The impact of ocean heat exchange on sea ice variability in the Barents Sea

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목 차

List of figures

1. Introduction

Sea ice declination in the Arctic has been detected over the past decades regardless of seasons (Notz and Stroeve 2016; Onarheim et al. 2018; Jakob et al. 2021), and the Barents Sea (BS), in particular, has been experiencing a 50% loss of annual sea ice concentration from 1998 to 2008 (Årthun et al. 2012; Benjamin et al. 2018). Most oceanic heat is transported into the Arctic sea through three different entrances (Jakob 2021), and the Barents Sea Opening (BSO) is considered as one of those gateways for the Atlantic water to enter the Arctic Ocean (Takuya et al. 2014), which generates the Polar Front (PF) characterized by a transition zone from the BS water to fresher and colder the Arctic water (Benjamin et al. 2018). Fluctuations of sea ice extent in the BS have been triggered by numerous factors as if anomalies of large-scale atmospheric circulation (Maslanik et al. 2007; Deser and Teng 2008; Zhang et al. 2008), regional winds and ice import from the Arctic (Hilmer et al. 1998; Koenigk et al. 2009; Kwok 2009), cyclone activity (Sorteberg and Kvingedal 2006; Simmonds and Keay 2009), and oceanic heat advection into the Barents Sea (Vinje 2001; Kauker et al. 2003; Francis and Hunter 2007).

The BS appears a seasonal variation of sea ice concentration; minimum in September and Maximum in March/April (Kvingedal 2005). Not only that, it also has a robust natural sea ice variability at interannual, decadal, and longer time scales in the past decades (Onarheim and Arthun 2017). However, winter sea ice area in the BS has been decreased since 1850 (Shapiro et al. 2003), which denotes the largest declination in the Arctic (Parkinson and Cavalieri 2008; Screen and Simmonds 2010b). Numerical simulations indicate that the interannual variability and longer-term decrease in the sea ice area imply the variation of the Atlantic inflow (Årthun and Schrum 2010; Sandø et al. 2010; Årthun et al. 2012; Koenigk and Brodeau 2014). A number of studies described that changes of sea ice extent in the BS have influenced on local weather and climate (Kohnemann et al. 2017; Pedersen and Christensen 2019), Arctic economics (Eicken 2013; Smith and Stephenson 2013; Melia et al. 2016; Pizzolato et al. 2016; Laliberté et al. 2016), fishery activities (Hollowed et al. 2013; Haug et al. 2017), natural resources (Jung et al. 2016), and ecosystem (Dalpadado et al. 2014).

For accurate climate prediction for the North Atlantic/Arctic region, understanding the internal mechanisms and time scales regarding the transportation of ocean heat anomalies is essential (Latif and Keenlyside 2011; Meehl et al. 2014; Marius and Tor 2015). Ocean heat transport (OHT) has been one of the strongest driving factors of recent sea ice variability (Francis and Hunter 2007; Carmack et al. 2015; Årthun et al. 2019; Jakob et al 2021). One of major sources of oceanic heat supply in the BS is the Norwegian Atlantic Current; a poleward extension of the Gulf Stream and the North Atlantic Current (Polyakov et al. 2005; Takuya et al. 2014). Once warm and saline Atlantic water encounters the Eurasian, it splits into two branches, one for the Fram Strait (Rudels et al. 2015) and the other for BSO (Schauer et al. 2002). Those branches transport oceanic heat to the sea ice at the north of Svalbard and the BS (Sandø et al. 2010; Schlichtholz 2011; Årthun et al. 2012; Lind and Ingvaldsen 2012; Onarheim et al. 2014; Lien et al. 2017). Since the majority of the ocean heat in the BS is discharged to the atmosphere owing to the extremely large gap of air-sea temperature difference (Simonsen and Haugan 1996), this region takes an important part of modulating the Arctic heat budget and climate variability (Smedsrud et al., 2013; Årthun & Eldevik, 2016; Qiang et al. 2019).

When it comes to the influence of the BS on global climate, Serreze et al. (2007) show that the BS has the most vigorous air-sea interaction in the Arctic, which leads to a substantial impact on the polar climate structure. Furthermore, Honda et al. (2009) made a point that the Eurasian continent, where had recently had an extreme winter (Petoukhov and Semenov 2010; Peings and Magnusdottir 2014; Vihma 2014; Screen 2014; Screen and Simmonds 2014; Cohen et al. 2014), is subject to a dynamic atmospheric response from the modification of a stationary Rossby wave caused by anomalous turbulent heat fluxes in the BS and Kara sea from late autumn to early winter. Francis and Vavrus (2012) suggested that the declination of sea ice edge

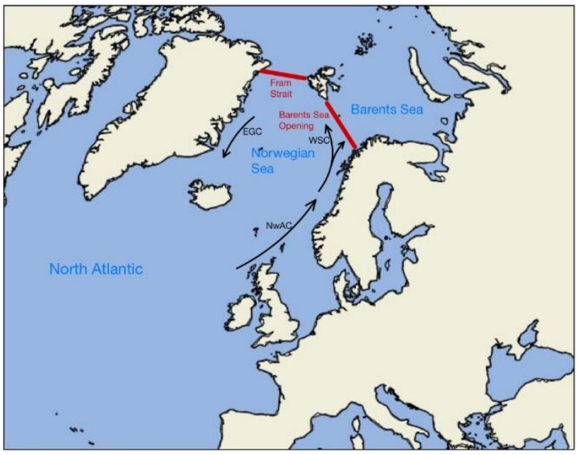

Fig. 1. Map of North Atlantic Ocean and Arctic Ocean showing regional seas(blue), oceanic gateways(red), and currents(black) used in this work.

enables more heat and moisture to enter the atmosphere in the high latitudes from boreal autumn and winter and makes the temperature gradient between equatorial and polar regions decrease, possibly leading to shift or weaken the midlatitude jet stream. However, suggestions for the distant influence of the Arctic sea ice variability on the mid-latitude and the tropical area make numerous debates and still remain unclear (Cohen et al. 2014, 2020; Walsh 2014; Barnes and Screen 2015; Overland et al. 2016; Peings 2019; Blackport et al. 2019, 2020; Mori et al. 2019a,b; Screen and Blackport 2019).

In this paper I focus on the oceanic and atmospheric heat exchange in the BS to break down the internal mechanism of forming total heat budget of the BS. Specifically, I deal with the variability of OHT to the BS associated with subpolar ocean circulation in the Atlantic sea. This work makes it possible to better understand the heat exchange structure of the BS and contributions of each variable component.

2. Data and methods

I make use of the output from 20 members of the Community Earth System2 Model2's Large Ensemble (CESM2-LE; Danabasoglu et al. 2020) from 1850 to 2100, which consists of the historical (1850-2014) and RCP8.5 (2015-2100) forcing scenarios. I note that RCP8.5 is a high-emission (worst case) scenario, and that its use in near-term predictions is controversial (Hausfather and Peters 2020). Other emission scenarios are not utilized in our study. Each member has the same external forcing but contains different initial conditions, which denotes discrepancies among the simulations are only caused by internal variability simulated by the model.

I examine winter sea ice, defined as November to March of the following year, and total heat budget over the BS. Specifically, sea ice concentration & thickness, potential temperature, ocean flow velocity of x and y direction, air-sea heat flux, and ice-ocean heat flux are used for this research.

The way I calculate the ocean heat transport is mainly attributed to Jakob et al. (2021). They define OHT as follows:

$$OHT = \rho C_p \int_S U(T - T_{ref})dS,$$

where ρ = 1025 kg m^{-3} is the constant water density, C_p = 4184 J K^{-1} kg^{-1} is the constant heat capacity of the ocean, U is the velocity, T is temperature, and S is the surface area of the section. In the CESM2, OHT can be directly calculated by the advective heat flux, UET and VNT from model variables. T_{ref} is an arbitrary reference temperature, which is 0℃ defined by CESM2 and used for the advective heat flux.

3. Results

In historical experiment and RCP8.5 scenario simulation, it shows that the overall sea ice concentration across the Arctic ocean will decrease as time goes by (Fig .2), and it also denotes that three main regions (Arctic-North Pacific Opening, center of Arctic sea, and the Barents sea) are some of the most vulnerable and sensible to Arctic climate change in terms of sea ice area variability. Specifically, speaking of the BS, its sea ice extent declination is observed, the edge at 45˚E, 77˚N in historical and 60˚E, 80˚N in the end of RCP8.5 scenario, and suggesting that most of sea ice in the BS will be disappeared in 2075-2100 time period.

I analyze three main heat exchange component: OHT, Volume Transport, Surface Heat Flux(including SW), and Qflux(the internal ocean heat flux due to the ice formation). First of

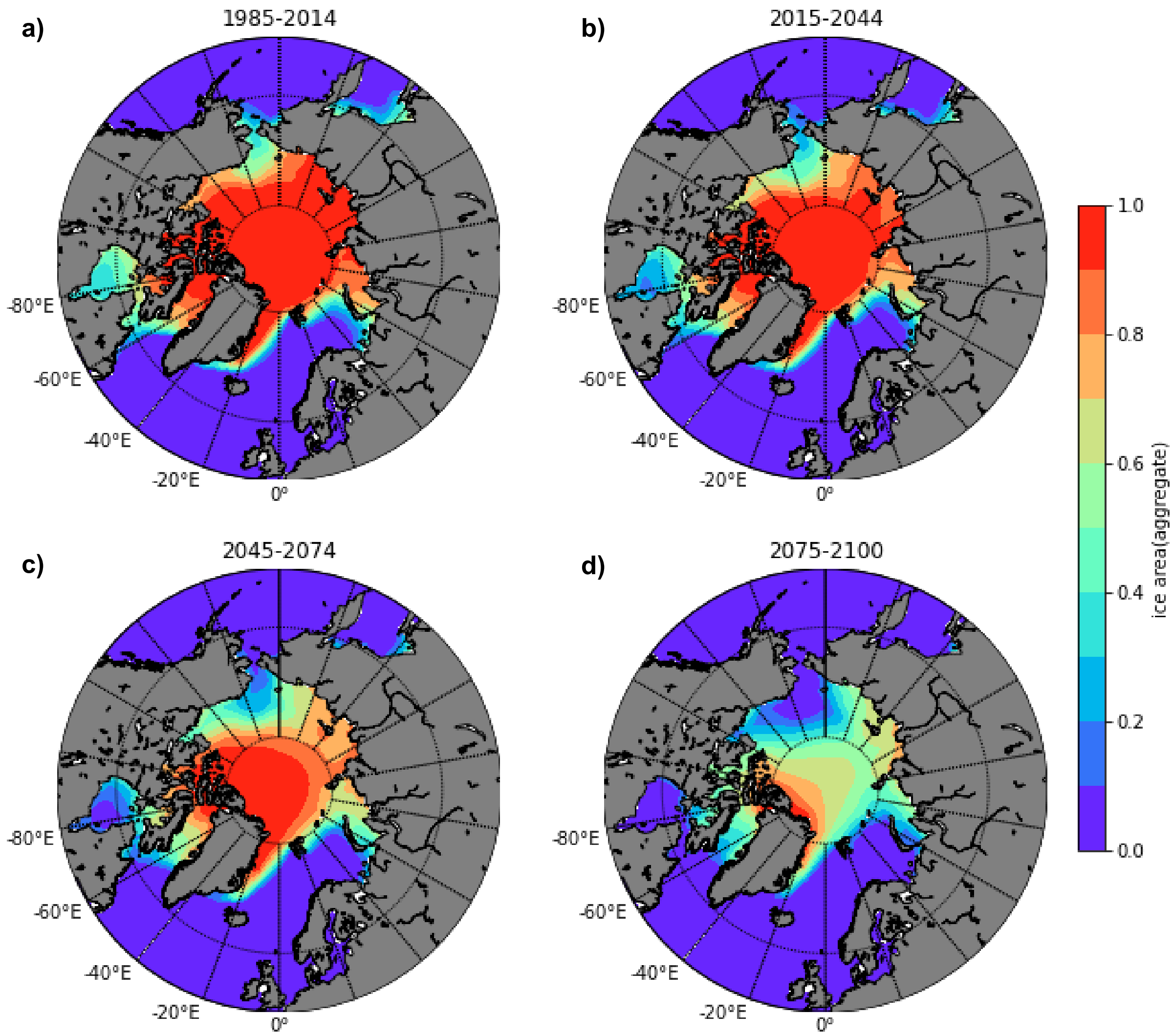

Fig. 2. Simulated Arctic winter (Nov-Mar) sea ice cover. (a) showing mean sea ice concentration in historical simulation, and (b)-(d) three periods in CESM2-LE.

all, analyzing the OHT variability over scenarios, it indicates that the heat flux advection at the BSO will be reduced over the RCP8.5 as the volume transport decreases (Fig .3). Furthermore, the maximum spot of OHT at the BSO, at 72˚N, appears 1.4 KW per meter square as 0.5 Sv of ocean mass is transported. However, its intensity weakens at the later time period, reaching down to 0.6 KW per meter square. Interestingly, although the strength of OHT weakens at the BSO, the ocean heat advection throughout the BS is inclined to spread over more than the historical experiment at the forcing simulation. In addition to this, as the volume transportation into the BS decreases, it seems to have more advection to the Fram Strait, and the OHT from NwAC tends to transfer and flow as the WSC into the Fram Strait.

I also examine Ocean Heat Content (OHC) over the BS from three different heat flux components as mentioned before. I target OHC up to 600m depth the same as the maximum depth of the BS. Vertical integration of potential temperature can be assumed as heat budget of a certain area, which is the way I calculate OHC in the BS. Although there are numerous factors influencing on heat content, even inspecting with those three variables, I will be able to better understand the individual contribution of each and the mechanism of heat budget system. Fig .3 represents the time series of each component and OHC in the BS. First and foremost, the OHC in the BS has an increasing tendency as simulation goes on, but Qflux is inclined to decrease conversely, which shows that the ice formation over the BS is reduced, leading to the declination

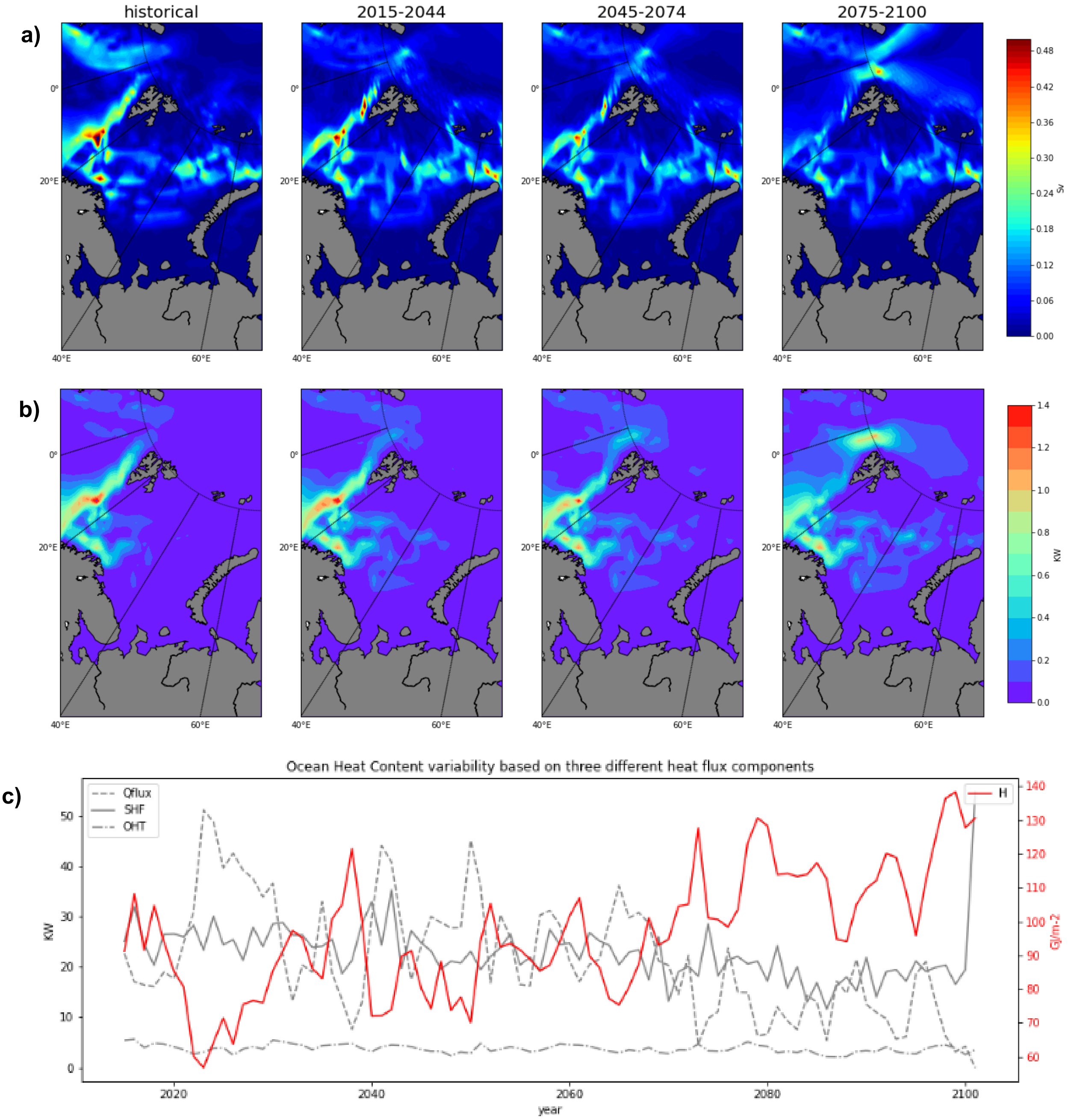

Fig .3 Volume Transport (a) and Ocean Heat Transport (b) variability at the BSO in historical and RCP8.5 Scenario. (c) denotes the time series of OHC variability from three heat flux factors. Dashed line, solid line, and dashed-solid line represent Qflux, SHF, and OHT, respectively.

of heat discharge to the surrounding ocean. Secondly, total surface heat flux over the BS decreases but its tendency is weaker than Qflux. In terms of interannual variability, SHF in the BS represents more variable than the other heat flux components. Lastly, the OHT at the BSO does not seem to vary throughout the entire simulation, but its variation shows significantly dynamic. To be more specific, its tendency indicates declination as I presented Fig .3, and the maximum value of vertical integrated OHT in the BSO represents over 5.5 KW per meter square, and it goes down and reaches to 3.0KW in the next 10 years, and then increases again at the around of the maximum point but not as much as it does.

Now I present the correlation between three different heat flux components and sea ice concentration. I classify three time period from

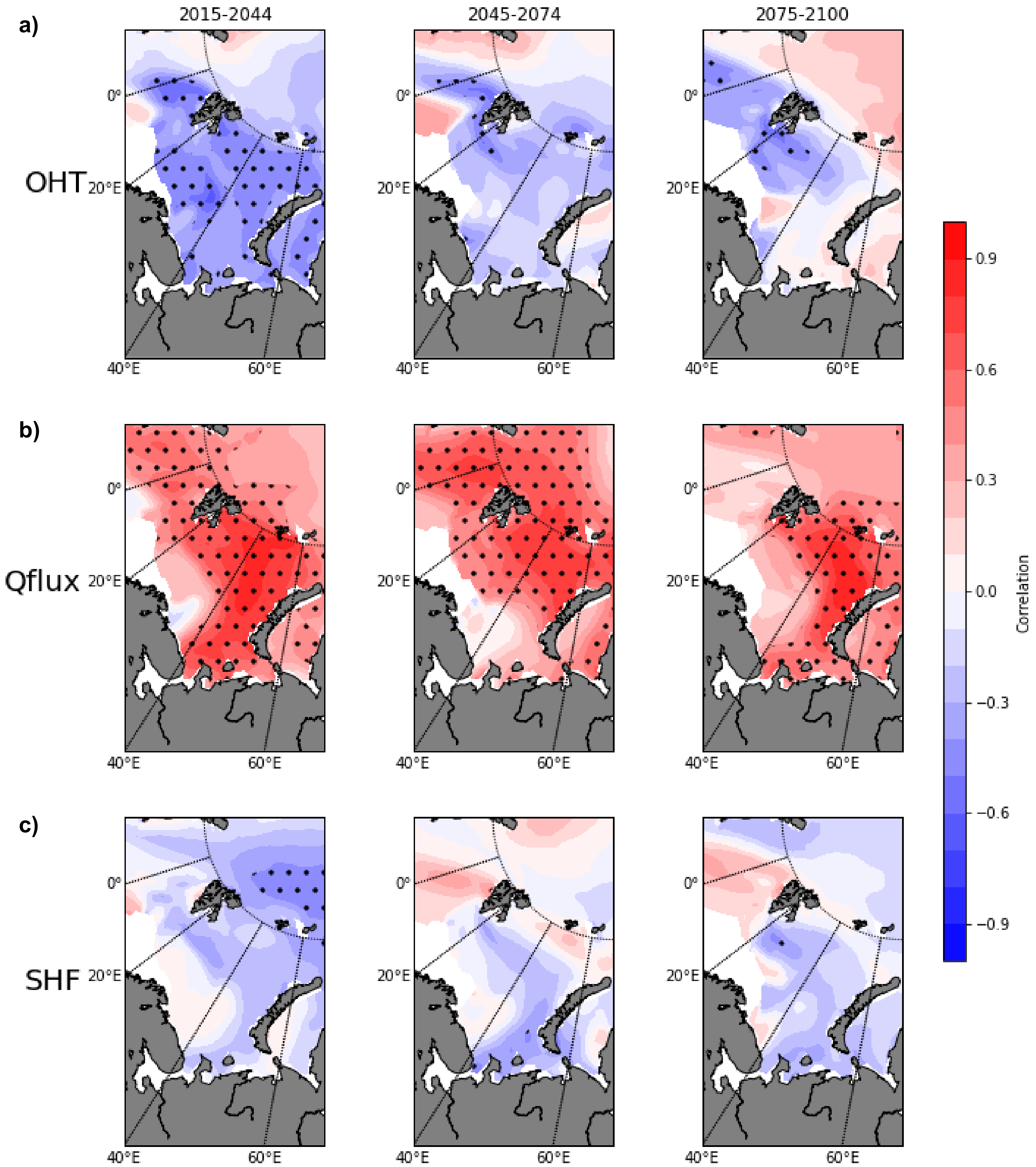

Fig .4 Maps showing correlation between the annual mean heat flux of each component and winter mean sea ice concentration in three period of CESM2-LE. (a) Ocean Heat Transport, (b) Qflux, and (c) Surface Hear Flux. Dots indicates significant values over 0.4.

the RCP8.5 scenario and examine how correlation of each variable change over the experiment. Firstly, regarding correlation with OHT, it is highly corelated with sea ice area at the first 30 years, but it does not keep the same state at the later time period. Additionally, Qflux shows high correlation not just the BS but all over the Atlantic side of the Arctic ocean, but it is more likely influential on the BS since its high correlating area does not vary regardless of classified time period. Last of all, total surface heat flux does not really have high correlation with sea ice area over the experiment.

4. Discussions

In this study, I focused on heat exchange in the BS to examine the cause and effect of sea ice concentration variability. I found that OHT through the BSO decrease, which is possibly originated from the weakened Atlantic Meridional Overturning Circulation, causing to reducing of the strength of Gulf Stream. However, OHT at the BSO reduces, the spread of heat flux throughout the entire BS is conversely wider than early time period. Ocean internal heat flux from the ice formation indicates the highest relatable factor among the three heat flux components, but the detail mechanism of heat exchange between ice and ocean requires to be more examined. Total surface heat flux has also an impact on the BS but not as much as other variables.

5. Conclusions

The BS is known for the place where one of the most sensible spot to Arctic climate change on the Arctic environment. Our study does not show the exact quantity and contribution of each heat flux component but denotes that how those influential factor to the BS heat content varies over the RCP 8.5 scenario. After this paper, atmospheric circulation variability and the interaction between the BS and adjacent ocean in the Arctic should be followed as subsequent research.

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