEMO ORCA global ocean circulation model version 3.6 (Madec, 2008). It is configured with ORCA0083 grid, which has a nominal resolution of $1/12^\circ$, on 75 vertical levels. The climatological initial conditions for temperature and salinity were taken in January from PHC2.1 at high latitudes (Steele et al., 2001), MEDATLAS in the Mediterranean (Jourdan et al., 1998), and the rest from Levitus et al. (1998). The surface forcing comes from the Drakkar project and it covers the period from 1958 to 2012 (dataset version 5.2). More information about this hindcast is given by Moat et al. (2016). We take monthly mean data from the hindcast, which spans from 1979 to 2012.

2.3 Computation of Meridional Energy Transport

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

2.3.1 Energy Budget in the Atmosphere

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

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

with c_p the specific heat capacity of dry air at a constant pressure (J/kgK), T the absolute temperature (K), L_v the specific heat of condensation (J/kg), q the specific humidity kg/kg , g the gravitational acceleration ($kg/m.s^2$), z the altitude (m) and v the zonal/meridional wind velocity (m/s). The northward propagation is positive. In addition, these four quantities can be divided into three groups: the dry static energy $I + \phi$, the moist static energy H and the kinetic energy k . A constant value of $c_p = 1004.64 J/kgK$ was used to compute the AMET with all the atmosphere reanalyses datasets.

In pressure coordinates, the total energy transport at a given latitude Φ_i can be expressed as:

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



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

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

5 where η indicates the number of the hybrid level.

Unfortunately, a direct estimation of AMET based on the equations above cannot provide a meaningful energy transport obtained from reanalyses data. It has been widely reported that reanalyses products suffer from mass inconsistency (Trenberth, 1991; Trenberth et al., 2002; Graversen, 2006; Graversen et al., 2007; Chiodo and Haimberger, 2010; Berrisford et al., 2011). Spurious sinks and sources mainly come from low spatial and temporal resolution, interpolation and regridding, and data assimilation. The interpolation from original model level to pressure level can introduce considerable error to the mass budget (Trenberth et al., 2002). Therefore we prevent interpolations onto the pressure levels and use data on the native model levels with a high temporal resolution. Trenberth (1991) provided a method to correct the mass budget through the use of the continuity equation. The method assumes that the mass imbalance mainly comes from the divergent wind fields and corrects the overall mass budget by adjusting the barotropic wind. The conservation of mass for a unit column of air can be represented as:

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

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

$$20 \quad E - P = \frac{\partial}{\partial t} \left(\int_{p_s}^{p_t} q \frac{dp}{g} \right) + \nabla \int_{p_s}^{p_t} (\mathbf{v} \cdot \mathbf{q}) \frac{dp}{g} \quad (5)$$

After determining the mass budget imbalance, we correct the barotropic wind fields (u_c, v_c) and calculate AMET. Figure 1 shows the total AMET and each component at 60°N estimated from ERA-Interim. In addition, recently there are some improved formulations of energy budget equations proposed by Mayer et al. (2017) and Trenberth and Fasullo (2018). But they mainly target on the tropical and extratropical regions and are not so relevant to our target area.



2.3.2 Energy Budget in the Ocean

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

$$5 \quad E = \oint_{\Phi=\Phi_i} \int_{z_b}^{z_0} \rho_0 c_{p_0} \theta \cdot v dz d\phi \quad (6)$$

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

$$10 \quad OHC = \oint_{\Phi=\Phi_i} \int_{z_b}^{z_0} \rho_0 c_{p_0} \theta dz d\phi \quad (7)$$

As a general problem known by oceanographers, there are sinks and sources in ocean reanalyses as well. However, the correction method adopted by the atmosphere is not feasible here, as a consequence of a varying sea surface height. So far there is no practical way to deal with the mass imbalance in the ocean. Moreover, the definition of OMET in this way cannot account for the recirculation (Zheng and Giese, 2009), which indicates the northward flow passing the Arctic acting as southward flow afterwards. To deal with this issue, we take a reference temperature θ_r ($^\circ C$). Then the quantification of OMET becomes:

$$15 \quad E = \oint_{\Phi=\Phi_i} \int_{z_b}^{z_0} \rho_0 c_{p_0} (\theta - \theta_r) \cdot v dz d\phi \quad (8)$$

Here we take θ_r equal to 0. Finally, operations in the “zonal” direction are different from their conventional meaning. As the three ocean reanalyses products used here are all built on a curvilinear grid, the zonal direction on the native model grid is curvilinear as well. Similar to the considerations made in Section 2.1, regridding from the native curvilinear grid to a uniform geographical grid will introduce large errors. So, we work on the original multi-pole grid and follow the native zonal directions when performing numerical operations. After applying this method the resulting OMET values are comparable to those in earlier publications (Trenberth and Caron, 2001; Wunsch, 2005; Trenberth and Fasullo, 2008).

2.4 Statistical Analysis

In order to understand the connection between MET and changes in the Arctic and compare to the results from numerical climate models or single reanalyses dataset (Graversen, 2006; Van der Swaluw et al., 2007; Graversen et al., 2008; Jungclaus



and Koenigk, 2010; Kapsch et al., 2013), in the following section we performed linear regressions on multiple fields with AMET and OMET. To test the significance of the regressions, we simply use student's t-test. Due to the slow response time of the ocean, the monthly mean OMET anomalies show a large autocorrelation. For a threshold of 0.6, we find a correlation time of 3 months. This effectively reduces the number of independent data points in the regression by a factor of 3. As a result, those regressions effectively influenced by the autocorrelation of OMET were performed after reducing the degree of freedom by 3. Another issue about autocorrelation is the implementation of low pass filter. Since a running mean of multiple years will increase the correlation, we only show the significance at monthly time scales. This means the relevant significance tests are performed with raw time series before applying the low pass filter.

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

3 Results

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

3.1 Overview of AMET and OMET

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

Apart from the climatology of MET, we are particularly interested in the variations across different time scales from midlatitudes towards the Arctic. The time series of AMET, integrated zonally over 60°N, are shown in Figure 3a. Again, we include "ERA-Interim res" only for reference. The seasonal cycle is dominant in each component as expected and the phase is very similar, but differences in the amplitudes are noted. The mean AMET provided by the chosen three atmospheric reanalyses agrees well. However, their variations differ from each other. In ERA-Interim, the standard deviation (std) of AMET is 0.88 PW, while MERRA2 has a relatively small std of 0.67 PW but in JRA55 the std is 1.21 PW. Hence it can be concluded that the



seasonal cycles of AMET presented by the chosen atmospheric reanalyses are different. After removing the seasonal cycle and applying a low pass filter, neither the amplitude nor the trend of the signals agree between the data sets (see Figure 3b). The std of the AMET anomaly in ERA-Interim is 0.07 PW, while in MERRA2 it is 0.12 PW and in JRA55 it is 0.04 PW. This implies that the variation of AMET anomalies are different in the chosen data sets. We further assess the sources of the difference in the next section.

For the ocean, all the reanalyses datasets agree well at almost all the latitudes except for the OMET between 30°N and 40°N, where the Gulf Stream resides. The difference can be explained by the models. GLORYS2V3 and SODA3 both have been generated with eddy-permitting models while ORAS4 has not. The eddy-permitting reanalyses with higher resolution, like GLORYS2V3 and SODA3, are capable of addressing the large scale turbulence. It has been shown that their eddy-permitting capacity can account for the large scale eddy variability and represent the eddy energy associated with both the Gulf Stream and the Kuroshio pathways well (Masina et al., 2017). Whereas, in ORAS4 the large scale eddies can not be resolved due to its relatively low resolution. To illustrate the differences, the spatial distributions of heat transport are shown in Figure 4. The plots show the monthly mean OMET at the Atlantic basin in January, 1996. At the latitude of the Gulf Stream (between 30°N and 40°N), a higher spatial variability, which represents more realistic patterns of the large scale eddy variability, is apparent in all datasets but ORAS4.

Similarly, we show the zonal integral of the OMET at 60°N in Figure 5. Differences in amplitude and trends can be observed in the unfiltered time series. The mean OMET and the std of all the OMET time series are similar (see Figure 5a). The mean OMET in ORAS4 is 0.47 PW, in GLORYS2V3 is 0.44 PW and in SODA3 is 0.46 PW. The NEMO hindcast gives a similar mean OMET of 0.47 PW. For the std of OMET, ORAS4 and the NEMO hindcast give 0.06 PW, while GLORYS2V3 and SODA3 give 0.07 PW. In terms of the difference in the OMET time series between the chosen products, it is not surprising that large differences appear after we take a running mean of 5 years when computing the OMET anomalies. However, the large variation of OMET anomalies in Figure 5b is not noticeable from their std. Given the time series of all the chosen reanalyses, ORAS4 resembles SODA3, especially after 1998. Whereas, GLORYS2V3 is clearly different from ORAS4 and SODA3 from 1998 to 2006. The differences can be tracked in the time series, which reveals that the initial years of GLORYS2V3 might experience some problems. The first 10 years in GLORYS2V3 are quite suspicious because of its large deviation from the other products. Such large differences should be noticeable in the heat content changes or surface fluxes. Nevertheless, after 2007 all the reanalyses time series agree well and the NEMO hindcast deviates from the reanalyses. It is noteworthy that the observations improve considerably around that period due to an increasing number of Argo floats in use (Riser et al., 2016). The reanalyses products used here are greatly influenced by the number of available in-situ observations. We further assess the sources of differences in the next section.

3.2 Source of Disparity

In order to further understand the difference between the AMET estimated from each atmosphere reanalyses product, we compare each component of AMET separately. Figure 6 gives the difference between each component of AMET at 60°N estimated from ERA-Interim against those from MERRA2 (Figure 6a) and JRA55 (Figure 6b). It can be noticed that the



differences mainly originate from meridional temperature transport ($vc_p T$). A simple linear regression shows the correlation between the difference of total energy transport and the difference of meridional temperature transport, taking ERA-interim and MERRA2, is 0.95, while for ERA-Interim and JRA55 that is 0.48. In addition, the correlation between the difference of total energy transport and the difference of geopotential energy transport (vgz), for ERA-interim and MERRA2 is 0.60 and
5 for ERA-Interim and JRA55 that is 0.07. For the other components, the correlations between them and the total difference are all smaller than 0.05. The results are all obtained with a confidence interval over 99%. This is generally the case as large differences in temperature transport between reanalyses products are found at all latitudes (not shown). Such differences are consistent with the fact that the temperature transport has the biggest contribution to the total AMET (see Figure 1). Note that the differences of each AMET component between every two products are of the same order of magnitude as the absolute
10 values of that component. Besides, the latent heat transport agrees well between all the chosen atmospheric products, in terms of the mean and anomalies (not shown). A similar result was found by Dufour et al. (2016) in their study using more reanalyses datasets.

In order to know the relative contribution of each field to the difference of the total AMET among the chosen reanalyses, a direct comparison of the vertical profile of temperature and meridional velocity fields between ERA-Interim and MERRA2
15 is presented in Figure 7. We take the monthly mean temperature and velocity fields of ERA-Interim and MERRA2 from 1994 to 1998, in which the biggest difference was observed (Figure 3, taking into account the running mean of 5 years). For the sake of a point-wise comparison, the fields from MERRA2 are interpolated onto the vertical grid of ERA-Interim. This shows that these two reanalyses products differ substantially regarding each variable field (Figure 7a and b). By taking the product of the mean temperature (meridional wind velocity) and the difference between meridional wind velocity (temperature), we
20 can qualitatively identify the relative contribution from the difference between each variable field (Figure 7c and d). This shows that the difference in meridional wind velocity between MERRA2 and ERA-Interim is responsible for the difference in temperature transport ($vc_p T$). 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.

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

For the ocean, fortunately independent observations of OMET in the Atlantic Ocean are available. First, OMET estimated from ORAS4, GLORYS2V3, SODA3 and the NEMO ORCA hindcast is evaluated against OMET measured at 26.5°N . Given in Figure 8, the inter-comparison shows that the reanalyses products capture roughly the mean amplitude of the OMET. Some large events are captured as well, such as the strong weakening in 2009. Statistically, the mean OMET provided by RAPID
35 ARRAY is $1.21 \pm 0.27PW$. It is higher than all the chosen products here. The mean OMET in ORAS4 is $0.66 \pm 0.27PW$, in



GLORYS2V3 it is $0.89 \pm 0.52PW$, in SODA3 it is $0.81 \pm 0.52PW$ and in NEMO hindcast is $1.05 \pm 0.21PW$. This means that all chosen products underestimate the mean OMET at $26.5^\circ N$ in the Atlantic basin. Of all products, ORAS4 has the largest bias. The std of OMET given by ORAS4 is the same as that from RAPID ARRAY, while both in GLORYS2V3 and SODA3 we find a higher std of OMET. The NEMO hindcast has a relatively small OMET std of 0.21 PW. In terms of the correlation and standard deviation, ORAS4 and the NEMO hindcast agree well with observations. It is noteworthy that NEMO does not assimilate ocean data. The simulation is only constrained by the surface fluxes. To conclude, the heat transport at $26.5^\circ N$ is too low in these products.

Moreover, the comparison of time series in the chosen reanalyses and OSNAP observations is given in Figure 9. Due to the limited length of the OMET time series, only ORAS4 and SODA3 are included in the comparison. It can be noticed that the OMET given by ORAS4 is quite comparable to that in OSNAP in terms of the amplitude and variations. For most of the time within the observation period, OMET in ORAS4 falls into the range of the OSNAP observation including the uncertainty margins. The mean of OMET in ORAS4 is $0.39 \pm 0.11PW$, which is quite similar to the mean OMET $0.45 \pm 0.07PW$ of OSNAP. However, OMET in SODA3 has a larger mean and standard deviation than the OMET in OSNAP and thus deviates from the observation.

Just as in the atmosphere we would like to study the temperature and meridional current velocity contributions to the ocean heat transport to identify the sources of the difference between products. However, due to the nature of curvilinear grid, the comparison of local fields after interpolation is not trustworthy. To get further insight, we calculate the ocean heat content (OHC), since the convergence of the heat transports are likely related to OHC change. A full budget analysis was not feasible as most datasets did not include the surface fluxes. Figure 10 illustrates the OHC (Figure 10a) and the OHC anomalies (Figure 10b) quantified from ORAS4, GLORYS2V3, SODA3 and the NEMO ORCA hindcast. It depicts the OHC integrated from $60^\circ N$ to $70^\circ N$ over all depths. The mean OHC in ORAS4 is $6.85 \pm 0.45 * 10^{22} J$, in GLORYS2V3 is $6.19 \pm 0.40 * 10^{22} J$ and in the NEMO hindcast is $6.89 \pm 0.39 * 10^{22} J$, while SODA3 shows a much smaller mean OHC of $4.51 \pm 0.40 * 10^{22} J$. The variations are very similar between chosen products. To conclude, for the OHC there are large difference between chosen products while their variations agree very well. Since OHC is a function of temperature fields only, this can imply that temperature profiles are different among all the chosen ocean reanalyses datasets. ORAS4 and the NEMO hindcast agree well. The differences of OHC between chosen products are partially consistent with the differences that we found for OMET. However, the OHC anomalies agree better with each other than the absolute OHC, which indicates that the trend of OHC is captured in a similar way among all the ocean reanalyses products.

3.3 MET and the Arctic

In previous sections it is found that MET of different reanalyses products at subpolar and subtropical latitudes differ substantially from each other. In order to further evaluate AMET and OMET given by different reanalyses and provide more insight, we investigate the links between MET and remote regions. We focus on the Arctic because previous studies indicate a strong role for subpolar MET in low frequency variability in the Arctic region. Given the complexity of the interaction between MET and the Arctic and the short time series available, determining cause-effect relations is out of scope for this paper. That is, we



aim to compare the relation between MET and the Arctic within each reanalysis product to investigate the physical plausibility and compare it with previous studies that use data from one reanalysis product or from coupled climate models (e.g. Graversen (2006); Van der Swaluw et al. (2007); Graversen et al. (2008); Jungclaus and Koenigk (2010); Kapsch et al. (2013)).

Many of these studies perform linear regressions between a time series of MET and gridpoint values of other physical variables. Here we follow the same procedure and perform linear regressions of multiple fields on AMET and OMET at 60°N for all the chosen products. We show linear regressions including all calendar months in order to compare directly to previous studies with models and reanalysis data. We do note that correlations can be higher when focusing on a particular season. For the sake of consistency, the regressions are carried out on the surface fields included in each respective reanalyses product. For instance, the regression of SLP on AMET estimated from ERA-Interim, involves SLP fields from ERA-Interim itself. For the ocean reanalyses, as they all apply forcing derived from ERA-Interim, the regressions are performed on the fields from ERA-Interim. Following the regressions performed on SLP by Van der Swaluw et al. (2007) and Jungclaus and Koenigk (2010), we repeated the same procedure here with AMET at annual scale.

The regression of SLP on AMET at 60°N in each atmospheric product is shown in Figure 11. In ERA-Interim, AMET is anticorrelated with SLP over the Greenland. It suggests that an increase in subpolar AMET is linked to a northward advection over the North Atlantic which can bring relatively warm and humid air into the Arctic. Such pattern is consistent with the relatively warm air over the Greenland Seas shown in Figure 12a. This figure shows the regression of 2 meter temperature (T2M) on AMET in ERA-Interim. A further eddy decomposition of AMET following the method from Peixoto and Oort (1992) indicates that heat transported by standing eddies has the biggest contribution to the total AMET (no shown), which is consistent with Graversen and Burtu (2016).

Given the difference in AMET amongst products, MERRA2 and JRA55 provide an entirely different story about AMET and the statistical relation with subpolar and Arctic atmospheric circulation. Hence, there is also large uncertainty in the assertion that heat and humidity transport by stationary eddies contribute to the changes in the subpolar and Arctic regions at annual to interannual scale.

Using ERA-40, Graversen (2006) found similar correlation between AMET and surface air temperature (SAT) at the Greenland Sea and Barents Sea as Figure 12a, without time lag. This is also consistent with a model study by Jungclaus and Koenigk (2010). Nevertheless, these patterns are found only in ERA-Interim, but not in the other reanalysis.

Moreover, similar to Van der Swaluw et al. (2007) and Jungclaus and Koenigk (2010), we investigate the link between the variability of OMET and variations of sea ice at interannual (~ 5 year) time scales. Unlike atmospheric fields, there are strong trends in OMET and Sea Ice Concentration (SIC). We removed them by applying a polynomial fit to the time series on each grid point. We find that the second order polynomial fit is able to capture the trend without losing variations at annual scale, for both the OMET and SIC. Hereafter we only address detrended OMET and SIC. The regressions of detrended SIC anomalies on detrended OMET anomalies at 60°N for all seasons are shown in Figure 13. The anticorrelation between SIC and OMET can be identified in the Greenland Sea, the Barents Sea, the Kara Sea and the East Siberian Sea within ORAS4 (Figure 13a) and SODA3 (Figure 13c). Meanwhile, GLORYS2V3 tells an entirely different story. This is mainly due to the difference between OMET in this dataset compared to the other ocean datasets during the 1990s as shown in Figure 5.



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

In this section we compared the reanalysis data with findings from previous studies. We found that ERA-Interim is most consistent with the results given by coupled numerical models, while MERRA2 and JRA55 do not corroborate model studies. For the ocean, results from ORAS4 and SODA3 are more consistent with literature. 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
10 plausible interannual to decadal variations in AMET.

4 Discussion

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

The regression of SIC on OMET suggests that sea ice variation is sensitive to changes of meridional energy transport at subpolar latitudes, which is noticed by other studies on SIC and MET as well (Van der Swaluw et al., 2007; Jungclaus and Koenigk, 2010; van der Linden et al., 2016). ORAS4 and SODA3 show a large anticorrelation between SIC and OMET around
25 Greenland Sea and Barents Sea. However, GLORYS2V3 does not show this relation. From the time series it seems that this product may have unrealistic heat transports in the first decade of the analysis. The strong connection between OMET from mid-to-high latitudes and the Arctic sea ice indicates a link between midlatitudes and the Arctic. Many studies that explored these remote links found large scale patterns over the Atlantic (Czaja and Frankignoul, 2002; Gastineau and Frankignoul, 2015; Delworth et al., 2017) However, the physical mechanism remains disputable. Overland et al. (2015) and Overland
30 (2016) propose that the multiple linkages between the Arctic and midlatitudes are based on the amplification of existing jet stream wave patterns, which might also be driven by the tropical and midlatitudes SST anomalies (Screen and Francis, 2016; Svendsen et al., 2018). Cohen et al. (2014) lists possible pathways for the teleconnection between the Arctic and midlatitudes, including changes in storm tracks, the jet stream, and planetary waves and their associated energy propagation. However, due



to the shortness of time series, a small signal-to-noise ratio, uncertain external forcing, and the internal atmospheric variability (Overland, 2016; Barnes and Screen, 2015), this question has no easy answer.

Previous studies have shown that the variations of total OMET are very sensitive to the changes of its overturning component (e.g. McCarthy et al. (2015); Lozier et al. (2019)). Hence, AMOC can serve as a indicator of the changes of OMET. In our case, a quantitative estimation of the difference in AMOC among the chosen datasets is beyond our scope. However, the downward trend of AMOC, which has been reported by several studies (Smeed et al., 2014; McCarthy et al., 2015; Oltmanns et al., 2018), is consistent the downward trend observed in OMET at 60°N in our chosen oceanic reanalyses (see Figure 5). After visiting six oceanic reanalyses datasets, Karspeck et al. (2017) find the reanalyses products are less consistent in their year-to-year AMOC variations. The discrepancy between AMOC represented by each reanalyses product may explain the difference in OMET in each reanalyses dataset.

5 Conclusions

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

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

Acknowledgements. The research was supported by the Netherlands eScience Center, Wageningen University, the National Oceanography Center in UK, and Blue Action project (European Union's Horizon 2020 research and innovation programme, grant number: 727852). The high resolution NEMO ORCA hindcast was complete in the project North Atlantic Climate System: Integrated Study (ACSIS) [grant



number NE/N018044/1]. The authors are grateful for the high performance computational infrastructure (HPC cloud and Cartesius) provided by SURFsara in the Netherlands. We would like to express our gratitude to all the researchers working on the reanalyses datasets and making the data open to the public. We also want to thank the OSNAP (Overturning in the Subpolar North Atlantic Program) project and the RAPID-WATCH MOC monitoring project for making the observation data in the North Atlantic freely available.



References

- Årthun, M., Eldevik, T., Smedsrud, L., Skagseth, Ø., and Ingvaldsen, R.: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat, *Journal of Climate*, 25, 4736–4743, 2012.
- Balmaseda, M. A., Mogensen, K., and Weaver, A. T.: Evaluation of the ECMWF ocean reanalysis system ORAS4, *Quarterly Journal of the Royal Meteorological Society*, 139, 1132–1161, 2013.
- 5 Barnes, E. A. and Screen, J. A.: The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it?, *Wiley Interdisciplinary Reviews: Climate Change*, 6, 277–286, 2015.
- Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., and Uppala, S.: The ERA-interim archive, ERA report series, pp. 1–16, 2009.
- 10 Berrisford, P., Kållberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A., Poli, P., and Sato, H.: Atmospheric conservation properties in ERA-Interim, *Quarterly Journal of the Royal Meteorological Society*, 137, 1381–1399, 2011.
- Carton, J. A., Chepurin, G. A., and Chen, L.: SODA3: a new ocean climate reanalysis, *Journal of Climate*, 2018.
- Chiodo, G. and Haimberger, L.: Interannual changes in mass consistent energy budgets from ERA-Interim and satellite data, *Journal of Geophysical Research: Atmospheres*, 115, 2010.
- 15 Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., et al.: Recent Arctic amplification and extreme mid-latitude weather, *Nature geoscience*, 7, 627, 2014.
- Comiso, J. C. and Hall, D. K.: Climate trends in the Arctic as observed from space, *Wiley Interdisciplinary Reviews: Climate Change*, 5, 389–409, 2014.
- Czaja, A. and Frankignoul, C.: Observed impact of Atlantic SST anomalies on the North Atlantic Oscillation, *Journal of Climate*, 15, 606–623, 2002.
- 20 Dee, D. P., Uppala, S. M., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, d. P., et al.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Quarterly Journal of the royal meteorological society*, 137, 553–597, 2011.
- Delworth, T. L., Rosati, A., Anderson, W., Adcroft, A. J., Balaji, V., Benson, R., Dixon, K., Griffies, S. M., Lee, H.-C., Pacanowski, R. C., et al.: Simulated climate and climate change in the GFDL CM2. 5 high-resolution coupled climate model, *Journal of Climate*, 25, 2755–2781, 2012.
- 25 Delworth, T. L., Zeng, F., Zhang, L., Zhang, R., Vecchi, G. A., and Yang, X.: The central role of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical component of the Atlantic Multidecadal Oscillation, *Journal of Climate*, 30, 3789–3805, 2017.
- Dufour, A., Zolina, O., and Gulev, S. K.: Atmospheric moisture transport to the Arctic: Assessment of reanalyses and analysis of transport components, *Journal of Climate*, 29, 5061–5081, 2016.
- 30 ECMWF: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate, Copernicus Climate Change Service Climate Data Store (CDS), 2017.
- Fasullo, J. T. and Trenberth, K. E.: The annual cycle of the energy budget. Part II: Meridional structures and poleward transports, *Journal of Climate*, 21, 2313–2325, 2008.
- 35 Ferry, N., Parent, L., Garric, G., Barnier, B., Jourdain, N. C., et al.: Mercator global Eddy permitting ocean reanalysis GLORYS1V1: Description and results, *Mercator-Ocean Quarterly Newsletter*, 36, 15–27, 2010.



- Ferry, N., Barnier, B., Garric, G., Haines, K., Masina, S., Parent, L., Storto, A., Valdivieso, M., Guinehut, S., and Mulet, S.: NEMO: the modeling engine of global ocean reanalyses, *Mercator Ocean Quarterly Newsletter*, 46, 46–59, 2012a.
- Ferry, N., Parent, L., Garric, G., Bricaud, C., Testut, C., Le Galloudec, O., Lellouche, J., Drevillon, M., Greiner, E., Barnier, B., et al.: GLORYS2V1 global ocean reanalysis of the altimetric era (1992–2009) at meso scale, *Mercator Ocean–Quarterly Newsletter*, 44, 2012b.
- 5 Francis, J. A., Vavrus, S. J., and Cohen, J.: Amplified Arctic warming and mid-latitude weather: new perspectives on emerging connections, *Wiley Interdisciplinary Reviews: Climate Change*, 8, e474, 2017.
- Ganachaud, A. and Wunsch, C.: Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data, *Nature*, 408, 453, 2000.
- Ganachaud, A. and Wunsch, C.: Large-scale ocean heat and freshwater transports during the World Ocean Circulation Experiment, *Journal*
10 *of Climate*, 16, 696–705, 2003.
- Gastineau, G. and Frankignoul, C.: Influence of the North Atlantic SST variability on the atmospheric circulation during the twentieth century, *Journal of Climate*, 28, 1396–1416, 2015.
- Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R.,
15 et al.: The modern-era retrospective analysis for research and applications, version 2 (MERRA-2), *Journal of Climate*, 30, 5419–5454, 2017.
- Gimeno-Sotelo, L., Nieto, R., Vázquez, M., and Gimeno, L.: The role of moisture transport for precipitation in the inter-annual and inter-daily fluctuations of the Arctic sea ice extension, *Earth System Dynamics*, 10, 121–133, 2019.
- 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.
- 20 Graversen, R. G. and Burtu, M.: Arctic amplification enhanced by latent energy transport of atmospheric planetary waves, *Quarterly Journal of the Royal Meteorological Society*, 142, 2046–2054, 2016.
- Graversen, R. G., Källén, E., Tjernström, M., and Körnich, H.: Atmospheric mass-transport inconsistencies in the ERA-40 reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 133, 673–680, 2007.
- Graversen, R. G., Mauritsen, T., Tjernström, M., Källén, E., and Svensson, G.: Vertical structure of recent Arctic warming, *Nature*, 451, 53,
25 2008.
- Hall, M. M. and Bryden, H. L.: Direct estimates and mechanisms of ocean heat transport, *Deep Sea Research Part A. Oceanographic Research Papers*, 29, 339–359, 1982.
- Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., Onoda, H., Onogi, K., Miyaoka, K., and Takahashi, K.: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, *Journal of the Meteorological Society of Japan*.
30 *Ser. II*, 94, 269–302, 2016.
- Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S., Kanzow, T., Bryden, H. L., Hirschi, J., Marotzke, J., Meinen, C., Shaw, B., et al.: Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5 N, *Journal of Climate*, 24, 2429–2449, 2011.
- Jourdan, D., Balopoulos, E., Garcia-Fernandez, M.-J., and Maillard, C.: Objective analysis of temperature and salinity historical data set over the Mediterranean Basin, in: *OCEANS’98 Conference Proceedings*, vol. 1, pp. 82–87, IEEE, 1998.
- 35 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.
- Kapsch, M.-L., Graversen, R. G., and Tjernström, M.: Springtime atmospheric energy transport and the control of Arctic summer sea-ice extent, *Nature Climate Change*, 3, 744, 2013.



- Karspeck, A., Stammer, D., Köhl, A., Danabasoglu, G., Balmaseda, M., Smith, D., Fujii, Y., Zhang, S., Giese, B., Tsujino, H., et al.: Comparison of the Atlantic meridional overturning circulation between 1960 and 2007 in six ocean reanalysis products, *Climate Dynamics*, 49, 957–982, 2017.
- Kobayashi, S., Ota, Y., Harada, Y., Ebata, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., et al.: The JRA-55 reanalysis: General specifications and basic characteristics, *Journal of the Meteorological Society of Japan. Ser. II*, 93, 5–48, 2015.
- Levitus, S., Boyer, T., Conkright, M., O'Brien, T., Antonov, J., Stephens, C., Stathoplos, L., Johnson, D., and Gelfeld, R.: NOAA Atlas NESDIS 18, World Ocean Database 1998: vol. 1: Introduction, US Government Printing Office, Washington DC, 346, 1998.
- Lozier, M., Li, F., Bacon, S., Bahr, F., Bower, A., Cunningham, S., de Jong, M., de Steur, L., Fischer, J., Gary, S., et al.: A sea change in our view of overturning in the subpolar North Atlantic, *Science*, 363, 516–521, 2019.
- 10 Madec, G.: NEMO reference manual, ocean dynamic component: NEMO-OPA, Note du Pôle modélisation, Inst. Pierre Simon Laplace, Fr, 2008.
- Marzocchi, A., Hirschi, J. J.-M., Holliday, N. P., Cunningham, S. A., Blaker, A. T., and Coward, A. C.: The North Atlantic subpolar circulation in an eddy-resolving global ocean model, *Journal of Marine Systems*, 142, 126–143, 2015.
- Masina, S., Storto, A., Ferry, N., Valdivieso, M., Haines, K., Balmaseda, M., Zuo, H., Drevillon, M., and Parent, L.: An ensemble of eddy-permitting global ocean reanalyses from the MyOcean project, *Climate Dynamics*, 49, 813–841, 2017.
- Mayer, M. and Haimberger, L.: Poleward atmospheric energy transports and their variability as evaluated from ECMWF reanalysis data, *Journal of Climate*, 25, 734–752, 2012.
- Mayer, M., Haimberger, L., Edwards, J. M., and Hyder, P.: Toward consistent diagnostics of the coupled atmosphere and ocean energy budgets, *Journal of Climate*, 30, 9225–9246, 2017.
- 20 McCarthy, G., Smeed, D., Johns, W., Frajka-Williams, E., Moat, B., Rayner, D., Baringer, M., Meinen, C., Collins, J., and Bryden, H.: Measuring the Atlantic meridional overturning circulation at 26 N, *Progress in Oceanography*, 130, 91–111, 2015.
- Miller, G. H., Alley, R. B., Brigham-Grette, J., Fitzpatrick, J. J., Polyak, L., Serreze, M. C., and White, J. W.: Arctic amplification: can the past constrain the future?, *Quaternary Science Reviews*, 29, 1779–1790, 2010.
- Moat, B., Josey, S., Sinha, B., Blaker, A., Smeed, D., McCarthy, G., Johns, W., Hirschi, J.-M., Frajka-Williams, E., Rayner, D., et al.: Major variations in subtropical North Atlantic heat transport at short (5 day) timescales and their causes, *Journal of Geophysical Research: Oceans*, 121, 3237–3249, 2016.
- Mogensen, K., Balmaseda, M. A., and Weaver, A.: The NEMOVAR ocean data assimilation system as implemented in the ECMWF ocean analysis for System 4, European Centre for Medium-Range Weather Forecasts, 2012.
- Molod, A., Takacs, L., Suarez, M., and Bacmeister, J.: Development of the GEOS-5 atmospheric general circulation model: Evolution from MERRA to MERRA2, *Geoscientific Model Development*, 8, 1339–1356, 2015.
- 30 Nummelin, A., Li, C., and Hezel, P. J.: Connecting ocean heat transport changes from the midlatitudes to the Arctic Ocean, *Geophysical Research Letters*, 44, 1899–1908, 2017.
- Oltmanns, M., Karstensen, J., and Fischer, J.: Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers, *Nature Climate Change*, 8, 300, 2018.
- 35 Onarheim, I. H., Eldevik, T., Årthun, M., Ingvaldsen, R. B., and Smedsrud, L. H.: Skillful prediction of Barents Sea ice cover, *Geophysical Research Letters*, 42, 5364–5371, 2015.
- Oort, A. H. and Vonder Haar, T. H.: On the observed annual cycle in the ocean-atmosphere heat balance over the Northern Hemisphere, *Journal of Physical Oceanography*, 6, 781–800, 1976.



- Outten, S., Esau, I., and Otterå, O. H.: Bjerknes Compensation in the CMIP5 Climate Models, *Journal of Climate*, 31, 8745–8760, 2018.
- Overland, J., Francis, J. A., Hall, R., Hanna, E., Kim, S.-J., and Vihma, T.: The melting Arctic and midlatitude weather patterns: Are they connected?, *Journal of Climate*, 28, 7917–7932, 2015.
- Overland, J. E.: A difficult Arctic science issue: Midlatitude weather linkages, *Polar Science*, 10, 210–216, 2016.
- 5 Peixoto, J. P. and Oort, A. H.: *Physics of climate*, 1992.
- Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., Gilbert, D., Xu, J., Pouliquen, S., Thresher, A., et al.: Fifteen years of ocean observations with the global Argo array, *Nature Climate Change*, 6, 145, 2016.
- Sandø, A., Gao, Y., and Langehaug, H.: Poleward ocean heat transports, sea ice processes, and Arctic sea ice variability in NorESM1-M simulations, *Journal of Geophysical Research: Oceans*, 119, 2095–2108, 2014.
- 10 Screen, J. A. and Francis, J. A.: Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability, *Nature Climate Change*, 6, 856, 2016.
- Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: A research synthesis, *Global and planetary change*, 77, 85–96, 2011.
- Shaffrey, L. and Sutton, R.: Bjerknes compensation and the decadal variability of the energy transports in a coupled climate model, *Journal*
- 15 *of Climate*, 19, 1167–1181, 2006.
- Simmons, A., Poli, P., Dee, D., Berrisford, P., Hersbach, H., Kobayashi, S., and Peubey, C.: Estimating low-frequency variability and trends in atmospheric temperature using ERA-Interim, *Quarterly Journal of the Royal Meteorological Society*, 140, 329–353, 2014.
- Simmons, A., Berrisford, P., Dee, D., Hersbach, H., Hirahara, S., and Thépaut, J.-N.: A reassessment of temperature variations and trends from global reanalyses and monthly surface climatological datasets, *Quarterly Journal of the Royal Meteorological Society*, 143, 101–119,
- 20 2017.
- Smeed, D., McCarthy, G., Cunningham, S., Frajka-Williams, E., Rayner, D., Johns, W., Meinen, C., Baringer, M., Moat, B., Duchez, A., et al.: Observed decline of the Atlantic meridional overturning circulation 2004–2012, *Ocean Science*, 10, 29–38, 2014.
- Steele, M., Morley, R., and Ermold, W.: PHC: A global ocean hydrography with a high-quality Arctic Ocean, *Journal of Climate*, 14, 2079–2087, 2001.
- 25 Susan Lozier, M., Bacon, S., Bower, A. S., Cunningham, S. A., Femke de Jong, M., De Steur, L., deYoung, B., Fischer, J., Gary, S. F., Greenan, B. J., et al.: Overturning in the Subpolar North Atlantic Program: A new international ocean observing system, *Bulletin of the American Meteorological Society*, 98, 737–752, 2017.
- Svendsen, L., Keenlyside, N., Bethke, I., Gao, Y., and Omrani, N.-E.: Pacific contribution to the early twentieth-century warming in the Arctic, *Nature Climate Change*, 8, 793, 2018.
- 30 Trenberth, K. E.: Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses, *Journal of Climate*, 4, 707–722, 1991.
- Trenberth, K. E. and Caron, J. M.: Estimates of meridional atmosphere and ocean heat transports, *Journal of Climate*, 14, 3433–3443, 2001.
- Trenberth, K. E. and Fasullo, J. T.: An observational estimate of inferred ocean energy divergence, *Journal of Physical Oceanography*, 38, 984–999, 2008.
- 35 Trenberth, K. E. and Fasullo, J. T.: Applications of an Updated Atmospheric Energetics Formulation, *Journal of Climate*, 31, 6263–6279, 2018.
- Trenberth, K. E. and Solomon, A.: The global heat balance: Heat transports in the atmosphere and ocean, *Climate Dynamics*, 10, 107–134, 1994.



- Trenberth, K. E., Stepaniak, D. P., and Caron, J. M.: Accuracy of atmospheric energy budgets from analyses, *Journal of Climate*, 15, 3343–3360, 2002.
- Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthélemy, A., Bricaud, C., Carton, J., Fučkar, N., Garric, G., Iovino, D., et al.: An assessment of ten ocean reanalyses in the polar regions, *Climate Dynamics*, pp. 1–38, 2018.
- 5 Uppala, S. M., Kållberg, P., Simmons, A., Andrae, U., Bechtold, V. D. C., Fiorino, M., Gibson, J., Haseler, J., Hernandez, A., Kelly, G., et al.: The ERA-40 re-analysis, *Quarterly Journal of the royal meteorological society*, 131, 2961–3012, 2005.
- van der Linden, E. C., Bintanja, R., Hazeleger, W., and Graversen, R. G.: Low-frequency variability of surface air temperature over the Barents Sea: causes and mechanisms, *Climate dynamics*, 47, 1247–1262, 2016.
- Van der Swaluw, E., Drijfhout, S., and Hazeleger, W.: Bjerknes compensation at high northern latitudes: The ocean forcing the atmosphere,
10 *Journal of climate*, 20, 6023–6032, 2007.
- Vonder Haar, T. H. and Oort, A. H.: New estimate of annual poleward energy transport by Northern Hemisphere oceans, *Journal of Physical Oceanography*, 3, 169–172, 1973.
- Wunsch, C.: The total meridional heat flux and its oceanic and atmospheric partition, *Journal of climate*, 18, 4374–4380, 2005.
- Yang, X.-Y., Fyfe, J. C., and Flato, G. M.: The role of poleward energy transport in Arctic temperature evolution, *Geophysical Research
15 Letters*, 37, 2010.
- Zhang, R.: Mechanisms for low-frequency variability of summer Arctic sea ice extent, *Proceedings of the National Academy of Sciences*, p. 201422296, 2015.
- Zheng, Y. and Giese, B. S.: Ocean heat transport in simple ocean data assimilation: Structure and mechanisms, *Journal of Geophysical Research: Oceans*, 114, 2009.

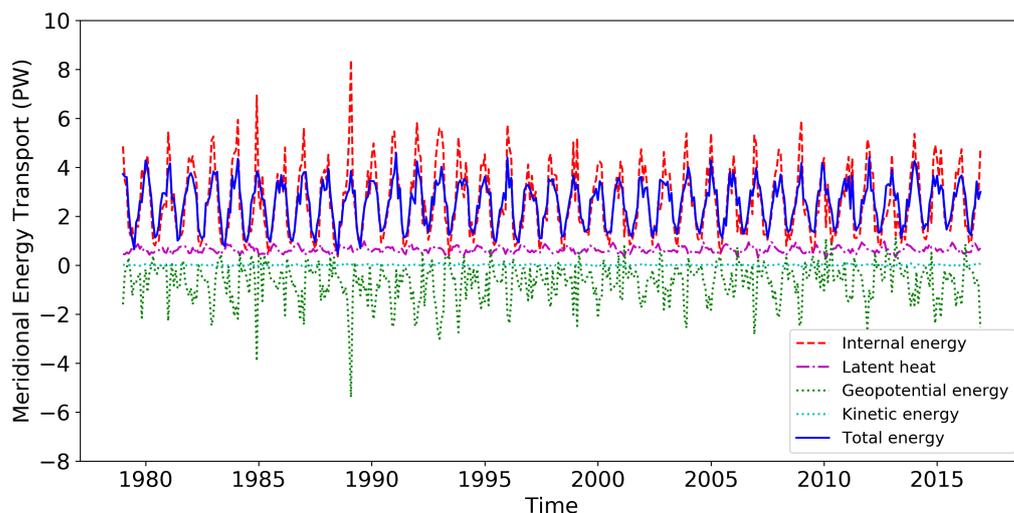


Figure 1. Estimation of AMET and each component at 60°N with ERA-Interim from 1979 to 2016. The unit is Peta Watt (PW).

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

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

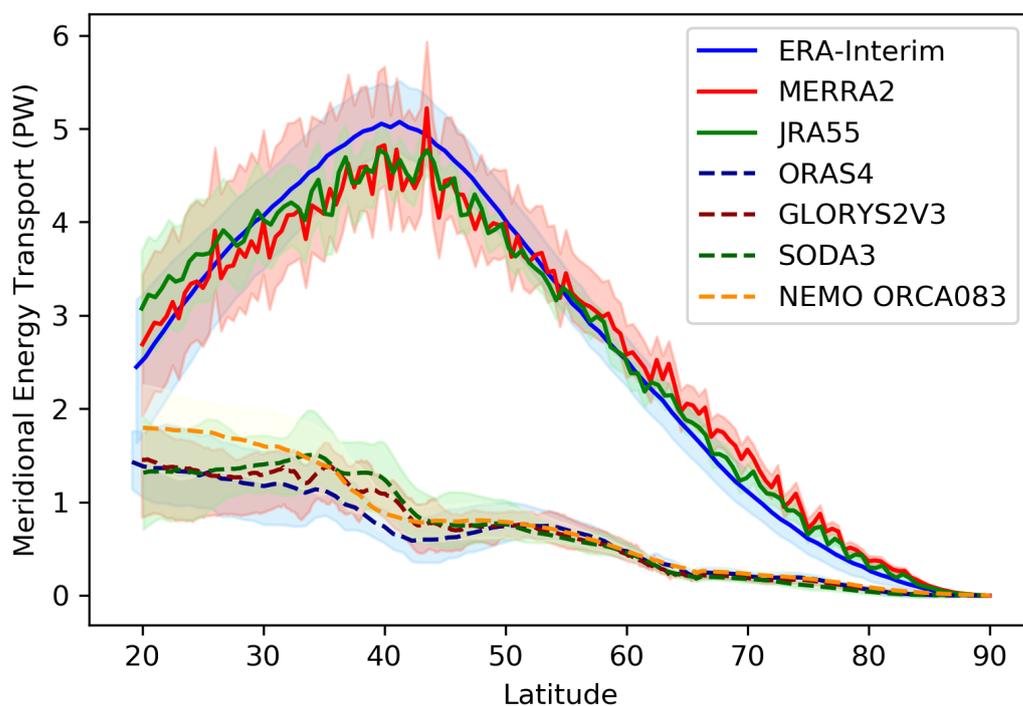


Figure 2. Mean AMET and OMET over the entire time span of each product as function of latitude in the Northern Hemisphere. AMET are illustrated with solid lines while OMET with dash lines. The shaded regions represent the full range of MET across the entire time series at each latitude. The time span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

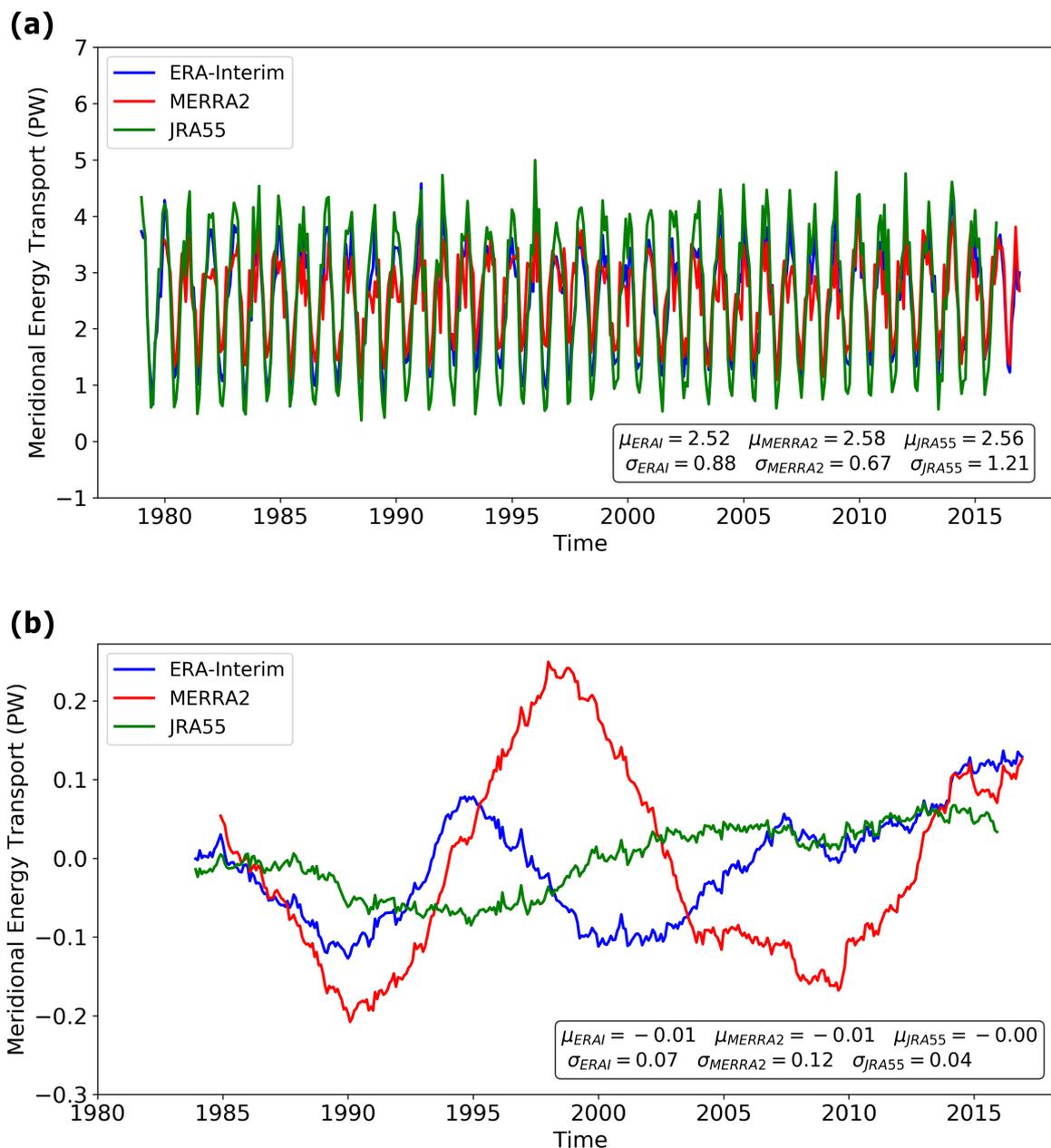


Figure 3. Time series of zonal integral of AMET at 60°N without/with low pass filter. (a) The original time series (top) and (b) the ones with low pass filter (bottom) include signals from ERA-Interim (blue), MERRA2 (red) and JRA55 (green). For the low pass filtered ones, we take a running mean of 5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

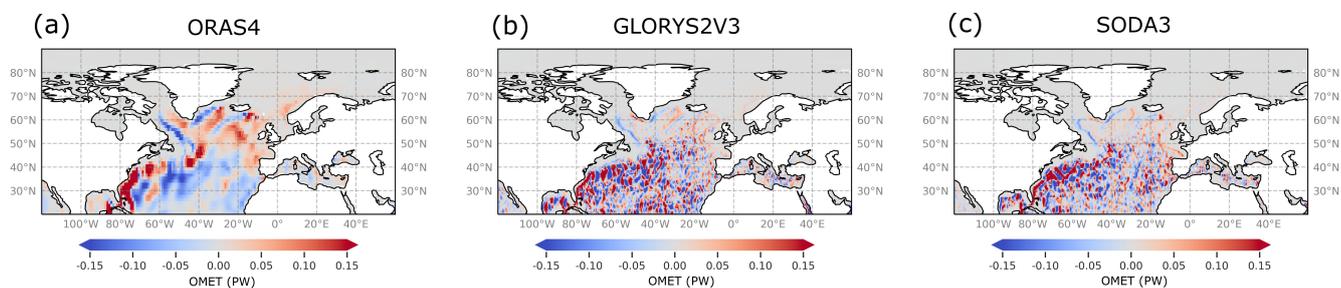


Figure 4. Monthly mean of OMET in January 1996 from three ocean reanalyses products (a) ORAS4 (b) GLORYS2V3 and (c) SODA3.

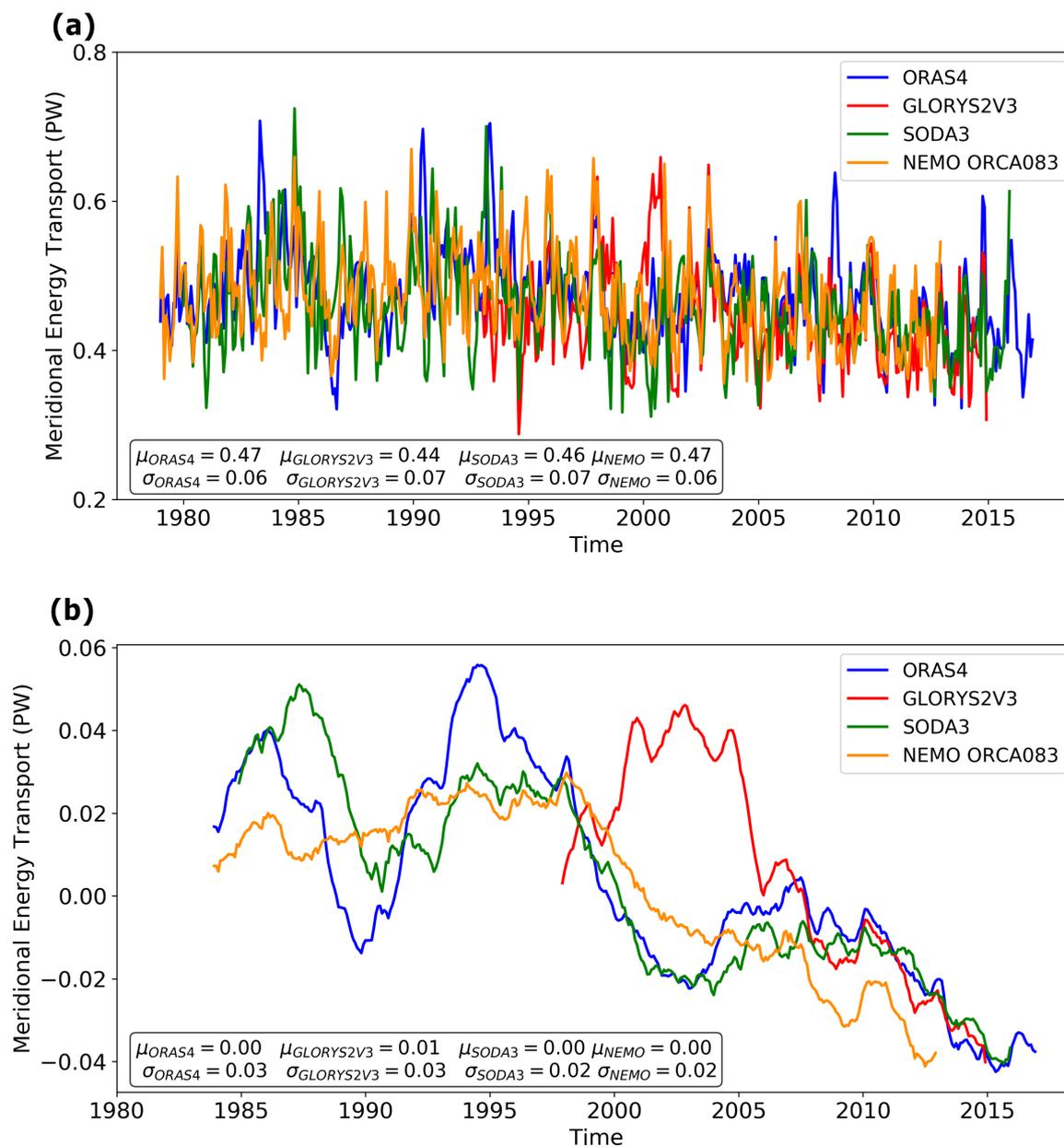


Figure 5. Time series of zonal integral of OMET at 60°N without/with low pass filter. (a) The original time series (top) and (b) the ones with low pass filter (bottom) include signals from ORAS4 (blue), GLORYS2v3 (red) and SODA3 (green). For the low pass filtered ones, we take a running mean of 5 years.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

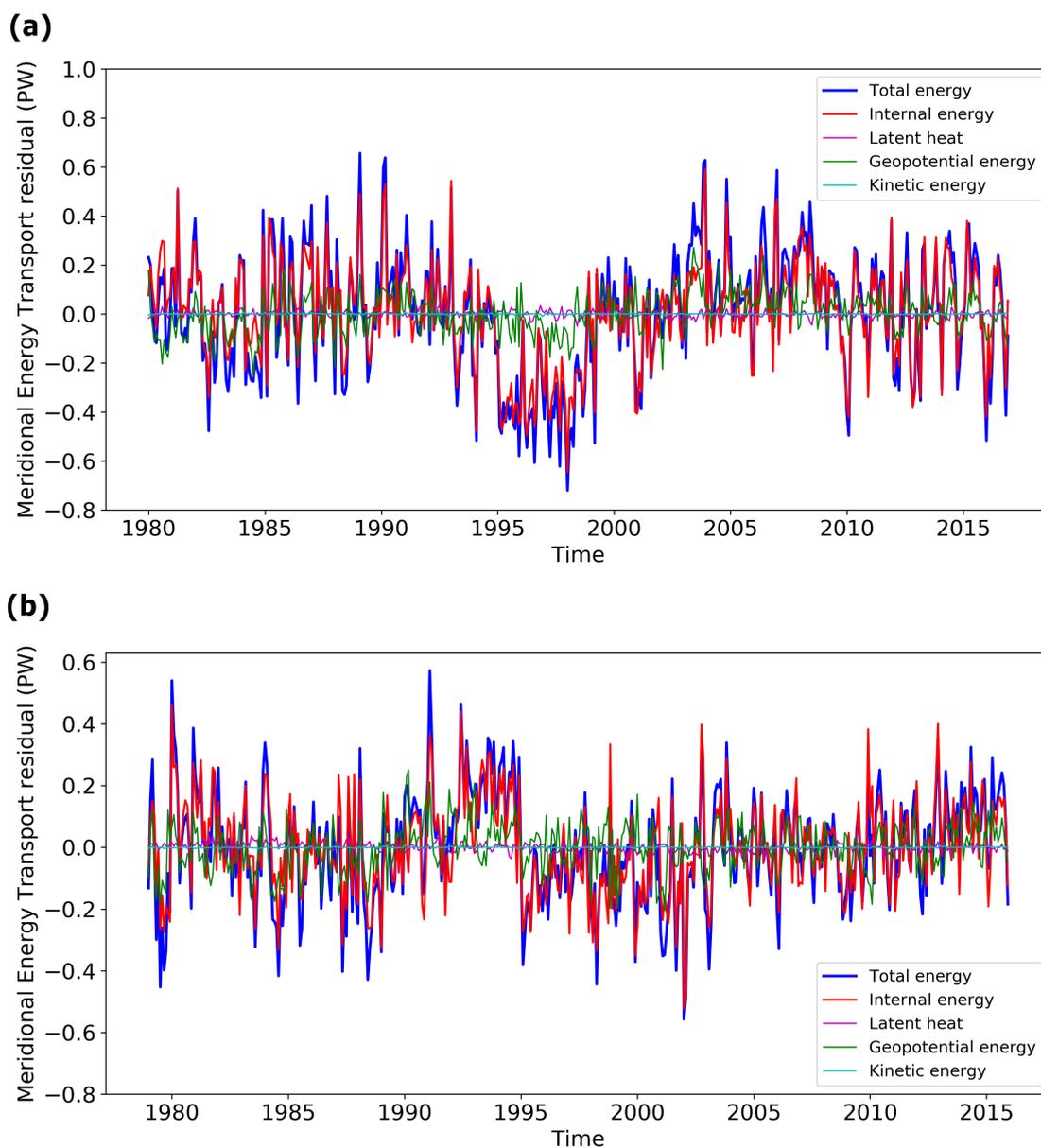


Figure 6. Difference in total AMET and each component between ERA-Interim, MERRA2 and JRA55 at 60°N in the same period. (a) The deviation between ERA-Interim and MERRA2, as well as (b) the deviation between ERA-Interim and JRA55, are defined as the component-wise subtraction. The unit is Peta Watt (PW).

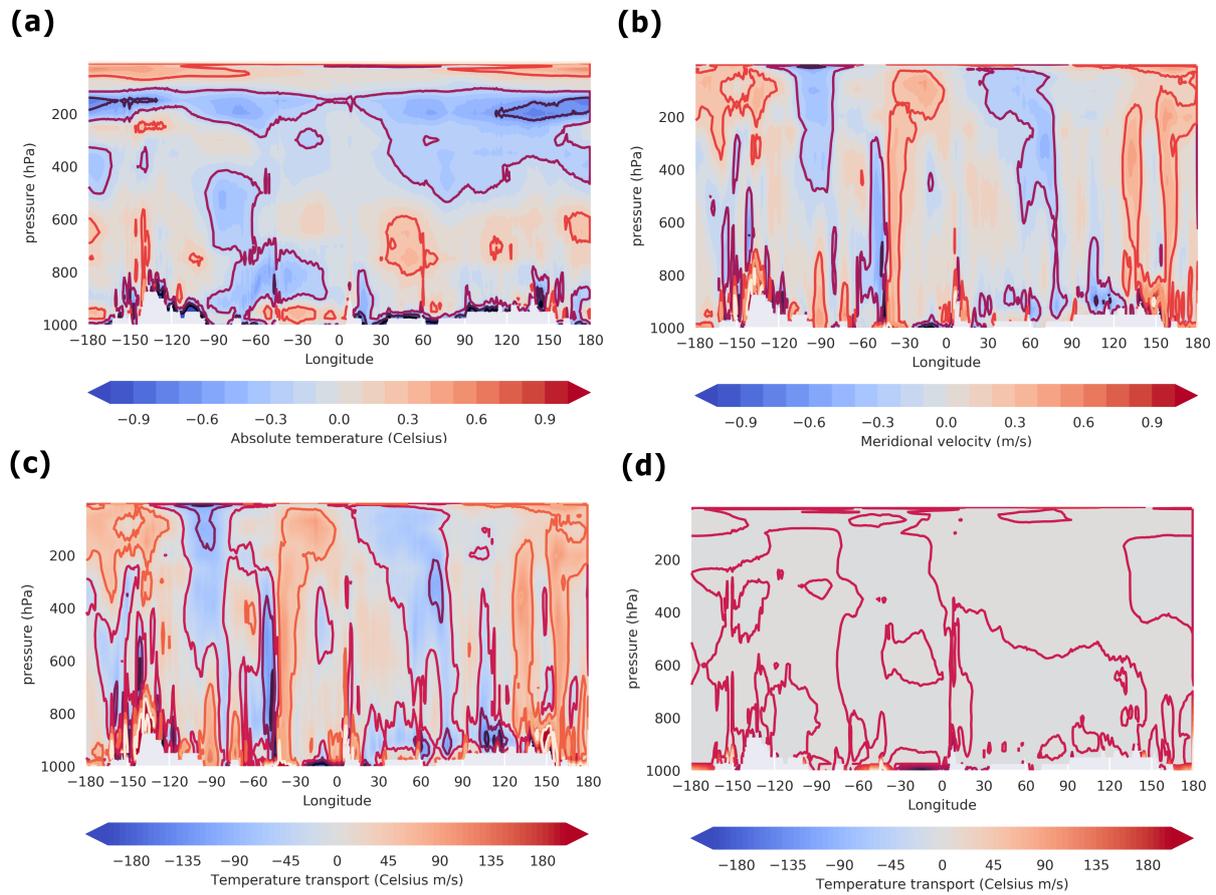


Figure 7. Difference in temperature, meridional wind velocity and temperature transport between MERRA2 and ERA-Interim at 60°N. The vertical profile of (a) temperature difference and (b) meridional wind velocity difference are calculated from the climatology of each fields from 1994 to 1998, respectively. The contributions to the total difference in temperature transport by the difference in (c) meridional wind velocity and (d) temperature between MERRA2 and ERA-Interim, are calculated as $T_{mean} \cdot (v_{erai} - v_{merra2})$ and $v_{mean} \cdot (T_{erai} - T_{merra2})$.

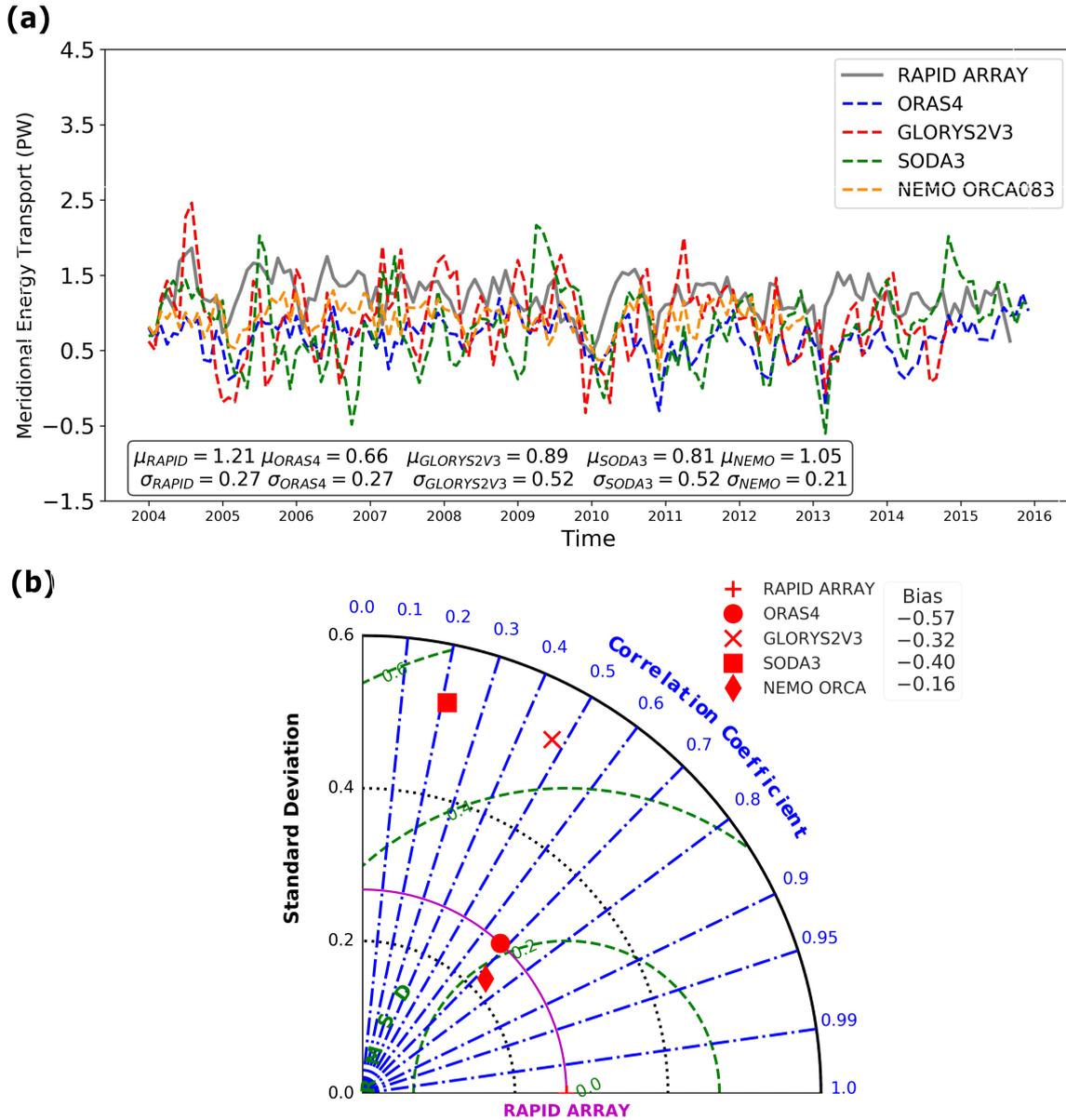


Figure 8. OMET estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the NEMO ORCA0083 hindcast (orange) compared to the RAPID ARRAY observation (gray) at 26.5°N across the Atlantic basin. The time series of OMET is presented in (a). The statistical properties are shown in (b) Taylor Diagram, 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.

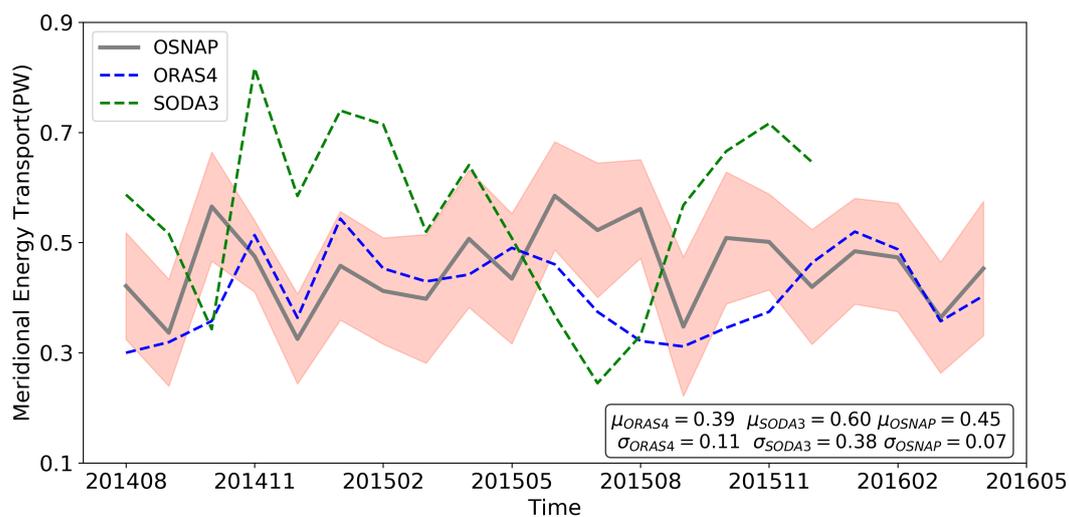


Figure 9. OMET estimated from ORAS4 (blue), SODA3 (green) and compared to the OSNAP observation (gray) at subpolar Atlantic basin. The range of uncertainty from OSNAP observation is marked by the red shade. σ is the standard deviation and μ is the mean of the entire time series.

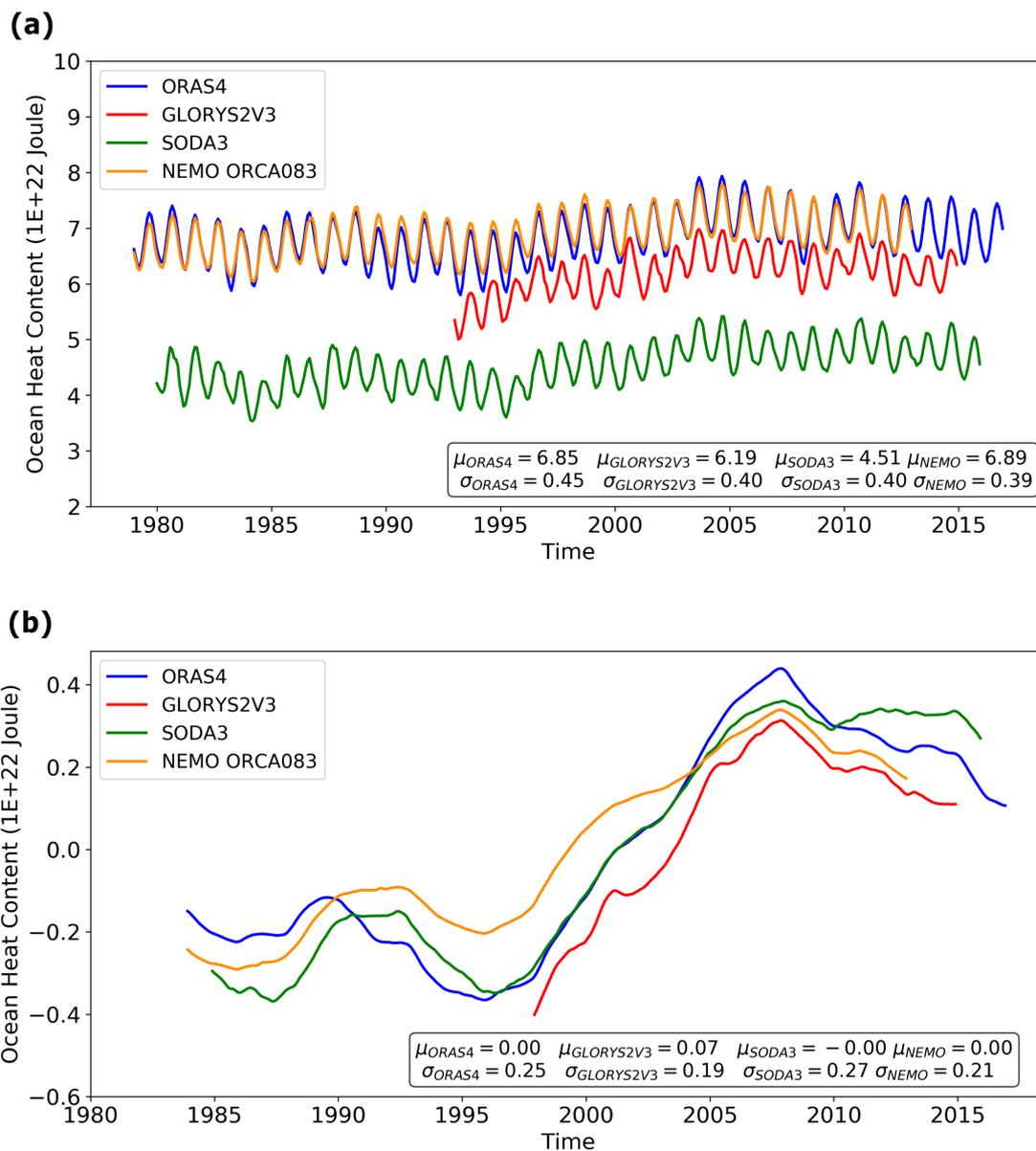


Figure 10. Time series of (a) ocean heat content (OHC) and (b) OHC anomalies with a low pass filter at 60°N . The OHC is the integral from surface to the bottom between 60°N and 70°N . It is estimated from ORAS4 (blue), GLORYS2V3 (red), SODA3 (green) and the NEMO ORCA hindcast (yellow).

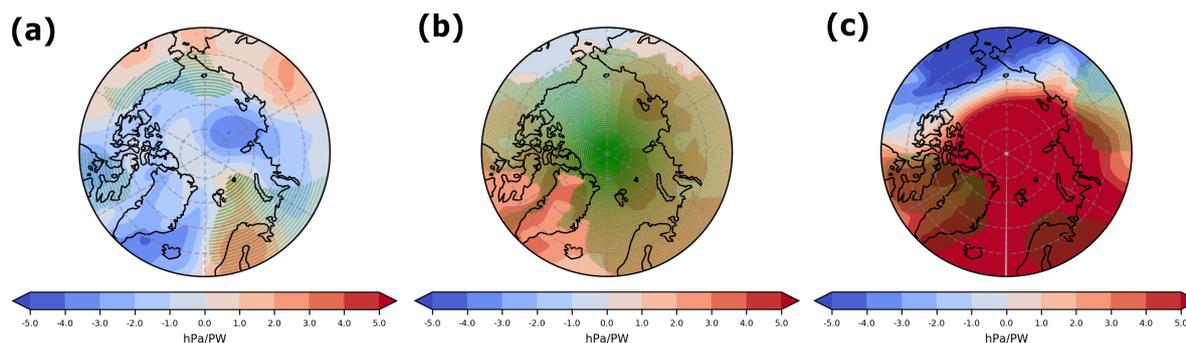


Figure 11. Regression of sea level pressure (SLP) anomalies on AMET anomalies at 60°N at annual scale with no time lag. All seasons are included. The monthly mean fields are used here after taking a running mean of 1 year. From left to right, they are the regression of SLP on AMET of (a) ERA-Interim, (b) MERRA2 and (c) JRA55. The green shades indicate a significance level of 95%.

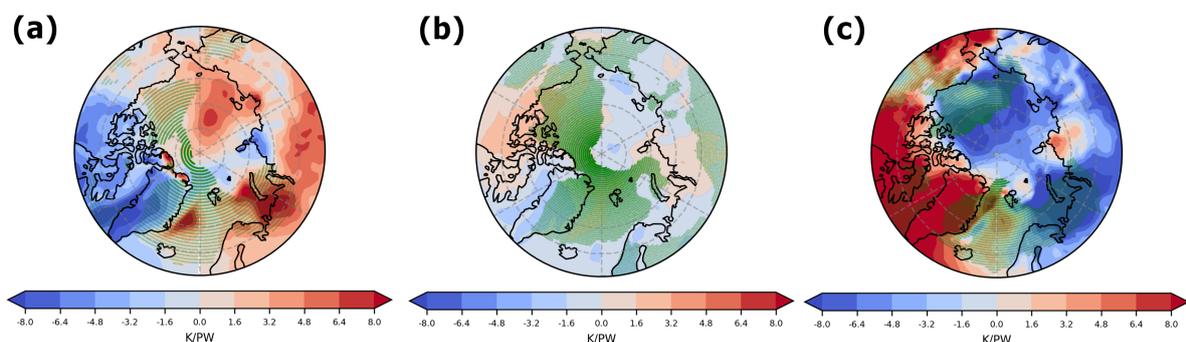


Figure 12. Regression of 2 meter temperature (T2M) anomalies on AMET anomalies at 60°N at interannual scale with no time lag. All seasons are included. The monthly mean fields are used here after taking a running mean of 5 years. From left to right, they are the regression of T2M on AMET of (a) ERA-Interim, (b) MERRA2 and (c) JRA55. The green shades indicate a significance level of 95%.

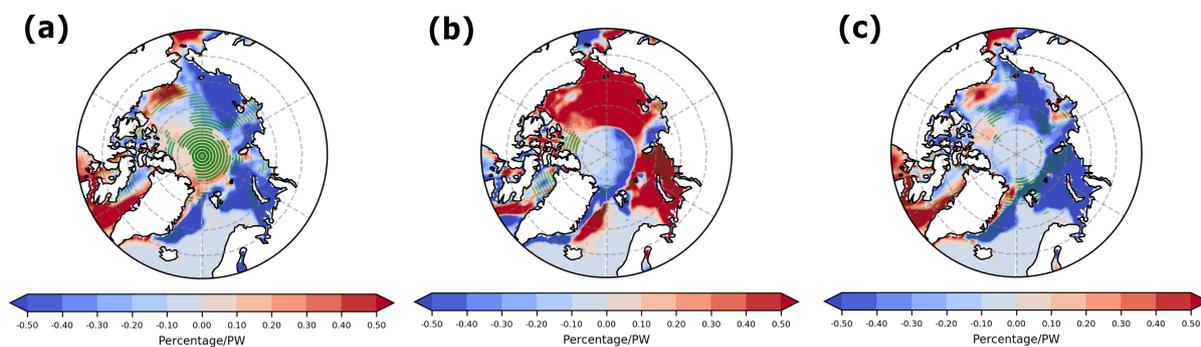


Figure 13. Regression of sea ice concentration (SIC) anomalies on OMET anomalies at 60°N for all seasons at interannual scale. OMET leads the SIC by one month. Both the SIC and OMET are detrended. From left to right, they are the regression of SIC on OMET of (a) ORAS4, (b) GLORYS2V3 and (c) SODA3. The green shades indicate a significance level of 95%.