ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

A review of interactions between ocean heat transport and Arctic sea ice

To cite this article: David Docquier and Torben Koenigk 2021 *Environ. Res. Lett.* **16** 123002

ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW

OPEN ACCESS

RECEIVED
18 June 2021

REVISED
14 September 2021

ACCEPTED FOR PUBLICATION
18 October 2021

PUBLISHED
17 November 2021

A review of interactions between ocean heat transport and Arctic sea ice

David Docquier[1,2,*] and Torben Koenigk[1,3]

1 Swedish Meteorological and Hydrological Institute, Rossby Centre, Norrköping, Sweden
2 Royal Meteorological Institute of Belgium, Brussels, Belgium
3 Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
* Author to whom any correspondence should be addressed.

E-mail: docquier.david@gmail.com

Keywords: ocean heat transport, Arctic sea ice, observations, modeling

Abstract
Arctic sea ice has been retreating at fast pace over the last decades, with potential impacts on the weather and climate at mid and high latitudes, as well as the biosphere and society. The current sea-ice loss is driven by both atmospheric and oceanic processes. One of these key processes, the influence of ocean heat transport on Arctic sea ice, is one of the least understood due to the greater inaccessibility of the ocean compared to the atmosphere. Recent observational and modeling studies show that the poleward Atlantic and Pacific Ocean heat transports can have a strong influence on Arctic sea ice. In turn, the changing sea ice may also affect ocean heat transport, but this effect has been less investigated so far. In this review, we provide a synthesis of the main studies that have analyzed the interactions between ocean heat transport and Arctic sea ice, focusing on the most recent analyses. We make use of observations and model results, as they are both complementary, in order to better understand these interactions. We show that our understanding in sea ice - ocean heat transport relationships has improved during recent years. The Barents Sea is the Arctic region where the influence of ocean heat transport on sea ice has been the largest in the past years, explaining the large number of studies focusing on this specific region. The Pacific Ocean heat transport also constitutes a key driver in the recent Arctic sea-ice changes, thus its contribution needs to be taken into account. Although under-studied, the impact of sea-ice changes on ocean heat transport, via changes in ocean temperature and circulation, is also important to consider. Further analyses are needed to improve our understanding of these relationships using observations and climate models.

1. Introduction

1.1. Context
Observations show that the annual mean Arctic air surface temperature has increased more than twice as fast as the global average since the late twentieth century, a process called 'Arctic amplification' (Chapman and Walsh 1993, Cohen *et al* 2020, IPCC 2021). Together with this warming, the annual mean Arctic sea-ice area decreased by 2 million km^2 between 1979 and 2020 (figure 1), corresponding to a relative loss of 18% over that time period, based on the Ocean and Sea Ice Satellite Application Facility (OSI SAF) observations (Lavergne *et al* 2019). This loss has been more pronounced in summer (−3.2 million km^2 in September, i.e. −48%) compared to winter (−1.4 million km^2 in March, i.e. −9%), as shown in figures 1 and 2 and previous studies (Onarheim *et al* 2018, Stroeve and Notz 2018, Meredith *et al* 2019, IPCC 2021). Sea ice has also thinned since 1980 (Lindsay and Schweiger 2015, Kwok 2018, Meredith *et al* 2019), leading to a decrease in annual mean Arctic sea-ice volume of 12 000 km^3 (relative loss of 49%) between 1979 and 2020, based on the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS; figure 3). The absolute loss in sea-ice volume is relatively similar across seasons, while the relative loss is stronger in summer (−77% in September) compared to winter (−34% in March), due to smaller initial volume in summer compared to winter (figure 3).

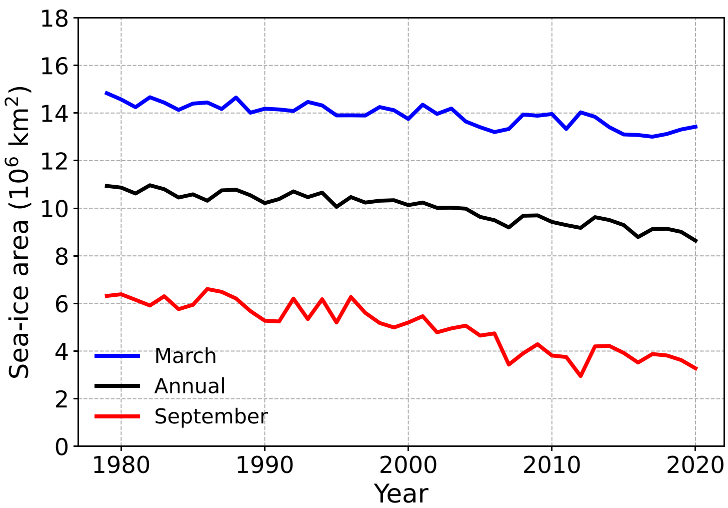

Figure 1. Time evolution of Arctic sea-ice area between 1979 and 2020 based on OSI SAF satellite observations: annual mean (black), March mean (blue), September mean (red).

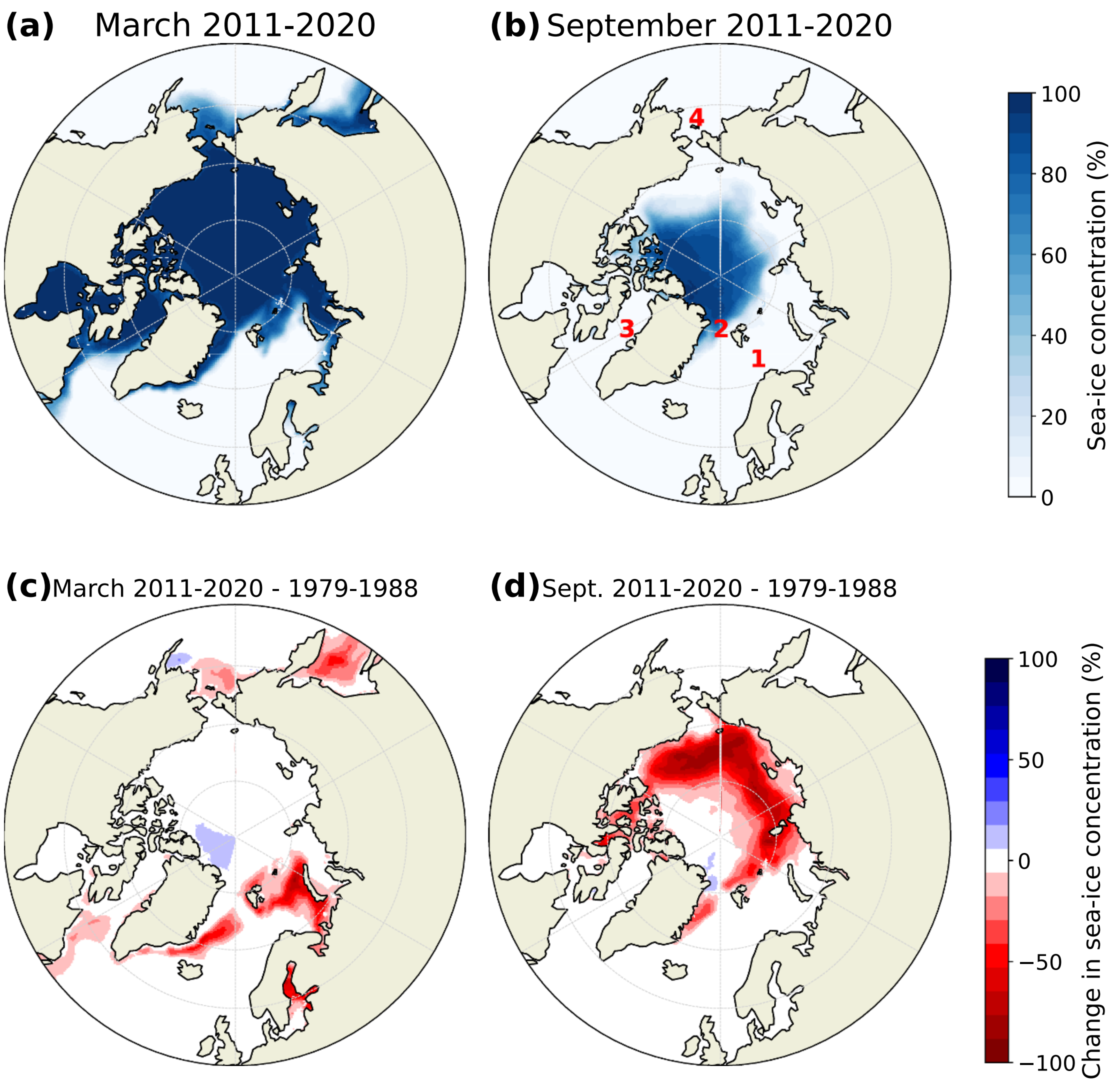

Figure 2. (a) March and (b) September Arctic sea-ice concentration averaged over 2011–2020, and change in (c) March and (d) September sea-ice concentration between 2011–2020 and 1979–1988, based on OSI SAF satellite observations. Location of the four main Arctic gateways is represented by red numbers in panel (b) (1: Barents Sea Opening; 2: Fram Strait; 3: Davis Strait; 4: Bering Strait).

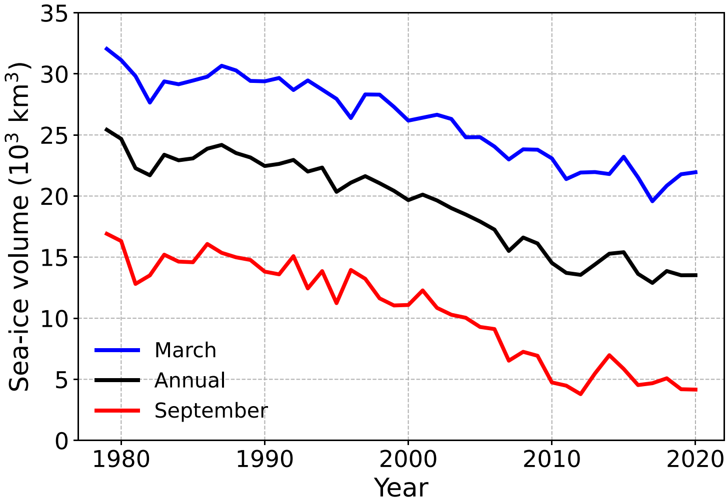

Figure 3. Time evolution of Arctic sea-ice volume between 1979 and 2020 based on PIOMAS reanalysis: annual mean (black), March mean (blue), September mean (red).

Arctic warming and sea-ice reduction have had large impacts on the Arctic ecosystem with subsequent effects on societies and local communities. With the reduction of sea ice, new shipping routes through the Arctic have opened and the exploitation of natural resources (such as oil and gas) has become more economically feasible, but these have put our environment at risk (Meredith *et al* 2019). Although debated, Arctic sea-ice reductions have been linked to changes in weather and climate conditions at lower latitudes (McCusker *et al* 2016, Ogawa *et al* 2018, Koenigk *et al* 2019, Cohen *et al* 2020). Especially, a more frequent occurrence of cold winter weather conditions over Eurasia and North America has been associated with sea-ice loss (Francis and Vavrus 2012, Mori *et al* 2019, Cohen *et al* 2020). Thus, changes in Arctic sea-ice conditions are not only relevant for local Arctic climate conditions but are also of potential importance for climate at lower latitudes.

The recent changes in Arctic sea-ice area and volume are driven by both anthropogenic global warming and internal climate variability (Kay *et al* 2011, Notz and Marotzke 2012, Swart *et al* 2015, Notz and Stroeve 2016, England *et al* 2019, Meredith *et al* 2019, Olonscheck *et al* 2019). Both anthropogenic global warming and internal variability influence Arctic sea ice via different atmospheric (Ding *et al* 2017) and ocean (Carmack *et al* 2015) processes. Ocean processes are probably the least understood causes due to the more difficult accessibility of the ocean compared to the atmosphere, thus deserving particular attention. It has recently been recognized that poleward ocean heat transport has a strong influence on the recent changes in Arctic sea ice (Arthun *et al* 2012, Polyakov *et al* 2017, Serreze *et al* 2019).

The two oceans that bring warm water to the Arctic regions are the Atlantic and Pacific oceans. Heat from the Atlantic Ocean enters the Arctic Ocean through three main gateways (figure 2(b)). The Barents Sea Opening, located between northern Norway and Bear Island (south of Svalbard), is the most important Arctic gateway with an annual mean ocean heat transport of 73 TW based on moorings (Smedsrud *et al* 2010). Observations show that Atlantic Water heat transport at the Barents Sea Opening has increased by 2.4 TW decade^{-1} over 1998–2016, due to both strengthening and warming of Atlantic Water inflow, leading to substantial loss in Barents sea-ice area (Arthun *et al* 2012, Docquier *et al* 2020). The two other Arctic gateways on the Atlantic side are Fram Strait and Davis Strait, with annual mean ocean heat transports of 36 TW (Schauer and Beszczynksa-Möller 2009) and 20 TW (Curry *et al* 2011), respectively. The positive trend in ocean heat transport at Fram Strait since 1997 has been mainly driven by increased ocean temperature (Beszczynska-Möller *et al* 2012, Wang *et al* 2020), while there has been no significant change through Davis Strait (Curry *et al* 2011). The only Arctic gateway on the Pacific side is Bering Strait (figure 2(b)), with an annual mean ocean heat transport of 14 TW (Woodgate 2018). Despite this fairly modest contribution, an increase in ocean heat transport at Bering Strait has been observed since 1990, mainly due to increased flow (Woodgate 2018).

1.2. Motivation and structure

As described in section 1.1, Arctic sea ice has been dramatically retreating in the past decades, and part of this retreat has been due to enhanced poleward ocean heat transport, justifying the need to better understand the relationships between the two. However, our understanding of these relationships is far from being complete and many uncertainties are linked to the observational and modeling systems used. Also, there is more and more evidence that the Pacific Ocean, which provides a smaller contribution of heat transport to the Arctic compared to the Atlantic

Ocean, also greatly impacts Arctic sea ice (Serreze *et al* 2019). Additionally, recent studies also show an effect of sea-ice changes on ocean heat transport and circulation (Sévellec *et al* 2017). Thus, a review summary on the interactions between the two major oceans (Atlantic and Pacific) and Arctic sea ice is necessary.

Carmack *et al* (2015) provide a review on the role of ocean heat transport on Arctic sea ice based on observations, mainly mooring-based for ocean heat transport and satellite-based for sea ice. Here, we update their findings including research on this topic in the last years from both observational and modeling studies. In addition, we review the latest findings on the potential influence of Arctic sea ice on ocean heat transport.

In section 2, we present the criteria used to select the featured articles, as well as the main tools used for observing and modeling Arctic sea-ice concentration and thickness, and ocean heat transport. In section 3, we present key recent studies analyzing interactions between ocean heat transport and Arctic sea ice. In our study, we define the Arctic Ocean in its broad sense as the ocean centered around the North Pole that is covered by sea ice at least in winter (figure 2(a)). For ocean heat transport, we mainly focus on the four Arctic gates described in section 1.1 and depicted in figure 2(b), but we do not strictly restrict our analysis to them. Sections 3.1 and 3.2 focus on the impact of ocean heat transport from the Atlantic and Pacific, respectively, on Arctic sea ice, while section 3.3 looks at the reverse influence of Arctic sea ice on ocean heat transport. A summary and outlook is provided in section 4.

2. Methods

2.1. Article selection criteria

A series of criteria have been used to select the featured articles:

- Article relevance: articles that are directly connected to the topic have been considered. Other articles that are indirectly connected have also been considered depending on their importance to convey the key messages of our review.
- Robustness: the goal of the review is to provide a global picture of the interactions between ocean heat transport and Arctic sea ice. Thus, we have insisted more on the results that are confirmed by multiple studies and are derived from different sources (observations and models, or independent measurements, or multiple models), and less on the results that are only confirmed by one or a few studies, in agreement with the Intergovernmental Panel on Climate Change (IPCC) confidence levels. We have ensured that contradicting results are adequately represented.
- Recent articles: we have mainly focused on the most recent analyses, updating the review from Carmack *et al* (2015), but we have also taken into account important articles that have been published earlier on.

2.2. Observations

In this section, we shortly describe the availability of recent observations of sea-ice concentration and sea-ice thickness (which are used to compute Arctic sea-ice area and volume) and ocean heat transport at the Arctic gates, as well as the methods to retrieve these observations.

Observations of Arctic sea-ice concentrations have mainly come from satellite passive microwave radiometers for more than four decades. They have started in late 1978 with the Scanning Multichannel Microwave Radiometer (SMMR), continued with the Special Sensor Microwave Imager (SSM/I) from 1987, and then with the Special Sensor Microwave Imager/Sounder (SSMIS) since 2009 (Stroeve and Notz 2018). Several algorithms have been developed to convert the brightness temperature retrieved by radiometers into sea-ice concentration, with weaker performance in summer partly due to the presence of melt ponds (Ivanova *et al* 2015). The Arctic sea-ice area is computed by summing the product of sea-ice concentration and grid-cell area over all grid points included in the Arctic Ocean. An alternative diagnostic to sea-ice area is sea-ice extent, which is the total ocean area including all grid points with at least 15% sea-ice concentration. While sea-ice extent allows to partly remove the observational uncertainty related to melt ponds, sea-ice area is a preferred diagnostic when comparing climate models to observations due to uncertainties related to grid geometry (Notz 2014).

Changes in Arctic sea-ice thickness have not been monitored with such a long-term and consistent record. Until the end of the twentieth century, only *in-situ* data were available, including measurements of sea-ice draft (ice depth below the waterline) by the US Navy submarine cruises between 1975 and 2000 (Rothrock *et al* 2008). It was only in 1993 that satellite altimeter observations started with ESA's ERS-1/2, although the spatial coverage was limited up to 81.5° N. Near Arctic-wide observations of sea-ice thickness have been obtained since 2003, thanks to the NASA's Ice, Cloud and land Elevation Satellite (ICESat) satellite laser altimeter. However, the ICESat record is limited to October–November and February–March over 2003–2009 due to laser failure (Kwok *et al* 2009). Since 2010, the ESA's CryoSat-2 radar altimeter has allowed to provide sea-ice thickness measurements up to 88° N (Laxon *et al* 2013). Since late 2018, Arctic-wide ice thickness measurements have also come from ICESat-2 (Petty *et al* 2020). Note, however, that large uncertainties affect satellite observations of sea-ice thickness, due to errors in snow depth and densities of snow, ice and water as these quantities are used to convert the measured sea-ice freeboard (ice thickness above the waterline) into sea-ice thickness.

Combining sea-ice concentration and sea-ice thickness allows to compute Arctic sea-ice volume. Due to the spatial and temporal gaps of sea-ice thickness measurements and the relatively large uncertainty inherent to thickness retrievals (Stroeve *et al* 2014, Zygmuntowska *et al* 2014), reanalysis data have also been used for sea-ice volume. In particular, PIOMAS has provided data since 1979 (Zhang and Rothrock 2003, Schweiger *et al* 2011). These data agree relatively well with satellite observations over the central Arctic (Schweiger *et al* 2011) and simulate sea-ice thickness with error statistics similar to the observational uncertainty (Schweiger *et al* 2019).

As ocean heat transport at a specific transect is derived from the product of ocean temperature and velocity integrated over this transect, the two latter quantities need to be known. Ocean temperature is obtained via hydrographic stations and moorings and ocean velocity is measured through current meter moorings. *In-situ* moorings have been deployed since 1990 at Bering Strait and have offered year-round observations of ocean velocity and temperature (Woodgate 2018). Accurate observations of ocean heat transport at the Barents Sea Opening and Fram Strait have only started in 1997 since current meter moorings have only been placed at this time (Ingvaldsen *et al* 2004, Beszczynska-Möller *et al* 2012). Ocean heat transport observations at the Davis Strait started only in 2004 (Curry *et al* 2011). Due to the short observational time period, uncertainties related to these measurements (e.g. mesoscale eddies, extrapolation of each current meter to represent boxes with uniform velocity, coverage of part of the transects; Ingvaldsen *et al* (2004)), mooring under-sampling and the relatively long time period of internal variability, the use of climate models is a good complement to these observations.

2.3. Models

In this section, we briefly describe the climate models used to represent Arctic sea ice, ocean heat transport and their interactions. We mainly focus on global climate models as these models take into account large-scale interactions between ocean heat transport and Arctic sea ice. But we also discuss results from regional models, which might improve the representation of smaller-scale ocean—sea ice interactions at the ice edge. A distinction needs to be done between ocean-only models, including sea ice, that are driven by atmospheric forcing on one hand, and coupled models that include ocean, sea ice, atmosphere and land on the other.

Climate models use mathematical equations to characterize the exchanges of energy, momentum and water in different parts of the ocean, sea ice, atmosphere and land. They divide the globe into a three-dimensional grid of cells in which the equations representing the different components of the climate system are computed. A finer grid size (higher resolution) allows us to provide a more detailed representation of climate processes but requires larger computer resources. Climate models are used to better understand the key climate processes, including the interactions between ocean heat transport and Arctic sea ice, and to provide insights into the future by making projections.

In recent years, three different modeling approaches to better understand the climate system have been designed. The first method is to combine a large set of models. The primary example is the Coupled Model Intercomparison Project (CMIP), which also informs the IPCC. In particular, the three phases CMIP3, CMIP5 and CMIP6 have provided multi-model frameworks to simulate the climate in the recent past and future following the same protocol (Meehl *et al* 2007, Taylor *et al* 2012, Eyring *et al* 2016). The second approach is to carry out sensitivity experiments with one or several climate models, in which certain aspects of the climate system or model parameters are modified. The third approach is to perform a large ensemble of simulations with the same model starting from slightly different initial states in order to reduce the uncertainty related to internal variability (Deser *et al* 2020). In our review, we take into account the three approaches as they are complementary.

Arctic sea-ice concentration and thickness are directly computed in the sea-ice component of climate models. As for observations, the modeled ocean heat transport at a specific transect is computed via ocean temperature and velocity, which are computed in each model grid cell in the ocean component. The main advantage of a global climate model over observations is that it covers the whole globe and a much longer time period, allowing to separate internal variability from external forcing. However, it suffers from uncertainties related to incomplete understanding and inadequate representation of the climate system, and grid-size limitations.

3. Review results

3.1. Influence of Atlantic Ocean heat transport on Arctic sea ice

In this section, we review the recent literature related to the influence of heat transport from the Atlantic Ocean on Arctic sea ice from both observational and modeling perspectives.

3.1.1. Observations

Relationships between Atlantic Ocean heat transport and Arctic sea-ice conditions have been recognized for more than a century (Helland-Hansen and Nansen 1909) and a number of studies since then

Table 1. Sensitivity of Barents and Arctic sea-ice area (SIA) to an increase in ocean heat transport (OHT) (unit: km^2 per 10 TW) according to observational and modeling studies. For the Barents SIA sensitivity, we use OHT at the Barents Sea Opening (BSO), and for the Arctic SIA, we use the total Arctic OHT. The period over which the sensitivity is computed is provided in brackets. For multi-model/multi-member studies, the multi-model/ensemble mean is provided. The observations and models used are provided below the author names for each study. We also indicate the number of years by which OHT leads SIA in the computation of the sensitivity if there is a lead-lag correlation.

Studies	Barents SIA—BSO OHT	Arctic SIA—Total Arctic OHT
Observational studies		
Arthun *et al* (2012) (NSIDC, IMR)	−145 000 (1998–2008) Annual mean values OHT leads SIA by two years	
This study (OSI SAF, IMR)	−12 000 (1998–2016) March SIA; annual mean OHT OHT leads SIA by one year	
Modeling studies		
Arthun *et al* (2012) (HAMSOM)	−70 000 (1948–2007) Annual mean values OHT leads SIA by one year	
Li *et al* (2017) (CMIP5)	−30 000 (1979–2015) March SIA; annual mean OHT	
Muilwijk *et al* (2019) (Ocean-only models)	−50 000 (present-day) Annual mean values	
Docquier *et al* (2020) (HighResMIP)	−80 000 (1950–2014) March SIA; annual mean OHT OHT leads SIA by one year	
Docquier *et al* (2021) (EC-Earth3)		−200 000/−300 000 (present-day, 50 yr) March/September SIA; annual mean OHT SST increase in the Atlantic Ocean
Docquier *et al* (2021) (EC-Earth3)		−330 000/−610 000 (present-day, 50 yr) March/September SIA; annual mean OHT SST increase in the Pacific Ocean

have shown a role of Atlantic warming on sea-ice reduction (Steele and Boyd 1998, Dickson *et al* 2000, Furevik 2001, Vinje 2001, Polyakov *et al* 2004, Francis and Hunter 2007, Schlichtholz 2011, Spielhagen *et al* 2011). However, the influence of Atlantic Ocean heat transport on Arctic sea ice has only been recently quantified, focusing on the Barents Sea (Arthun *et al* 2012). The Barents Sea occupies a key position between the warm Atlantic Water and the cold Arctic Ocean, favoring substantial heat loss to the atmosphere, without which this sea would be largely ice free in winter (Smedsrud *et al* 2013). Arthun *et al* (2012) show that the reduction in Barents sea-ice area between 1998 and 2008 is correlated with an increase in Atlantic Water heat transport at the Barents Sea Opening. They find a decrease of 145 000 km^2 in Barents sea-ice area per 10 TW increase in ocean heat transport (table 1, ocean heat transport leading sea-ice area by two years) using hydrographic data and current meter moorings from the Institute of Marine Research (IMR, Norway; Ingvaldsen *et al* (2004)). The increased heat transport at the Barents Sea Opening has been caused by both strengthening and warming of the Atlantic Water inflow (Arthun *et al* 2012). As the Barents Sea is practically ice free in summer, most recent changes have happened in winter, with a decrease in sea-ice area of >50% since 1979 (figure 2(c)) (Onarheim and Arthun 2017).

The influence of Atlantic Water heat transport on sea ice has been further demonstrated by skillful predictions of Barents sea ice-area based on observed sea-ice area in the Barents Sea and ocean heat transport at the Barents Sea Opening one or two years in advance (Onarheim *et al* 2015). The predicted Barents sea-ice area computed from this framework shows good agreement with observations, with 50% of the variance explained and a correct increase/decrease in sea-ice cover 88% of the time. The skill of the prediction is further increased by including meridional winds. This framework is supported by a 60 yr simulation from a regional ice-ocean model (Onarheim *et al* 2015).

There is also evidence that the Atlantic Water inflow has had an influence on sea ice in the western Nansen Basin (<70° E), located north of Barents Sea, between Svalbard and Franz Joseph Land, after the mid-1990s. In particular, local zones of thinner ice and lower ice concentration mirror the pathway of the Fram Strait branch of Atlantic Water (Ivanov *et al* 2012). The fact that winter minimum sea-ice thickness occurs in the ice pack interior above the Atlantic Water path shows that a substantial amount of Atlantic Water heat in the western Nansen Basin has contributed to ice melting from below. Ivanov *et al* (2012) hypothesize that the delivering of warm water from deep to under-ice layers comes from winter convective mixing.

Until recently, the heat brought by the Atlantic Water had been isolated from the surface in the eastern Eurasian Basin (>70° E) by large vertical density gradients associated with the Arctic halocline (Polyakov *et al* 2020). However, the conditions previously identified by Ivanov *et al* (2012) in the western Nansen Basin are now observed in the eastern Eurasian Basin (as far as 125° E). In particular, large sea-ice loss in the eastern Eurasian Basin since 2011 has also been linked to Atlantic Water inflow (Polyakov *et al* 2017). This eastward progression of Atlantic Water inflow is called 'atlantification' (Arthun *et al* 2012). The recent increased penetration of Atlantic Water into the eastern Eurasian Basin, as shown by moorings and buoys deployed in 2013–2015 (Polyakov *et al* 2017) and 2015–2018 (Polyakov *et al* 2020), is associated with stratification weakening, increased vertical mixing and pycnocline warming. This has led to enhanced upward Atlantic Water heat flux to the ocean surface, and thus to a reduction in ice growth in winter (Polyakov *et al* 2017). This process has continued at an increasing rate in more recent years, with ocean heat flux greater than 10 W m^{-2} for the winters of 2016–2018, compared to 3–4 W m^{-2} for 2007–2008, leading to a more than two-fold reduction of winter ice growth (Polyakov *et al* 2020).

3.1.2. Models

As for observations, the main region of interest in terms of ocean heat transport—Arctic sea ice relationships in modeling studies has been the Barents Sea as it has experienced the largest relative winter sea-ice loss in the past years compared to other Arctic seas (Onarheim *et al* 2018), combined with increased ocean heat transport through the Barents Sea Opening (Arthun *et al* 2012). We first review the literature associated with the influence of Atlantic Ocean heat transport on the Barents Sea ice, and then the one related to the impact of Atlantic Ocean heat transport on other Arctic seas. We decide to focus on the studies that provide a quantification of the influence of ocean heat transport on Arctic sea ice, but we acknowledge that additional modeling studies suggest an influence of ocean heat transport on sea ice without a clear quantification (Yang and Neelin 1997, Holland *et al* 2001, 2006, Holland and Bitz 2003, Hwang *et al* 2011).

3.1.2.1. Barents Sea

The global coupled atmosphere–ocean–sea ice model ECHAM5/MPIOM (European Center for Medium-Range Weather Forecasts Hamburg/Max Planck Institute Ocean Model) has been run over nearly 500 yr with pre-industrial external forcing to investigate seasonal to interannual variability in the Barents Sea (Koenigk *et al* 2009). Results from this simulation provide evidence that ocean heat transport into the Barents has a minor importance for interannual sea-ice variations, which are mostly driven by sea-ice import through local winds, but it starts to become more important at longer time scales.

However, other studies have later found that ocean heat transport at the Barents Sea Opening has an influence on Barents sea-ice area at seasonal, interannual and decadal time scales. Results with the regional ocean—sea ice model HAMSOM (Hamburg Shelf Ocean Model) forced by NCEP/NCAR atmospheric reanalysis suggest that there is a one-year lead-lag correlation between ocean heat transport and Barents sea-ice area, with a sea-ice retreat of 70 000 km^2 per 10 TW increase in ocean heat transport over the period 1948–2007 (table 1) (Arthun and Schrum 2010, Arthun *et al* 2012). The Regional Ocean Modeling System (ROMS) also shows evidence of a direct role of Atlantic Water heat transport at the Barents Sea Opening, associated with local winds, on Barents sea ice within seasons (Lien *et al* 2017).

Model simulations with the coupled global climate model EC-Earth2.3 using the CMIP5 forcing provide evidence that the largest Arctic warming over 1850–2100 occurs in the Barents Sea (Koenigk *et al* 2013). This leads to strong reductions in sea-ice concentration and thickness in the Barents Sea with varying amplitude depending on the emission scenario. Concurrently, the ocean heat transport at all Arctic straits, and especially at the Barents Sea Opening, increases in all simulations, mainly via increased temperature of the Atlantic Water (Koenigk *et al* 2013, Koenigk and Brodeau 2014). The increased ocean heat transport leads to enhanced bottom ice melt in these simulations, contributing to sea-ice retreat (Koenigk and Brodeau 2014).

Over the period 1979–2015, the trend in CMIP5 multi-model mean March Barents sea-ice extent (−2700 km^2 per year) is much weaker than that observed (−9700 km^2 per year) (Li *et al* 2017). Also, the trends in CMIP5 March Barents sea-ice extent have little correlation with the trends in global mean surface air temperature across all CMIP5 models ($R = -0.2$), but they are strongly anti-correlated with the trends in annual mean Atlantic Water heat transport at the Barents Sea Opening ($R = -0.8$). Results from Li *et al* (2017) suggest that enhanced ocean heat transport at the Barents Sea Opening associated with regional internal variability have had a major role in reducing the winter sea-ice cover in the Barents Sea since 1979.

The use of seven coupled global climate models that followed the High Resolution Model Intercomparison Project (HighResMIP) protocol (which is one of the CMIP6-endorsed MIPs), with at least two different horizontal resolutions for each model, confirms the strong anti-correlation between annual mean ocean heat transport at the Barents Sea Opening and March Barents sea-ice area (Docquier *et al* 2020). The sensitivity of March Barents sea-ice area to ocean heat transport at the Barents Sea Opening is −80 000 km^2 per 10 TW on average (table 1, ocean heat transport leading sea-ice area by one year), with large variations between models (−18 000 to −137 000 km^2 per 10 TW). This study reveals that an increased ocean resolution allows us to better represent the different ocean currents flowing into the Barents Sea as well as the Atlantic Water heat transport at the Barents Sea Opening. A higher ocean resolution also improves the strong water cooling at the sea-ice edge and further formation of warm intermediate Atlantic Water. However, no clear impact of model resolution on sea ice—ocean heat transport relationships is found.

Another multi-model study with eight different ocean-only models and one fully coupled model finds that a stronger wind forcing over the Greenland Sea leads to an increased ocean heat transport at the Barents Sea Opening and a reduced sea-ice extent in the Barents and Kara Seas (Muilwijk *et al* 2019). In particular, an average reduction of 50 000 km^2 in sea-ice area in the Barents and Kara Seas combined is found for an increase in ocean heat transport of 10 TW (table 1), consistent with Arthun *et al* (2012).

3.1.2.2. Other Arctic seas

Ocean heat transport at the Barents Sea Opening does not only influence sea ice in the Barents Sea but appears to also influence the whole Arctic Ocean. In particular, the Community Earth System Model (CESM) Large Ensemble (LE), constituted of 40 members run over 1920–2100, provides evidence that heat transport at the Barents Sea Opening is a major source of internal Arctic sea-ice variability during winter (Arthun *et al* 2019). This relationship remains strong in the future, using the Representative Concentration Pathway (RCP) 8.5, and weakens as sea ice retreats. The future increase in ocean heat transport in these experiments is reflected in a northward penetration of warm water into the Arctic Ocean, resulting in a strong reduction in sea-ice thickness (−1.2 m in the eastern Arctic Ocean on average).

An analysis using different model projections from the Community Climate System Model version 3 (CCSM3) shows that abrupt reductions in the Arctic sea-ice extent occur when ocean heat transport to the Arctic rapidly increases through the twenty-first century (Holland *et al* 2006). These rapid 'pulse-like' events in ocean heat transport lead changes in sea ice (particularly sea-ice thickness) by about 1–2 years via increased melt rate. Increased ocean heat transport is associated with strengthened ocean currents and warmer waters entering the Arctic Ocean (Holland *et al* 2006).

Results from the NorESM1-M global coupled climate model provide evidence that the increased ocean heat transport at the Barents Sea Opening causes a reduction in Barents sea-ice area through reduced basal growth, while sea-ice area reduction in the central Arctic is mostly controlled by increased ocean heat transport to the Arctic through Fram Strait, resulting in increased bottom melting (Sando *et al* 2014). The CESM-LE large ensemble (1850–2100, using RCP8.5 scenario) suggests that ∼80% of the rapid sea-ice declines in the Arctic are correlated with increased ocean heat transport, mainly at the Barents Sea Opening and Bering Strait (Auclair and Tremblay 2018). A rapid sea-ice decline is a period of ⩾4 yr during which the trend in the 5-year running mean minimum sea-ice extent is ⩽−0.3 million km^2 yr^{-1} (Auclair and Tremblay 2018). A set of sensitivity experiments performed with EC-Earth3 and starting from present-day climate confirms that an increased total ocean heat transport at all Arctic gates leads to a large reduction in Arctic sea-ice area (Docquier *et al* 2021). In these experiments, the sea-surface temperature is artificially increased in different parts of the North Atlantic and North Pacific Oceans, leading to enhanced ocean heat transport into the Arctic. Sea-ice loss is mainly driven by reduced basal growth along the sea-ice edge and enhanced basal melt in the central Arctic, in agreement with Sando *et al* (2014).

Three other multi-model studies compute the northward ocean heat transport at a specific latitude (between 60° N and 70° N), instead of the typical Arctic gates, and analyze its relationship with Arctic sea ice. The first analysis focuses on ∼20 CMIP3 models and shows that models that simulate a stronger poleward ocean heat transport at 60° N also have a smaller September Arctic sea-ice extent (Mahlstein and Knutti 2011). According to Mahlstein and Knutti (2011), the northward ocean heat transport largely contributes to the uncertainty in future Arctic climate projections. The second study finds that the Arctic warming between 1961 and 2099 is driven by the net atmospheric surface flux in about half of the models and by the meridional ocean heat flux at 66° N in the other half of the models, based on 26 CMIP5 models (Burgard and Notz 2017). A significant negative correlation between Atlantic Ocean heat flux and Arctic sea-ice area is found across all models ($R = -0.4$). The third analysis confirms the strong decline in Arctic sea-ice area with enhanced poleward Atlantic Ocean heat transport north of 60° N at interannual time scales using five HighResMIP models at different horizontal resolutions over the historical period (1950–2014) (Docquier *et al* 2019).

Additionally, a finer ocean resolution results in lower Arctic sea-ice area and volume and generally enhances Atlantic Ocean heat transport, with the limitation that three models used in this study have the same ocean component.

3.2. Influence of Pacific Ocean heat transport on Arctic sea ice

Although the contribution of the Pacific Ocean to the total Arctic Ocean heat transport is relatively small compared to the Atlantic Ocean (∼10% according to the observational estimates provided in section 1.1), its influence on Arctic sea ice is important because the Pacific water enters the Arctic at depths closer to the surface compared to Atlantic water (Woodgate 2018). In this section, we review the recent literature associated with this influence from both observational and modeling perspectives.

3.2.1. Observations

Inflowing Pacific water through the Bering Strait dominates upper surface water masses in the Chukchi and Beaufort Seas. The reduction in sea-ice concentration in these Arctic seas over the past decades has been associated with enhanced ocean heat transport at the Bering Strait, which has been recorded since 1990 (Woodgate *et al* 2006, 2010, Woodgate 2018). The acceleration of the sea-ice concentration decrease after 1997–1998 is associated with increased Pacific water temperature and upward heat flux in the Chuckchi and Beaufort Seas, which delayed sea-ice formation (Shimada *et al* 2006).

Since 1990, almost without interruption, year-round measurements have been maintained in the Bering Strait region, typically at 2–3 sites (Woodgate 2018). Over the period 1990–2015, the increase in ocean heat transport at the Bering Strait has been ∼0.2 TW yr^{-1}, with lows in 2001 and 2012 (∼10 TW) and highs in 2007 and 2015 (∼17 TW), and has been mainly driven by volume transport increase (Woodgate 2018). The increase in ocean heat transport at the Bering Strait between 2001 and 2004 had a sea-ice melt potential of ∼640 000 km^2 for a 1 m thick ice layer (Woodgate *et al* 2006). The almost doubling of the Bering Strait heat transport between 2001 and 2007 acted as a trigger for the onset of the large Arctic sea-ice melt that occurred in 2007 (Woodgate *et al* 2010).

In the Chukchi Sea, the dates of ice retreat (first day of the year when the mean sea-ice concentration within this sector is less than 30%) and advance (first day after the seasonal ice extent minimum when the average sea-ice concentration in this sector exceeds 30%) have moved to ∼25 d earlier and ∼55 d later, respectively, between 1979 and 2014 (Serreze *et al* 2016). The resulting increased open-water period (+80 d) has been strongly related to ocean heat transport through the Bering Strait, and especially the transport in April–June, which explains 68% of the variance in the timing of sea-ice retreat in the Chukchi Sea (Serreze *et al* 2016).

Relatively high water temperatures in the Bering Strait have been recorded in 2017, resulting in a large ocean heat transport, thus partly explaining the early sea-ice retreat in the Chukchi Sea in autumn 2017 (Serreze *et al* 2019). Also, based on satellite measurements between 2002 and 2018, the November sea-surface temperature over the Chukchi and Bering Seas was at its highest value in 2018, as a response to an episode of previous atmospheric blocking over the Bering Sea (Kodaira *et al* 2020). Consequently, less sea ice formed in the Chukchi Sea in November 2018.

3.2.2. Models

The influence of the Pacific Ocean heat transport on the large Arctic sea-ice melt event that occurred in the summer of 2007, mentioned in section 3.2.1, is further supported by a modeling study performed with PIOMAS, forced by NCEP/NCAR atmospheric reanalysis (Steele *et al* 2010). The modeling results provide evidence that in summer 2007 the ocean gained twice the amount of ocean heat averaged over the previous seven years, in agreement with observations (Woodgate *et al* 2010). In the early summer, top melt from the atmosphere dominated the total sea-ice melt in the Pacific sector, while bottom melt due to ocean heat transport dominated later in the summer, with values 34% larger relative to the previous seven years (Steele *et al* 2010). Ocean heat transport is only one factor that contributed to the record minimum sea-ice extent in 2007, together with warm air temperatures, low initial sea-ice thickness, changes in atmospheric circulation, ice motion, clouds, and solar heating of leads (Perovich 2011).

Koenigk and Brodeau (2014) suggest that the contribution from Bering Strait in the increase in ocean heat transport is small compared to the contribution from the Barents Sea Opening over the twenty-first century using EC-Earth2.3. However, the Pacific water transported through the Bering Strait has a lower salinity than Atlantic water and stays closer to the ocean surface, thus contributing more substantially to bottom sea-ice melt than Atlantic water (Koenigk and Brodeau 2014). This is confirmed by a later study with EC-Earth3, in which bottom sea-ice melt is enhanced at the Bering Strait when the sea-surface temperature is artificially increased in the North Pacific Ocean (Docquier *et al* 2021). Combined with atmospheric warming of the North Atlantic Ocean, this leads to a more efficient melting of Arctic sea ice when the sea-surface temperature increases in the North Pacific Ocean compared to the North Atlantic Ocean. The loss in September Arctic sea-ice area is ∼610 000 km^{-2} per 10 TW increase in total Arctic Ocean heat transport when the sea-surface temperature is increased in the North Pacific Ocean (table 1), roughly twice more than if the increase comes from the North Atlantic (Docquier *et al* 2021).

The rapid sea-ice declines identified by Auclair and Tremblay (2018) using CESM-LE over 1920–2100 are correlated either with the Bering Strait or Barents Sea Opening ocean heat transport. The correlation between changes in annual mean Bering Strait ocean heat transport and September sea-ice concentration is of similar amplitude as between the Barents Sea Opening ocean heat transport and September sea-ice concentration. This seems counter-intuitive since the annual mean ocean heat transport at the Bering Strait is smaller than the one at the Barents Sea Opening. Auclair and Tremblay (2018) suggest that this could be due to the fact that Pacific water enters the Arctic over a broader shallow shelf compared to Atlantic water. This further highlights the importance of the Bering Strait in controlling sea-ice changes.

3.3. Influence of Arctic sea ice on ocean heat transport

In this section, we review the recent literature related to the influence of Arctic sea ice on ocean heat transport from both observational and modeling perspectives. As this influence has been under-studied compared to the reverse impact of ocean heat transport on Arctic sea ice presented in sections 3.1 and 3.2, we merge observational and modeling studies in the same section.

Some early studies report connections between formation of sea ice and ocean circulation, in particular deep ocean convection in the Labrador Sea (Dickson *et al* 1988, Goosse and Fichefet 1999, Belkin 2004). Bitz *et al* (2006) investigate the influence of changes in sea ice on ocean heat transport using CCSM3. They artificially decrease sea-ice albedo to mimic a strong reduction in Arctic sea ice. Following the reduction in Arctic sea-ice cover, the ocean warms in a 200 m layer just below the surface of the Arctic Ocean. This subsurface warming results from enhanced Atlantic Ocean heat transport (Bitz *et al* 2006).

The Atlantic Meridional Overturning Circulation (AMOC) is closely linked to the meridional transport of heat by the Atlantic Ocean (Marshall *et al* 2015, Weijer *et al* 2019), thus its monitoring is highly relevant to understand changes in ocean heat transport. In particular, it has been shown that the AMOC has slowed down since 2008 using data from an array of instruments at 26.5° N (Smeed *et al* 2018), potentially weakening the meridional ocean heat transport farther north, although the connection between the AMOC at 26.5° N and Arctic Ocean heat transport is complex and requires further analyses (Oldenburg *et al* 2018). Using the global ocean model NEMO (Nucleus for European Modelling of the Ocean) and the global climate model CESM, a recent study suggests that the Arctic sea-ice decline may explain at least part of the recent AMOC slowdown (Sévellec *et al* 2017). The potential underlying mechanism is that the current loss in Arctic sea ice increases the open-water area, resulting in strong anomalous solar heat flux into the ocean and subsequent warming. Additionally, the Arctic sea-ice decline and Greenland ice-sheet loss add freshwater into the Arctic Ocean. Together, these two processes would cause an AMOC slowdown via southward advection of buoyancy anomalies, and a reduction of poleward ocean heat transport (Sévellec *et al* 2017).

As the most rapid Arctic warming has occurred in the Barents Sea, experiencing the largest winter sea-ice loss (Stroeve and Notz 2018), it makes sense to ask what is the impact of sea-ice retreat in this specific region on ocean heat transport. Hydrographic observations from 1970 to 2016 show a sharp increase in ocean heat content in the upper 100 m from the mid-2000s, the 2010–2016 average being 3.8 standard deviations above the 1970–1999 average (Lind *et al* 2018). In parallel, net sea-ice import to the Barents Sea (mainly from the Kara Sea) has decreased since 2002–2003. The findings of Lind *et al* (2018) show that the reduced sea-ice import has resulted in less melt water, reduced stratification and more vertical mixing in the upper part of the water column, leading to increased upward heat and salt fluxes and finally enhanced ocean heat content in the upper 100 m.

Model results with the unstructured-grid Finite Element Sea ice Ocean Model (FESOM) provide evidence that following sea-ice decline in the Arctic, sea-ice export through the Fram Strait decreases and salinity in the Greenland Sea increases (Wang *et al* 2020). This link between Fram Strait ice export and Greenland Sea salinity is in agreement with previous modeling studies (Haak *et al* 2003, Koenigk *et al* 2006). The increase in Greenland Sea salinity lowers sea-surface height and strengthens the cyclonic gyre circulation in the Nordic Seas, resulting in increased volume transport of Atlantic water into the Arctic Ocean through the Fram Strait (Wang *et al* 2020). Thus, ocean heat transport through the Fram Strait increases and potentially melts more sea ice, so this is a positive feedback.

4. Conclusions

In this review, we have synthesized the information on the influence of ocean heat transport on Arctic sea ice, as well as the reverse impact of Arctic sea ice on ocean heat transport, based on the most recent literature. Our key results are the following:

(a) Major advances in understanding the ocean heat transport—Arctic sea ice relationships have been done using multiple observations and climate models. Despite an early attested influence of ocean heat transport on Arctic sea ice, a more precise quantification of this impact is relatively recent (∼ten years) thanks to improved observational and modeling systems. On the Atlantic side, an eastward progression of Atlantic water inflow, called 'atlantification', is currently underway, associated with reduced ice growth in winter. On the Pacific side, some episodes of large ocean heat transport have been recorded in 2007 and 2017, resulting in sea-ice retreat, especially in the Chukchi Sea. However, knowledge gaps still exist. From an observational perspective, this is partly due to the relatively difficult access of the deeper layers of the ocean, which hinders a fully accurate measurement of ocean heat transport. Also, the systematic pan-Arctic measurement of ocean heat transport and key sea-ice variables (concentration and thickness) is relatively new (from the late 1970s for sea-ice concentration, and from the 1990s for sea-ice thickness and Arctic Ocean heat transport), which does not provide a long temporal window of observations. From a modeling point of view, an incomplete representation of key climate processes in the Arctic and a too coarse grid resolution lead to uncertainties in the simulation of ocean heat transport and its interaction with Arctic sea ice.

(b) The sensitivity of Barents sea-ice area to an increase in ocean heat transport at the Barents Sea Opening amounts to $\sim -145\,000$ km^2 per 10 TW over the period 1998–2008, based on observations (Arthun *et al* 2012). Caution needs to be taken with respect with this number as it involves a relatively small time period, annual mean sea-ice area and data are not detrended. We have computed this sensitivity using a longer time period (1998–2016) and detrended data from IMR for annual mean ocean heat transport and OSI SAF for March sea-ice area (as this is the period when most changes happened in the Barents Sea in past years). We obtain a value ten times smaller ($-12\,000$ km^2 per 10 TW), which indicates the large sensitivity of this computation depending on the time period and the methodology used. Modeling studies have found a sensitivity ranging between $-30\,000$ and $-80\,000$ km^2 per 10 TW (table 1). Despite the uncertainty in the precise quantification of this sensitivity, ocean heat transport at the Barents Sea Opening has been shown to be a good predictor for Barents sea-ice conditions.

(c) While the Atlantic Ocean heat transport influence on Arctic sea ice is relatively well attested by observations and models (section 3.1), a considerably smaller amount of studies exists related to the impact of the Pacific Ocean heat transport (section 3.2). This is partly due to the fact that the contribution of the ocean heat transport at Bering Strait is only $\sim$10% of the total Arctic Ocean heat transport. Thus, changes happening there have been smaller in absolute value compared to changes on the Atlantic side. However, this does not mean that there is no impact on Arctic sea ice; on the contrary, significant changes in sea ice (especially in the Chukchi Sea) have been reported in past years due to enhanced ocean heat transport at the Bering Strait (Serreze *et al* 2019).

(d) The influence of Arctic sea ice on ocean heat transport (section 3.3), and the possibility of a feedback loop between the two, has been understudied compared to the reverse impact of ocean heat transport on Arctic sea ice. As several studies have shown that the recent sea-ice reduction have triggered changes in ocean circulation and temperature, thus impacting ocean heat transport, this influence also needs to be considered.

Based on the above results, we make the following recommendations for future work:

(a) The continuation of the ongoing efforts in observing ocean heat transport to the Arctic through the four main gates and Arctic sea-ice concentration and thickness is crucial to extend the current time series. In order to better understand the pathways of ocean heat entering the Arctic, it is especially important to monitor under-sea ice ocean observations. This would enable us to better quantify the risk that large amounts of inflowing warm water (e.g. from the intermediate warm Atlantic Water) come into contact with Arctic sea ice in the near future.

(b) Climate models need to be improved to incorporate the latest model developments and enhance our understanding of the interactions between Arctic sea ice and ocean heat transport. The inclusion of a more realistic runoff from land-water storage and ice-sheet melt is important in order to have a more realistic description of the ocean current system and its changes in the future, including the northward ocean heat transport. A finer model resolution will also allow us to gain precision into the different ocean and sea-ice processes. Additionally, the three approaches consisting in comparing multiple climate models together (such as CMIP), performing sensitivity experiments and carrying out large model ensemble simulations could be combined more effectively.

(c) More emphasis could be put on the influence of Bering Strait ocean heat transport on Arctic sea ice, as well as the impact of Arctic sea ice on ocean heat transport via changes in ocean temperature and circulation, as these processes are clearly important for the Arctic climate system.

(d) Maybe as important as improving observations and climate models, the techniques to evaluate and analyze observations and model data also need to be carefully designed. For example, the analysis of the influence of ocean heat transport on Arctic sea ice (and the reverse) would benefit from tools coming from nonlinear sciences.

In particular, the study of causal links between ocean heat transport and Arctic sea ice would enable us to go beyond classical correlation analyses (Liang 2014, Runge *et al* 2019).

Arctic sea ice is rapidly retreating and thinning, and ocean heat transport to the Arctic is increasing. Also, model projections suggest a continuation of the ongoing processes, with more or less intensity depending on the greenhouse gas emission scenario we will follow (SIMIP Community 2020, IPCC 2021). As these changes are having and will continue to have impacts on the climate system, the biodiversity and our societies, observing and modeling interactions between ocean heat transport and Arctic sea ice have never been as important as now.

Data availability statement

The data that support the findings of this study are openly available. The observed sea-ice concentration from OSI SAF (Lavergne *et al* 2019), used for producing figures 1 and 2, can be accessed via http://dx.doi.org/10.15770/EUM_SAF_OSI_0008 (OSI SAF, 2017) for the period 1979–2015 and https://osi-saf.eumetsat.int/products/osi-430-b-complementing-osi-450 for data from 2016. The PIOMAS (Zhang and Rothrock 2003, Schweiger *et al* 2011) sea-ice volume data, used to produce figure 3, can be accessed via the Polar Science Center of the University of Washington: http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly.

Acknowledgments

DD was supported by the OSeaIce project (https://cordis.europa.eu/project/id/834493), which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No. 834493. DD is currently funded by the Belgian Federal Science Policy Office under Contract B2/20E/P1/ROADMAP via the JPI-Climate/JPI-Oceans ROADMAP Project (http://www.jpi-climate.eu/joint-activities/joint-calls/CPILoud/ROADMAP). TK was supported by the NordForsk-funded Nordic Centre of Excellence Project (Award 76654) Arctic Climate Predictions: Pathways to Resilient, Sustainable Societies (ARCPATH). We thank the ERL editorial team for editing our manuscript and two anonymous reviewers for their careful revision of our paper and helpful comments.

ORCID iD

David Docquier https://orcid.org/0000-0002-5720-4253

References

Arthun M, Eldevik T and Smedsrud L H 2019 The role of Atlantic heat transport in future Arctic winter sea ice loss *J. Clim.* **32** 3327–41

Arthun M, Eldevik T, Smedsrud L H, Skagseth O and Ingvaldsen R B 2012 Quantifying the influence of Atlantic heat on Barents sea ice variability and retreat *J. Clim.* **25** 4736–43

Arthun M and Schrum C 2010 Ocean surface heat flux variability in the Barents sea *J. Mar. Syst.* **83** 88–98

Auclair G and Tremblay B 2018 The role of ocean heat transport in rapid sea ice declines in the Community Earth System Model Large Ensemble *J. Geophys. Res.* **123** 8941–57

Belkin I M 2004 Propagation of the 'Great Salinity Anomaly' of the 1990s around the northern North Atlantic *Geophys. Res. Lett.* **31** 8

Beszczynska-Möller A, Fahrbach E, Schauer U and Hansen E 2012 Variability in Atlantic water temperature and transport at the entrance to the Arctic ocean, 1997–2010 *ICES J. Mar. Sci.* **69** 852–63

Bitz C M, Gent P R, Woodgate R A, Holland M M and Lindsay R 2006 The influence of sea ice on ocean heat uptake in response to increasing CO_2 *J. Clim.* **19** 2437–50

Burgard C and Notz D 2017 Drivers of Arctic ocean warming in CMIP5 models *Geophys. Res. Lett.* **44** 4263–71

Carmack E *et al* 2015 Toward quantifying the increasing role of oceanic heat in sea ice loss in the new Arctic *Bull. Am. Meteorol. Soc.* **6** 2079–105

Chapman W L and Walsh J E 1993 Recent variations of sea ice and air temperature in high latitudes *Bull. Am. Meteorol. Soc.* **74** 33–48

Cohen J *et al* 2020 Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather *Nat. Clim. Change* **10** 20–29

Curry B, Lee C M and Petrie B 2011 Volume, freshwater and heat fluxes through Davis Strait, 2004–05 *J. Phys. Oceanogr.* **41** 429–36

Deser C *et al* 2020 Insights from Earth system model initial-condition large ensembles and future prospects *Nat. Clim. Change* **10** 277–86

Dickson R R, Meincke J, Malmberg S A and Lee A J 1988 The 'great salinity anomaly' in the northern North Atlantic 1968-1982 *Prog. Oceanogr.* **20** 103–51

Dickson R R, Osborn T J, Hurrell J W, Meincke J, Blindheim J, Adlandsvik B, Vinje T, Alekseev G V and Maslowski W 2000 The Arctic ocean response to the North Atlantic oscillation *J. Clim.* **13** 2671–96

Ding Q *et al* 2017 Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice *Nat. Clim. Change* **7** 289–95

Docquier D *et al* 2019 Impact of model resolution on Arctic sea ice and North Atlantic Ocean heat transport *Clim. Dyn.* **53** 4989–5017

Docquier D, Fuentes-Franco R, Koenigk T and Fichefet T 2020 Sea ice—ocean interactions in the Barents sea modeled at different resolutions *Front. Earth Sci.* **8** 1–21

Docquier D, Koenigk T, Fuentes-Franco R, Karami M P and Ruprich-Robert Y 2021 Impact of ocean heat transport on the Arctic sea-ice decline: a model study with EC-Earth3 *Clim. Dyn.* **56** 1407–32

England M, Jahn A and Polvani L 2019 Non-uniform contribution of internal variability to recent Arctic sea ice loss *J. Clim.* **32** 4039–53

Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58

Francis J A and Hunter E 2007 Drivers of declining sea ice in the Arctic winter: a tale of two seas *Geophys. Res. Lett.* **34** L17503

Francis J and Vavrus S 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes *Geophys. Res. Lett.* **39** L06801

Furevik T 2001 Annual and interannual variability of Atlantic water temperatures in the Norwegian and Barents seas: 1980–1996 *Deep-Sea Res.* I **48** 383–404

Goosse H and Fichefet T 1999 Importance of ice-ocean interactions for the global ocean circulation: a model study *J. Geophys. Res.* **104(C10)** 23337–55

Haak H, Jungclaus J, Mikolajewicz U and Latif M 2003 Formation and propagation of great salinity anomalies *Geophys. Res. Lett.* **30** 1473

Helland-Hansen B and Nansen F 1909 The Norwegian sea: its physical oceanography based upon the Norwegian researches 1900–1904 *Rep. Nor. Fish. Mar. Invest.* **2** 2

Holland M M and Bitz C M 2003 Polar amplification of climate change in coupled models *Clim. Dyn.* **21** 221–32

Holland M M, Bitz C M, Eby M and Weaver A J 2001 The role of ice–ocean interactions in the variability of the North Atlantic thermohaline circulation *J. Clim.* **14** 656–75

Holland M M, Bitz C M and Tremblay B 2006 Future abrupt reductions in the summer Arctic sea ice *Geophys. Res. Lett.* **33** L23503

Hwang Y T, Frierson D M W and Kay J 2011 Coupling between Arctic feedbacks and changes in poleward energy transport *Geophys. Res. Lett.* **38** L17704

Ingvaldsen R B, Asplin L and Loeng H 2004 The seasonal cycle in the Atlantic transport to the Barents sea during the years 1997–2001 *Cont. Shelf Res.* **24** 1015–32

IPCC 2021 Summary for policymakers *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge: Cambridge University Press)

Ivanov V V, Alexeev V A, Repina I, Koldunov N V and Smirnov A 2012 Tracing Atlantic water signature in the Arctic sea ice cover east of Svalbard *Adv. Meteorol.* **2012** 201818

Ivanova N *et al* 2015 Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations *Cryosphere* **9** 1797–817

Kay J E, Holland M M and Jahn A 2011 Interannual to multi-decadal Arctic sea ice extent trends in a warming world *Geophys. Res. Lett.* **38** L15708

Kodaira T, Waseda T, Nose T and Inoue J 2020 Record high Pacifc Arctic seawater temperatures and delayed sea ice advance in response to episodic atmospheric blocking *Sci. Rep.* **10** 20830

Koenigk T *et al* 2019 Impact of Arctic sea ice variations on winter temperature anomalies in northern hemispheric land areas *Clim. Dyn.* **52** 3111–37

Koenigk T and Brodeau L 2014 Ocean heat transport into the Arctic in the twentieth and twenty-first century in EC-Earth *Clim. Dyn.* **42** 3101–20

Koenigk T, Brodeau L, Graversen R G, Karlsson J, Svensson G, Tjernstrom M, Willen U and Wyser K 2013 Arctic climate change in 21st century CMIP5 simulations with EC-Earth *Clim. Dyn.* **40** 2719–43

Koenigk T, Mikolajewicz U, Haak H and Jungclaus J 2006 Variability of Fram Strait sea ice export: causes, impacts and feedbacks in a coupled climate model *Clim. Dyn.* **26** 17–34

Koenigk T, Mikolajewicz U, Jungclaus J H and Kroll A 2009 Sea ice in the Barents sea: seasonal to interannual variability and climate feedbacks in a global coupled model *Clim. Dyn.* **32** 1119–38

Kwok R 2018 Arctic sea ice thickness, volume and multiyear ice coverage: losses and coupled variability (1958–2018) *Environ. Res. Lett.* **13** 105005

Kwok R, Cunningham G F, Wensnahan M, Rigor I, Zwally H J and Yi D 2009 Thinning and volume loss of the Arctic ocean sea ice cover: 2003–2008 *J. Geophys. Res.* **114** C07005

Lavergne T *et al* 2019 Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records *Cryosphere* **13** 49–78

Laxon S W *et al* 2013 CryoSat-2 estimates of Arctic sea ice thickness and volume *Geophys. Res. Lett.* **40** 732–7

Li D, Zhang R and Knutson T R 2017 On the discrepancy between observed and CMIP5 multi-model simulated Barents sea winter sea ice decline *Nat. Commun.* **8** 14991

Liang X S 2014 Unraveling the cause-effect relation between time series *Phys. Rev.* E **90** 052150

Lien V S, Schlichtholz P, Skagseth O and Vikebo F B 2017 Wind-driven Atlantic water flow as a direct mode for reduced Barents sea ice cover *J. Clim.* **30** 803–12

Lind S, Ingvaldsen R B and Furevik T 2018 Arctic warming hotspot in the northern Barents sea linked to declining sea-ice import *Nat. Clim. Change* **8** 634–9

Lindsay R and Schweiger A 2015 Arctic sea ice thickness loss determined using subsurface, aircraft and satellite observations *Cryosphere* **9** 269–83

Mahlstein I and Knutti R 2011 Ocean heat transport as a cause for model uncertainty in projected Arctic warming *J. Clim.* **24** 1451–60

Marshall J, Scott J R, Armour K C, Campin J M, Kelley M and Romanou A 2015 The ocean's role in the transient response of climate to abrupt greenhouse gas forcing *Clim. Dyn.* **44** 2287–99

McCusker K, Fyfe J C and Sigmond M 2016 Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss *Nat. Geosci.* **9** 838–42

Meehl G A, Covey C, Delworth T, Latif M, McAvaney B, Mitchell J F B, Stouffer R J and Taylor K E 2007 The WCRP CMIP3 multimodel dataset *Bull. Am. Meteorol. Soc.* **88** 1383–94

Meredith M *et al* 2019 Polar regions *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* ed H-O Pörtner *et al* (Cambridge: Cambridge University Press)

Mori M, Kosaka Y, Watanabe M, Nakamura H and Kimoto M 2019 A reconciled estimate of the influence of Arctic sea-ice loss on recent Eurasian cooling *Nat. Clim. Change* **9** 123–9

Muilwijk M *et al* 2019 Arctic ocean response to Greenland sea wind anomalies in a suite of model simulations *J. Geophys. Res.* **124** 6286–322

Notz D 2014 Sea-ice extent and its trend provide limited metrics of model performance *Cryosphere* **8** 229–43

Notz D and Marotzke J 2012 Observations reveal external driver for Arctic sea-ice retreat *Geophys. Res. Lett.* **39** L08502

Notz D and Stroeve J 2016 Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission *Science* **354** 747–50

Ogawa F *et al* 2018 Evaluating impacts of recent Arctic sea ice loss on the northern hemisphere winter climate change *Geophys. Res. Lett.* **45** 3255–63

Oldenburg D, Armour K C, Thompson L and Bitz C M 2018 Distinct mechanisms of ocean heat transport into the Arctic under internal variability and climate change *Geophys. Res. Lett.* **45** 7692–770

Olonscheck D, Mauritsen T and Notz D 2019 Arctic sea-ice variability is primarily driven by atmospheric temperature fluctuations *Nat. Geosci.* **12** 430–4

Onarheim I H and Arthun M 2017 Towards an ice-free Barents sea *Geophys. Res. Lett.* **44** 8387–95

Onarheim I H, Eldevik T, Arthun M, Ingvaldsen R B and Smedsrud L H 2015 Skillful prediction of Barents sea ice cover *Geophys. Res. Lett.* **42** 5364–71

Onarheim I H, Eldevik T, Smedsrud L H and Stroeve J C 2018 Seasonal and regional manifestation of Arctic sea ice loss *J. Clim.* **31** 4917–32

OSI SAF 2017 *Global sea ice concentration climate data record v2.0 - Multimission, EUMETSAT SAF on ocean and sea ice* (http://dx.doi.org/10.15770/EUM_SAF_OSI_0008)

Perovich D K 2011 The changing Arctic sea ice cover *Oceanography* **24** 162–73

Petty A A, Kurtz N T, Kwok R, Markus T and Neumann T A 2020 Winter Arctic sea ice thickness from ICESat-2 freeboards *J. Geophys. Res.* **125** e2019JC015764

Polyakov I V *et al* 2017 Greater role for Atlantic inflows on sea-ice loss in the Eurasian basin of the Arctic ocean *Science* **356** 285–91

Polyakov I V *et al* 2020 Weakening of cold halocline layer exposes sea ice to oceanic heat in the eastern Arctic ocean *J. Clim.* **33** 8107–23

Polyakov I V, Alekseev G V, Timokhov L A, Bhatt U S, Colony R L, Simmons H L, Walsh D, Walsh J E and Zakharov V F 2004 Variability of the intermediate Atlantic water of the Arctic ocean over the last 100 years *J. Clim.* **17** 4485–97

Rothrock D A, Percival D B and Wensnahan M 2008 The decline in Arctic sea-ice thickness: separating the spatial, annual and interannual variability in a quarter century of submarine data *J. Geophys. Res.* **113** C05003

Runge J *et al* 2019 Inferring causation from time series in Earth system sciences *Nat. Commun.* **10** 2553

Sando A B, Gao Y and Langehaug R 2014 Poleward ocean heat transports, sea ice processes and Arctic sea ice variability in NorESM1-M simulations *J. Geophys. Res.* **119** 2095–108

Schauer U and Beszczynska-Möller A 2009 Problems with estimation and interpretation of oceanic heat transport-conceptual remarks for the case of Fram Strait in the Arctic ocean *Ocean Sci.* **5** 487–94

Schlichtholz P 2011 Influence of oceanic heat variability on sea ice anomalies in the Nordic seas *Geophys. Res. Lett.* **38** L05705

Schweiger A, Lindsay R, Zhang J, Steele M, Stern H and Kwok R 2011 Uncertainty in modeled Arctic sea ice volume *J. Geophys. Res.* **116** C00D06

Schweiger A, Wood K R and Zhang J 2019 Arctic sea ice volume variability over 1901–2010: a model-based reconstruction *J. Clim.* **32** 4731–52

Serreze M C, Barrett A P, Crawford A D and Woodgate R A 2019 Monthly variability in Bering Strait oceanic volume and heat transports, links to atmospheric circulation and ocean temperature and implications for sea ice conditions *J. Geophys. Res.* **124** 9317–37

Serreze M C, Crawford A D, Stroeve J C, Barrett A P and Woodgate R A 2016 Variability, trends and predictability of seasonal sea ice retreat and advance in the Chukchi sea *J. Geophys. Res.* **121** 7308–25

Sévellec F, Federov A V and Liu W 2017 Arctic sea-ice decline weakens the Atlantic meridional overturning circulation *Nat. Clim. Change* **7** 604–10

Shimada K, Kamoshida T, Itoh M, Nishino S, Carmack E, McLaughlin F, Zimmermann S and Proshutinsky A 2006 Pacific ocean inflow: influence on catastrophic reduction of sea ice cover in the Arctic ocean *Geophys. Res. Lett.* **33** L08605

SIMIP Community 2020 Arctic sea ice in CMIP6 *Geophys. Res. Lett.* **47** e2019GL086749

Smedsrud L H *et al* 2013 The role of the Barents sea in the Arctic climate system *Rev. Geophys.* **51** 415–49

Smedsrud L H, Ingvaldsen R, Nilsen J E O and Skagseth O 2010 Heat in the Barents sea: transport, storage and surface fluxes *Ocean Sci.* **6** 219–34

Smeed D A *et al* 2018 The North Atlantic Ocean is in a state of reduced overturning *Geophys. Res. Lett.* **45** 1527–33

Spielhagen R F, Werner K, Sorensen S A, Zamelczyk K, Kandiano E, Budeus G, Husum K, Marchitto T and Hald M 2011 Enhanced modern heat transfer to the Arctic by warm Atlantic water *Science* **331** 450–3

Steele M and Boyd T 1998 Retreat of the cold halocline layer in the Arctic Ocean *J. Geophys. Res.* **103** 10419–35

Steele M, Zhang J and Ermold W 2010 Mechanisms of summertime upper Arctic Ocean warming and the effect on sea ice melt *J. Geophys. Res.* **115** C11004

Stroeve J, Barrett A, Serreze M and Schweiger A 2014 Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness *Cryosphere* **8** 1839–54

Stroeve J and Notz D 2018 Changing state of Arctic sea ice across all seasons *Environ. Res. Lett.* **13** 103001

Swart N C, Fyfe J C, Hawkins E, Kay J E and Jahn A 2015 Influence of internal variability on Arctic sea-ice trends *Nat. Clim. Change* **5** 86–89

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Vinje T 2001 Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic seas during the period 1864-1998 *J. Clim.* **14** 255–67

Wang Q, Wekerle C, Wang X, Danilov S, Koldunov N, Sein D, Sidorenko D, von Appen W J and Jung T 2020 Intensification of the Atlantic water supply to the Arctic ocean through Fram Strait induced by Arctic sea ice decline *Geophys. Res. Lett.* **47** e2019GL086682

Weijer W *et al* 2019 Stability of the Atlantic Meridional Overturning Circulation: a review and synthesis *J. Geophys. Res.* **124** 5336–75

Woodgate R A 2018 Increases in the Pacific inflow to the Arctic from 1990 to 2015 and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data *Prog. Oceanogr.* **160** 124–54

Woodgate R A, Aagaard K and Weingartner T 2006 Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004 *Geophys. Res. Lett.* **33** L15609

Woodgate R A, Weingartner T and Lindsay R 2010 The 2007 Bering Strait oceanic heat flux and anomalous Arctic sea-ice retreat *Geophys. Res. Lett.* **37** L01602

Yang J and Neelin J D 1997 Decadal variability in coupled sea-ice-thermohaline circulation systems *J. Clim.* **10** 3059–76

Zhang J and Rothrock D A 2003 Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates *Mon. Weather Rev.* **131** 845–61

Zygmuntowska M, Rampal P, Ivanova N and Smedsrud L H 2014 Uncertainties in Arctic sea ice thickness and volume: new estimates and implications for trends *Cryosphere* **8** 705–20