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Key Points:
- CMIP5 models disagree on the main driver for the historical and future Arctic Ocean warming
- Differences in model behavior are mainly driven by differences in the meridional oceanic heat flux
- Future changes in net atmospheric surface flux and meridional oceanic heat flux are strongly linked through turbulent heat fluxes

Supporting Information:
- Supporting Information S1

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Drivers of Arctic Ocean warming in CMIP5 models

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Abstract We investigate changes in the Arctic Ocean energy budget simulated by 26 general circulation models from the Coupled Model Intercomparison Project Phase 5 framework. Our goal is to understand whether the Arctic Ocean warming between 1961 and 2099 is primarily driven by changes in the net atmospheric surface flux or by changes in the meridional oceanic heat flux. We find that the simulated Arctic Ocean warming is driven by positive anomalies in the net atmospheric surface flux in 11 models, by positive anomalies in the meridional oceanic heat flux in 11 models, and by positive anomalies in both energy fluxes in four models. The different behaviors are mainly characterized by the different changes in meridional oceanic heat flux that lead to different changes in the turbulent heat loss to the atmosphere. The multimodel ensemble mean is hence not representative of a consensus across the models in Arctic climate projections.

1. Introduction

The heat content of the Arctic Ocean is regulated by its lateral energy exchange through the meridional oceanic heat flux and its vertical energy exchange through the net atmospheric surface flux. It remains, however, unclear which of these two energy fluxes is primarily driving the observed [*Polyakov et al.*, 2010; *Zhang*, 2005; *Steele et al.*, 2008; *Serreze et al.*, 2007a] and projected [*Vavrus et al.*, 2011; *Koenigk and Brodeau*, 2013; *Stroeve et al.*, 2007, 2012] long-term Arctic Ocean warming. This is the question we address here.

For the historical period, the topic has been investigated using reanalyses. During the period from 1979 to 2001, in the annual mean state, nearly as much energy was gained by the ocean through the meridional oceanic heat flux as was lost to the atmosphere through the net atmospheric surface flux [*Serreze et al.*, 2007b]. Only a small amount of the energy inflow was taken up by the ocean in form of latent heat to melt sea ice, the sensible heat uptake being near to zero. From 2000 to 2015, however, both latent and sensible heat uptake by the ocean were observed and were found to be mainly driven by the meridional oceanic heat flux up to 2007 and mainly driven by the radiative fluxes from 2007 onward [*Mayer et al.*, 2016].

For a more extensive analysis on longer time scales, including future projections, general circulation models (GCMs) are needed. Up to now, the future evolution of the different components of the Arctic Ocean energy budget has only been investigated separately. On the one hand, the net atmospheric surface flux was found to increase over the whole Arctic domain (land and ocean) until the end of the 21st century, using the model ensemble from the third phase of the Coupled Model Intercomparison Project Phase 3 (CMIP3) [*Sorteberg et al.*, 2007]. On the other hand, the northward oceanic heat transport was found to increase as well until the end of the 21st century, using the EC-EARTH model [*Koenigk and Brodeau*, 2013]. These results suggest that both the net atmospheric surface flux and the meridional oceanic heat flux could, in principal, provide the necessary energy for Arctic Ocean warming. However, as the energy fluxes were investigated separately without direct comparison to each other and to changes in the ocean heat storage, the main driver of the long-term warming cannot clearly be inferred from these studies.

We investigate the Arctic Ocean energy budget as a whole to understand if the simulated long-term Arctic Ocean warming during the late 20th and the 21st century is mainly driven by changes in the net atmospheric surface flux or by changes in the meridional oceanic heat flux. To this purpose, we examine the evolution of the different components of the Arctic Ocean energy budget in data from 26 GCMs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). By studying the energy budget in a closed framework, we can directly attribute changes in the energy storage of the Arctic Ocean to changes in the two energy fluxes.

2. Methods and Data

2.1. Arctic Ocean Energy Budget

The total Arctic Ocean heat content H_{tot}, defined here for the ocean north of 66°N, can be decomposed as follows:

$$H_{tot} = H_{sens} + H_{lat} \tag{1}$$

where H_{sens} is the sensible heat content of the ocean water and H_{lat} the latent heat content of the sea ice and snow on sea ice. As shown in both observational studies from *Serreze et al.* [2007b] and *Mayer et al.* [2016], the change in latent heat content of snow can be neglected, and we will do so in this study as well.

The change in total ocean heat content in a given period, called hereafter total ocean heat storage ΔH_{tot}, is regulated by the energy fluxes at its boundaries integrated over the given time period and domain. These fluxes are the net atmospheric surface flux F_{sfc} and the meridional oceanic heat flux F_{mer}:

$$\Delta H_{tot} = \Delta H_{sens} + \Delta H_{lat} = \Delta H_{sfc} + \Delta H_{mer} \tag{2}$$

$$\Delta H_{sfc} = \int\int F_{sfc}\, \mathrm{d}A\, \mathrm{d}t = \int_{1\ \mathrm{year}} \int_{66°\mathrm{N}}^{90°\mathrm{N}} \left(F_{SW\downarrow} - F_{SW\uparrow} + F_{LW\downarrow} - F_{LW\uparrow} + F_{S} + F_{L} \right) \mathrm{d}A\, \mathrm{d}t \tag{3}$$

where $F_{SW\downarrow}$ and $F_{SW\uparrow}$ are the incoming and outgoing shortwave radiation, $F_{LW\downarrow}$ and $F_{LW\uparrow}$ are the incoming and outgoing longwave radiation, and F_S and F_L are the sensible and latent heat flux. All fluxes are defined as positive into the Arctic Ocean domain, except $\mathrm{F}_{SW\uparrow}$ and $\mathrm{F}_{LW\uparrow}$.

Due to energy conservation, the energy exchanged through the meridional oceanic heat flux can be computed as a residual from the two other components:

$$\Delta H_{mer} = \int\int F_{mer}\, \mathrm{d}A\, \mathrm{d}t = \Delta H_{tot} - \Delta H_{sfc}. \tag{4}$$

We investigate changes in the three components of the energy budget presented in equations (2)–(4) compared to a reference period defined here from 1861 to 1960. To this purpose, we compute anomalies of each of the components by subtracting their mean state during this reference period. Cumulated over 1961 to 2099, the resulting anomalies yield the total anomalous energy gained or lost by or through the different components over the late 20th and 21st century.

2.2. Data

We use data from 26 GCMs run in the CMIP5 framework (see Table S1 in the supporting information). The models used in this study were chosen following the availability of the following variables: incoming/outgoing longwave radiation, incoming/outgoing shortwave radiation, sensible/latent heat flux, sea ice concentration, sea ice thickness, and ocean potential temperature. Note that the more terms we include in our analysis, the fewer models can be used as not all institutes provide all the variables of interest to the CMIP5 archive. For example, we further use the water mass transport across the Barents Sea Opening, the Fram Strait, the Canadian Archipelago, and the Bering Strait from those seven models where these values appear reasonable (see Figure S1 in the supporting information). The sea ice export across Fram Strait is available for 10 models and can easily be computed for 2 additional models. The mass transport and sea ice export across the Fram Strait are used as proxies for the mass transport and sea ice export across the Denmark Strait, as changes in these variables are comparable in those two regions.

We conduct our analysis on data covering the period 1861 to 2099, using historical simulations for the period between 1861 and 2005 and Representative Concentration Pathway 4.5 simulations for the period between 2006 and 2099. If several realizations or ensemble members are available for a model, the ensemble mean is used.

2.3. Method Evaluation

We use one of the GCMs that provides all the components of the Arctic Ocean energy budget (MPI-ESM-LR), including snow on sea ice and the oceanic heat flux, to evaluate our method. We use equation (4) to compute the annual mean meridional oceanic heat flux F_{mer} and compare it to direct model output from the model for F_{mer}. This yields reasonable results (see Figure 1), with an average difference between the two values of F_{mer} of 0.192 ± 0.429 W/m^2, i.e., around 1% of the flux value. If the latent energy of snow is included in the computation of ΔH_{tot}, the difference changes by 0.001 W/m^2, confirming that the changes in snow cover can be neglected from an energetic point of view.

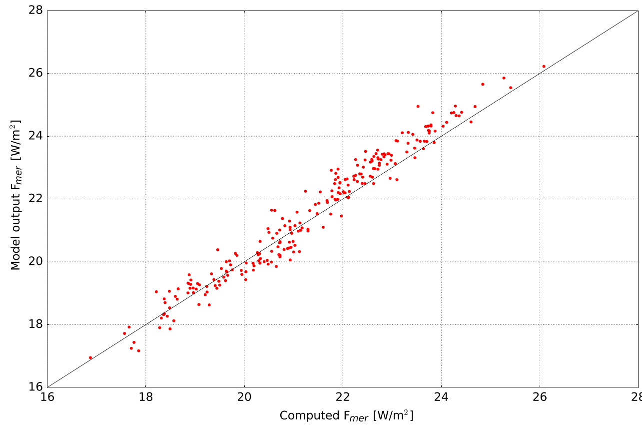

Figure 1. Annual mean meridional oceanic heat flux given by the model against annual mean meridional oceanic heat flux computed as a residual (in W/m^2) with equation (4) for MPI-ESM-LR.

3. Drivers of the Arctic Ocean warming

As a first step, we examine the relative roles of changes in the net atmospheric surface flux and meridional oceanic heat flux on the Arctic Ocean warming. The multimodel ensemble mean suggests that the ocean warming is mainly driven by positive anomalies in the meridional oceanic heat flux (see Figure 2, first row, first box). However, this does not represent a consensus across the individual models.

Although the total cumulated energy resulting from anomalies in the total ocean heat storage is positive in all models, the models disagree on the evolution of the net atmospheric surface flux and the meridional oceanic heat flux. In 11 models (model names in red in Figure 2, called M_{atm} hereafter), energy is gained by the ocean due to positive anomalies in the net atmospheric surface flux, while this gain is compensated partly by negative anomalies in the meridional oceanic heat flux. In 11 other models (model names in light blue in Figure 2, called M_{oc} hereafter), the opposite is true. In the four remaining models (model names in grey in Figure 2, called M_{both} hereafter), energy is gained by positive anomalies in both the net atmospheric surface flux and the meridional oceanic heat flux.

As a consequence, although we have used several models with the goal of inferring a robust conclusion, there is no consensus across the models about whether the ocean warming is mainly driven by changes in the vertical energy exchange with the atmosphere or in the lateral energy exchange with the ocean from lower latitudes. We therefore turn to the changes in the drivers of the net atmospheric surface flux and meridional oceanic heat flux to understand the processes steering the different evolution of the energy fluxes in the models.

4. Drivers of Changes in the Energy Fluxes

We examine differences between the end of the 21st century (2079–2099) and the reference period (1861–1960) in variables influencing the net atmospheric surface flux and the meridional oceanic heat flux (see Figure 3). Our goal is to understand the different behaviors between the three model categories defined in section 3. We compute the correlation coefficient between the change in the variables and the change in both the net atmospheric surface flux (upper values in Figure 3) and the meridional oceanic heat flux (lower values in Figure 3). The net atmospheric surface flux and meridional oceanic heat flux are strongly negatively correlated ($r = -0.97$). In addition, we find significant correlations ($p < 0.05$, bold in Figure 3) with the net atmospheric surface flux for seven variables and with the meridional oceanic heat flux for 12 variables. Note that the values of the correlation coefficients might be biased slightly high because of model interdependence [*Knutti et al.*, 2013]. In the following, we present changes influencing the net atmospheric surface flux and the meridional oceanic heat flux, then we suggest processes linking changes in the two energy fluxes.

4.1. Changes in the Net Atmospheric Surface Flux

Changes in the net atmospheric surface flux are driven by changes in the shortwave radiation, longwave radiation, and turbulent (sensible and latent) heat fluxes. All models show an increase in net shortwave radiation linked to the decrease in outgoing shortwave radiation. Also, they all show an increase in both incoming and

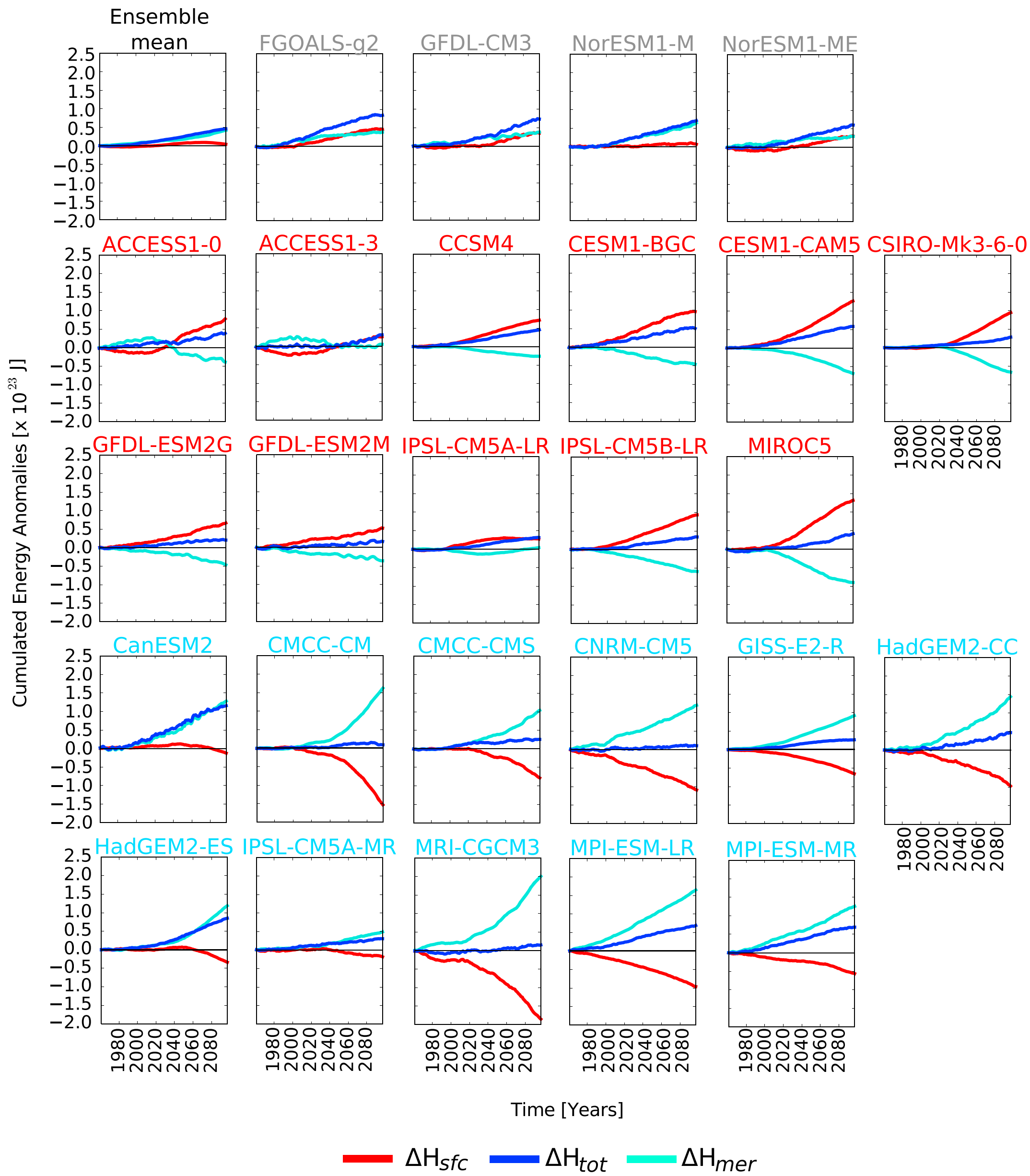

Figure 2. Cumulated anomalies relative to the reference period (1861–1960) for ΔH_{tot} (dark blue line), ΔH_{sfc} (red line), and ΔH_{mer} (light blue line) (in 10^{23} J). The models are divided into three categories: M_{atm} (red font), M_{oc} (light blue font), and M_{both} (grey font).

outgoing longwave radiation but disagree on which of the two longwave fluxes increases more. Hence, the models disagree on the sign of the change in the net longwave radiation. Still, all models agree on an increase in the sum of the net radiative fluxes, i.e., an increase in radiative heat gain by the ocean. However, changes in shortwave radiation, longwave radiation, and the sum of the two are not significantly correlated with the changes in the net atmospheric surface flux.

In contrast, the changes in turbulent heat fluxes are significantly correlated with the change in the net atmospheric surface flux ($r = 0.68$). The net atmospheric surface flux decreases with increasing turbulent heat loss to the atmosphere. The changes in the different atmospheric surface fluxes suggest that the negative anomalies in net atmospheric surface flux in M_{oc} models are primarily driven by an increase in turbulent heat loss from the ocean to the atmosphere which is larger than the increase in radiative heat gain by the ocean. The positive anomalies in net atmospheric surface flux in M_{atm} and M_{both} models are primarily driven by an

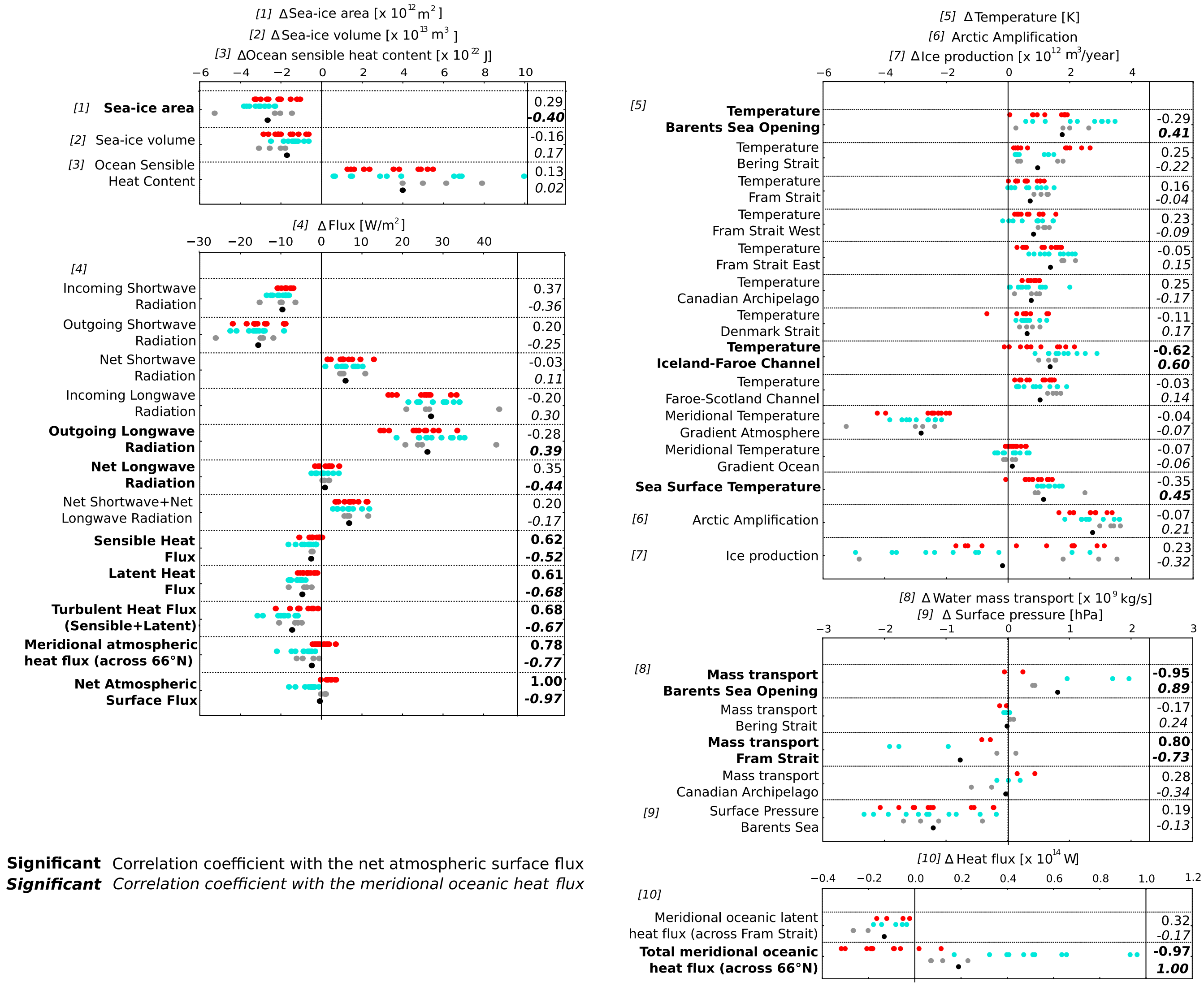

Figure 3. Change in variables having an influence on the Arctic Ocean net atmospheric surface flux and meridional oceanic heat flux between end of the 21st century (2079 to 2099) and the reference period (1861 to 1960) for each model. Colors stand for the model categories (red: M_{atm}, light blue: M_{oc}, grey: M_{both}, and black: multimodel ensemble mean). Coefficients and variables in bold show a significant correlation between the change in the given variable and the change in the net atmospheric surface flux and/or the change in meridional oceanic heat flux. Numbers in brackets represent which units describe the given variable(s). The positive direction for the mass transports is into the domain.

increase in radiative heat gain by the ocean which is larger than the increase in turbulent heat loss from the ocean to the atmosphere.

4.2. Changes in the Meridional Oceanic Heat Flux

The available variables do not allow us to accurately compute the heat transports at the different Arctic Ocean lateral boundaries. This is because the meridional mass transport in different depths is not provided. We therefore use changes in mass transport, temperature, and sea ice export averaged at the different boundary regions as proxies to understand changes in oceanic heat inflow and outflow.

For the inflow, we examine the inflow regions of our domain (Bering Strait, Iceland-Faroe Channel, and Faroe-Scotland Channel) and, additionally, the Barents Sea Opening inside the domain. We find the strongest correlation between the meridional oceanic heat flux and the mass transport at the Barents Sea Opening (r = *0.89*). Additionally, the water temperature increases in all inflow regions, significantly correlated with the change in meridional oceanic heat flux in the Iceland-Faroe Channel (r = *0.60*) and at the Barents Sea

Opening ($r = 0.41$). Changes in the meridional oceanic heat inflow are therefore strongly linked to changes in mass transport and water temperature on the Atlantic side.

For the outflow, we examine the outflow regions of our domain (Denmark Strait and Canadian Archipelago) and, additionally, the Fram Strait inside the domain. We find that the water temperature increases and the sea ice export decreases in all models in these regions, which both lead to an increase in the energy outflow. We also find a strong negative correlation between the meridional oceanic heat flux and the mass transport at the Fram Strait ($r = -0.73$). We suggest that this is a consequence of the increased mass transport through the Barents Sea Opening owing to mass conservation.

The Fram Strait is both inflow (eastern part) and outflow region (western part) concurrently. We attempt to examine the two parts separately by dividing the Atlantic Water layer (upper 1000 m) within the Fram Strait meridionally. Doing so, we do not find any significant correlation between temperature changes in either of the two regions and changes in the meridional oceanic heat flux or changes in the net atmospheric surface flux. As the mass transport is only given across a horizontal line through the whole width of the Fram Strait and cannot be divided similarly, we cannot draw any conclusion in regard to differences in the mass transport changes.

We infer from the changes in temperature and mass transport in the inflow and outflow regions that positive anomalies in the net meridional oceanic heat flux in M_{oc} and M_{both} models are primarily driven by an increase in both the water mass transport and the water temperature at the inflow, especially the Barents Sea Opening. Negative anomalies in the net meridional oceanic heat flux in M_{atm} models seem to be primarily driven by an increase in the water temperature at the outflow and decrease in sea ice export which both lead to an increase in energy outflow that compensates the small increase in energy inflow in these models.

4.3. Processes Linking Changes in the Energy Fluxes

We now turn to analyzing the interrelationship between the net atmospheric surface flux and the meridional oceanic heat flux to identify the main driver for the differences between the model categories. In doing so, it is instructive to first briefly consider the linkages between the oceanic and atmospheric meridional heat fluxes. In a steady climate, these two fluxes are linked because of Bjerknes compensation, a process in which changes in the oceanic meridional heat flux are compensated by changes in the atmospheric meridional heat flux [*Bjerknes*, 1964; *Van der Swaluw et al.*, 2007; *Jungclaus and Koenigk*, 2010].

In the model simulations considered here, the climate is not in steady state. Nevertheless, we find a strong negative correlation between the two different meridional heat fluxes ($r=-0.77$). Hence, we conjecture that Bjerknes compensation is at work also in the simulated transient climate, which implies that differences in the Arctic Ocean energy budget evolution are ultimately driven by changes in the oceanic meridional heat flux.

This also applies to the explanation for the different model categories that we identified. In all models, increasing net radiative fluxes provide a surplus of energy to the ocean, leading to an increase in sea surface temperature and sea ice area loss. These effects in turn lead in all models to an increase in turbulent heat loss to the atmosphere, counteracting the increase in radiative heat gain. In M_{oc} models, the sea surface warming, sea ice loss, and consequent increase in turbulent heat loss are amplified by the additional heat gain through the increased meridional oceanic heat flux, leading to a negative change in the net atmospheric surface flux. The ocean loses additional heat to the atmosphere. In contrast, in M_{atm} models, the additional turbulent heat loss is decreased because of the decrease in the meridional oceanic heat flux. Hence, in these models, the change in net atmospheric surface flux is positive, the ocean gains additional heat from the atmosphere.

Although the models disagree on the source of energy for the ocean warming, they agree that changes in the meridional oceanic heat flux are largely compensated by respective changes in the net atmospheric surface flux (Figure 4). The resulting change in ocean heat storage is comparably small ($\Delta H_{\mathrm{tot}} = +4.6 \pm 2.6 \times 10^{22}$ J between 1961 and 2099) but very similar across the models, with a regression fit being close to a one-to-one fit (Figure 4, $r = -0.95$).

Hence, under the same forcing, the models agree on the order of magnitude of the surplus energy stored by the Arctic Ocean. However, because of differences in meridional oceanic heat flux, they disagree on the dominating mode of transport for the surplus energy from low to high latitudes.

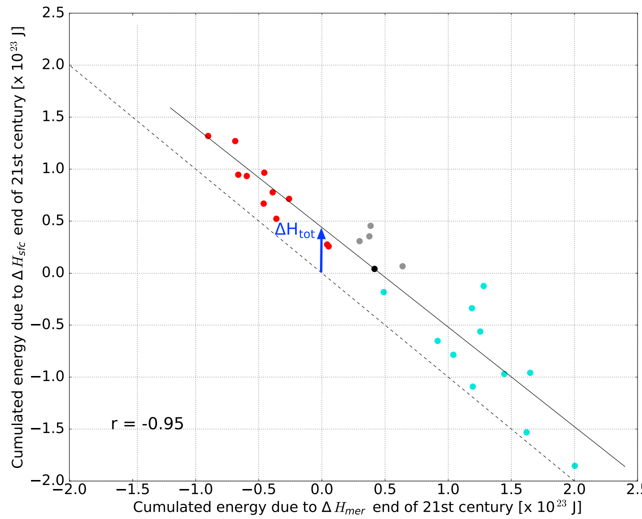

Figure 4. Sum of the anomalies to the reference period in ΔH_{sfc} as a function of the sum of the anomalies to the reference period in ΔH_{mer} (in 10^{23} J) from 1961 to 2099 for each model. The plain line is a linear regression fit. The dashed line represents the one-to-one fit. Colors represent the model categories; see Figure 3. The blue arrow shows the intercept of the linear regression, which represents the total ocean heat gain, if all models would lie on the regression line.

5. Additional Remarks

Additionally to relationships between the three main components of the Arctic Ocean energy budget, the evolution of the other variables (see Figure 3) allows us to briefly investigate further relationships discussed in previous literature. First, the chain of effects between meridional oceanic heat flux, sea surface temperature, sea ice area, and turbulent heat fluxes has been observed in the Barents Sea [*Ikeda*, 1990; *Ådlandsvik and Loeng*, 1991; *Årthun et al.*, 2012; *Smedsrud et al.*, 2013]. However, in addition, the formation of a low-pressure system in the Barents Sea as a consequence of the increased turbulent heat loss to the atmosphere was observed in these studies. In CMIP5 atmospheric pressure data, there is no indication of a significant correlation between the surface pressure in the Barents Sea and the change in meridional oceanic heat flux (see Figure 3).

Second, the change in meridional oceanic heat flux is significantly correlated with sea ice area loss rather than sea ice volume loss. In regions with seasonal ice cover (e.g., Barents Sea), the warming of the ocean water leads to a reduction in the mean annual sea ice cover due to delayed freezing, as discussed by *Bathiany et al.* [2016]. This results in a pronounced loss of sea ice area instead of a pronounced loss of sea ice volume.

Third, we cannot find a significant correlation between the magnitude of simulated Arctic amplification and the change in meridional oceanic heat flux in the models. This is in contrast with previous studies. An increase in the meridional oceanic heat transport was found to lead to a higher surface warming through the resulting increase in turbulent heat loss to the atmosphere [*Holland and Bitz*, 2003; *Mahlstein and Knutti*, 2011; *Marshall et al.*, 2014, 2015; *Nummelin et al.*, 2017]. Still, the lack of significant correlation is not necessary at odds with these studies because they examined correlations between Arctic amplification and meridional oceanic heat flux at latitudes different than 66°N. On the opposite, it would be plausible that Arctic amplification reduces the water temperature gradient between lower and higher latitudes which would lead, in isolation, to a decrease in the meridional oceanic heat flux. However, although all models agree on a decrease in the atmospheric meridional temperature gradient, we find that only nine models show a decrease in the oceanic meridional temperature gradient. In the remaining 17 models, the oceanic meridional temperature gradient increases (see Figure 3).

Finally, an increase in the temperature of the meridional oceanic inflow, as seen in our results, could be explained by weaker heat loss from the ocean to the atmosphere in subpolar latitudes due to a faster atmospheric warming than oceanic warming [*Nummelin et al.*, 2017]. A similar mechanism was shown to drive the delayed ocean warming in the Southern Ocean as well [*Armour et al.*, 2016]. Additionally, our results also show an increase in mass transport at the inflow. One explanation for this increase would be that a thinner ice cover would lead to an increase in the sea ice production [*Bitz et al.*, 2006]. This would lead to a strengthening in the oceanic ventilation, leading to a higher ocean heat content. However, we do not find any correlation between the change in ice production and the change in meridional oceanic heat flux. This might be a consequence of our method, as we only look at changes in ice production on a large scale, while the explanation by *Bitz et al.* [2006] relies on regional changes in ice production.

6. Summary and Conclusions

We show that the CMIP5 models agree on a positive trend in ocean sensible heat content and a negative trend in sea ice area and volume in the Arctic Ocean from 1961 to 2099. They disagree, however, on the main driver for this overall warming. Ocean warming and decrease in sea ice cover are driven by positive anomalies in the net atmospheric surface flux in 11 models, by positive anomalies in the meridional oceanic heat flux in 11 models and by positive anomalies in both energy fluxes in four models.

The net atmospheric surface flux exhibits positive anomalies when the increase in radiative heat gain by the ocean is larger than the increase in turbulent heat loss to the atmosphere. When the increase in turbulent heat loss to the atmosphere is larger than the increase in radiative heat gain by the ocean, the net atmospheric surface flux exhibits negative anomalies. The disagreement in the sign of the change in the net atmospheric surface flux stands in opposition to *Sorteberg et al.* [2007], who found a robust positive twentieth century trend in the net atmospheric surface flux in CMIP3 models. As they considered land surfaces as well, this points to the difference in the evolution of the surface energy budget between land and ocean surfaces [*Laîné et al.*, 2016].

Positive anomalies in the meridional oceanic heat flux are driven by an increase in the water mass transport and water temperature of the oceanic inflow, mainly through the Barents Sea Opening. Negative anomalies are driven by an increase in the water temperature of the oceanic outflow that overcompensates the small increase in energy inflow. This is in agreement with studies based on observations [*Schauer et al.*, 2004; *Spielhagen et al.*, 2011] and model simulations [*Koenigk and Brodeau*, 2013], which point toward an increase in both mass transport and temperature as a driver for an increase in the meridional oceanic heat flux.

We also find that changes in net atmospheric surface flux and meridional oceanic heat flux are strongly linked. The magnitude of the increase in turbulent heat loss, driven by the change in meridional oceanic heat flux, is responsible for the sign of the change in the net atmospheric surface flux. Our results therefore underline the importance of the meridional oceanic heat flux for the evolution of the Arctic Ocean energy budget as a whole. This result is in agreement with *Mahlstein and Knutti* [2011], who found that the meridional oceanic heat flux is responsible for the large spread in the future warming of the Arctic atmosphere in CMIP3 models, although it contributes only a small amount to the total energy budget.

However, the influence of the meridional atmospheric heat flux is not negligible. Changes in the ocean-atmosphere exchange in the subpolar ocean were shown to be a source for differences in the meridional oceanic heat flux between models [*Nummelin et al.*, 2017]. Both components of the meridional heat flux and their interactions before reaching the Arctic region are therefore important to explain the different behaviors of the models.

Unfortunately, the observational record of ocean heat transport is only about 15 years long [*Onarheim et al.*, 2015; *Mayer et al.*, 2016]. Hence, we cannot infer robustly which of the models are evolving closest to the “real” world behavior. More observations on longer time scales are needed to better understand the meridional oceanic heat flux and to improve its representation in climate models.

Finally, the disagreement of the simulated changes in the components of the Arctic Ocean energy budget highlights a high uncertainty in future projections for the Arctic. The multimodel ensemble mean is not a good proxy for the future evolution of the Arctic climate system.

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