



# The Physical System of the Arctic Ocean and Subarctic Seas in a Changing Climate

Camila Campos and Myriel Horn

## Abstract

The Earth's climate is changing and the poles are particularly sensitive to the global warming, with most evident implications over the Arctic. While summer sea ice reduced significantly compared to the previous decades, and the atmospheric warming is amplified over the Arctic, changes in the ocean are less obvious due to its higher inertia. Still, impacts of the changing climate on high-latitude and polar oceans are already observable and expected to further increase. The northern seas are essential regions for the maintenance of the Atlantic Meridional Overturning Circulation, which in turn is a key aspect of the maritime climate. Alterations in heat and freshwater/salinity content in the Arctic Ocean and adjacent seas impact and are closely linked to buoyancy flux distributions, which control the vertical and horizontal motion of water masses, thus impacting the climate system on a longer time scale. In this context, we set our focus on the Arctic Ocean and Atlantic subarctic seas, review some of the contemporary knowledge and speculations on the complex coupling between atmosphere, sea ice, and ocean, and describe the important elements of its physical oceanography. This assessment is an attempt to raise awareness that investigating the pathways and timescales of oceanic responses and contributions is fundamental to better understand the current climate change.

## Introduction

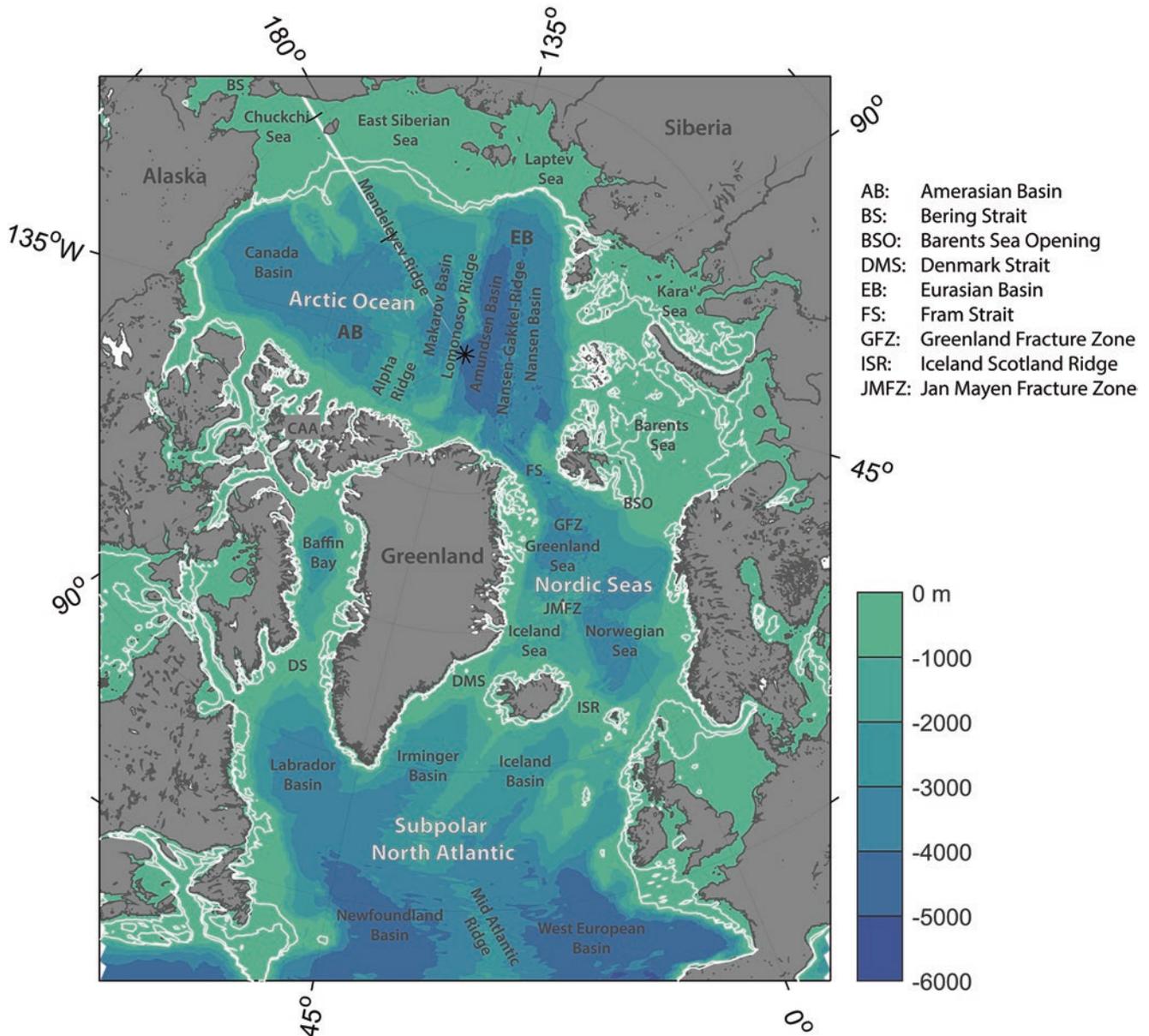
The Arctic region (Fig. 1) is a relative small fraction of the globe's surface, but plays a crucial role in determining global climate dynamics due to the intimate and complex couplings between cryosphere, atmosphere, ocean, and land (Serreze et al. 2007). Currently, the Arctic is undergoing remarkable environmental changes and has been in focus of the climate sciences community (Winton 2008; Overland 2016).

The Arctic near surface air temperature is warming twice as fast as the global average (Serreze and Francis 2006). This accelerated response is known as the Arctic amplification (Winton 2008; Serreze and Barry 2011; Cohen et al. 2014), and one of the most dramatic indicators of the Arctic warming has been the decline in the sea ice cover. Satellite observations reveal that the area of the Arctic sea ice during summer has steadily decreased by more than 40% in recent decades (Fig. 2) (Comiso et al. 2008; Pistone et al. 2014). Notwithstanding, observations further show a year-round loss of sea ice extent and thickness (Lindsay and Schweiger 2015; Rothrock et al. 2008), which suggest that from year to year more melt and less recovery is taking place.

The observed rate of sea ice extent reduction during the last three to four decades has occurred faster than anticipated by models participating on the Intergovernmental Panel on Climate Change Fourth Assessment Report: the observed trend for the September sea ice extent was  $-9.12 \pm 1.54\%$  per decade for the period 1979–2006, while the mean decline trend of all the models participating in the report was  $-4.3 \pm 0.3\%$  per decade (Stroeve et al. 2007). The accelerated sea ice decline has likely occurred due to a combination of decadal-scale variability in the coupled ice-ocean-atmosphere-land system and radiative greenhouse gas forcing (e.g., Serreze and Barry 2011; IPCC 2014; Zhang 2015). According to model studies, the Arctic sea ice will continue shrinking and thinning year-round in the course of the twenty-first century as the global mean surface temperature rises, with projections of summer ice free Arctic in the near

Both authors contributed equally.

C. Campos · M. Horn (✉)  
Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany  
e-mail: [camila.campos@awi.de](mailto:camila.campos@awi.de); [myriel.horn@awi.de](mailto:myriel.horn@awi.de)



**Fig. 1** The northern seas (produced with the help of the colormap from Thyng et al. 2016). Bathymetric and geographical map derived from the 2-min ETOPO2 database

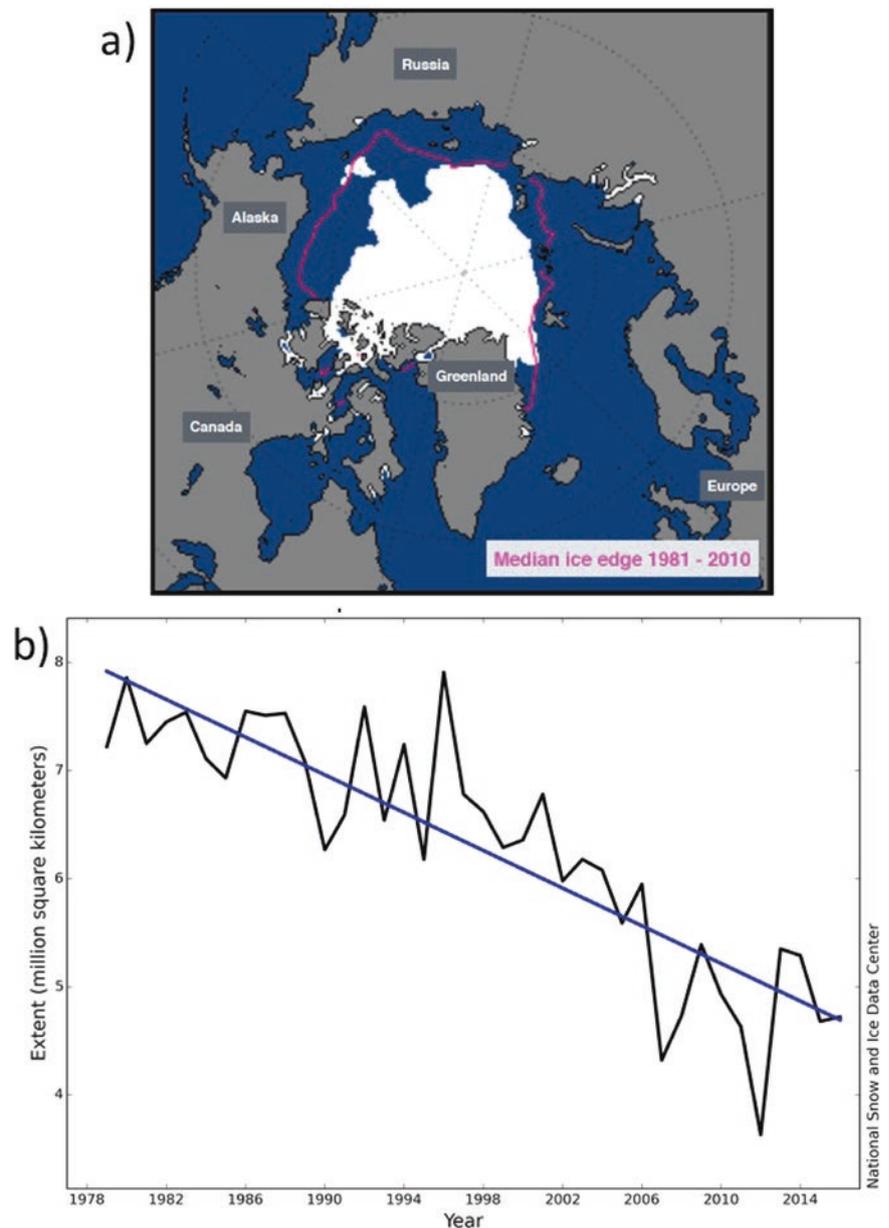
future (Wang and Overland 2009; IPCC 2014). Nevertheless, the impacts of these projections for the weather and climate locally and elsewhere are not sufficiently well understood.

Numerous studies have been published on the relation between Arctic sea ice decline and weather and climate. While some have addressed the question how Arctic sea ice decline impacts climate (Budikova 2009; Vihma 2014; Semmler et al. 2016), Lang et al. (2017) and several others have reviewed the recent decline in Arctic sea ice and the processes responsible for it (Polyakov et al. 2012; Stroeve et al. 2012; Barnes and Screen 2015). By far, the majority of these studies focus on atmospheric pathways and, therefore,

our understanding of the mechanisms, pathways, and timescales by which the ocean controls or responds to these changes remains quite limited.

Previous studies addressed how the inflow of the warm Atlantic Water (AW) to the Arctic Ocean contributes to the decline of the sea ice extent and thickness (e.g., Carmack et al. 2015; Onarheim et al. 2014). Itkin et al. (2014) has addressed this problem from the reverse perspective, and showed in idealized experiments that a weaker (i.e., thinner) sea ice cover allows higher momentum transfer into the Arctic Ocean and impacts the surface and intermediate ocean circulation. In other words, there is an intrinsic two-way

**Fig. 2** Arctic summer sea ice decline (Fetterer et al. 2016, provided by the National Snow and Ice Data Center NSIDC, with permission). (a) Arctic September (minimum) sea ice extent in 2016 (white area) compared to the median ice edge for the period 1981 to 2010 (fuchsia line) and (b) average monthly September sea ice extent for the years 1979–2016, blue line: decline rate of 13.2% per decade relative to the 1981–2010 average



relation between the ocean and the sea ice, and any change in sea ice cover may impact the dynamics and thermodynamics of the ocean. Recent observations suggest that a diminishing sea ice cover to the northeast of Svalbard is responsible for reducing the stratification of the ocean and allowing more upward heat transfer, which preconditions the ice to further melting (Polyakov et al. 2010, 2017).

A significant increase in liquid freshwater content has been observed in the upper Arctic Ocean in the past two decades (Rabe et al. 2011; Giles et al. 2012; Morison et al. 2012; Rabe et al. 2014), while the Arctic sea ice volume has been shrinking significantly (Lindsay and Schweiger 2015). Sea ice and liquid fresh water are important factors for the Arctic Ocean, where they insulate the atmosphere from the

warm Atlantic-derived water at intermediate depths, by limiting the upward heat transport, hence influencing the sea ice formation and melting as well as the air temperature.

After a freshening of the subpolar North Atlantic and Nordic Seas from the 1960s to the 1990s, both regions became again more saline thereafter (Curry and Mauritzen 2005; Boyer et al. 2007; Mauritzen et al. 2012). The Nordic Seas and the subpolar North Atlantic are the main regions in the northern hemisphere, where deep water formation takes place and thereby are key regions for global climate (Rhein et al. 2011). Freshwater changes could potentially influence this overturning system and thereby have a profound impact on our climate (Koenigk et al. 2007; Rennermalm et al. 2007).

In this chapter, we provided an introductory overview on the complex interactions of the coupled Arctic system in a changing climate with specific interest in the ways in which Arctic Ocean and adjacent seas may respond and modulate the observed and projected changes over high and mid-latitude. Next, we give an overview of the complex interplay between the dynamics and thermodynamics of the sea ice, atmosphere and ocean. We start by addressing the sea ice cycle, variability, and importance in the climate system (Section “[Arctic sea ice](#)”). In Section “[Arctic – subarctic atmosphere](#)” we give background information on the Arctic – Subarctic atmosphere (Section “[Atmospheric circulation: Why does it matter?](#)”) and present the main atmospheric circulation modes (Section “[Major modes of atmospheric circulation in the Arctic](#)”). Then, we finally get to discuss the changing climate from the ocean perspective (Section “[Ocean](#)”): at first, we describe the main geographical features and the hydrography of the northern seas; subsequently, we address recent research and discussion of the global relevance of the region in a changing world. Final remarks are given in Section “[Outlook](#)”.

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## Arctic Sea Ice

### Sea Ice Cycle

The sea ice cover has a natural cycle as a consequence of the periodic changes of incident solar radiation over high latitudes. As the cold season arrives, atmospheric temperatures rapidly begin to drop. This leads to a positive thermal gradient from ocean to the surrounding air, resulting in a direct loss of sensible heat from the upper ocean. Dynamical instability in the upper meters of the ocean is generated as a consequence to density changes caused by cooling, and a vertical mixing is maintained until a significant layer of the upper water column approaches homogeneous temperature. Once the ocean freezing temperature of  $-1.9\text{ }^{\circ}\text{C}$  is achieved, sea ice structures begin to form, and during this process a salt solution (brine) is expelled into the ocean further increasing its density. However, if mixing is deep enough, the surface waters may not reach freezing temperatures due to mixing with the warmer waters at intermediate depths and sea ice formation will not occur.

After initial formation in fall, sea ice continues growing through winter months and increases in vertical and horizontal extent. It can be characterized by highly complex and variable macrostructures, such as ridges, melt ponds, leads and polynyas. By the end of wintertime, the sea ice extent has reached its maximum. During spring, the solar radiation gradually increases thereby initiating the melting phase, which carries on until the next cooling season. If all the sea ice melts away, the area is characterized by the presence of

first year ice. However, if sea ice persists until the end of the warm season a perennial (multiyear) sea ice cover establishes. The fundamental differences between them relate to the vertical growth and surface roughness.

Overall, freezing and melting are controlled by net surface heat energy flux variations during the year, and environmental conditions, e.g., wind and oceanic currents, play a role in determining expansion and thickening. Furthermore, the horizontally confined Arctic Ocean allows for thicker sea ice growth (in comparison to the Southern Ocean), and winter sea ice thickness ranges on average from 3 to 4 m. For more details the reader is referred to Thomas and Dieckmann (2010).

### Sea Ice Role in the Climate System

Sea ice is a highly reflective surface, with albedo ranging from 50% to 70%. Albedo is a measure of a surface’s reflectivity, and may be even higher if a snow cover is present. A thicker ice pack supports a greater layer of snow and this system can reflect up to 90% of solar energy. Additionally, it acts as an insulator between ocean and atmosphere, and, therefore, restricts heat and momentum fluxes at this interface. If the atmosphere or the ocean warms up (above melting temperatures) sea ice melts and, since the exposed ocean surface has a much lower albedo than sea ice, the overall albedo of polar areas decrease. The low reflectance oceanic surface takes in extra heat, driving major changes in the regional radiative equilibrium and further sea ice melt. The described processes is the so-called ice-albedo feedback mechanism and is accounted as the main reason of nonlinear changes over polar regions (Winton 2008; Serreze and Barry 2011; Vihma 2014). Changes to ocean density caused by the sea ice cycle are important processes for the local oceanic stratification and global oceanic circulation.

A few specific areas of the high latitude oceans are crucial for the production of dense water masses, which contribute to the lower limb of the global oceanic overturning circulation. The upper layers of the ocean are densified through cooling of surface waters and the injection of brine during sea ice formation resulting in vertical mixing and deep convection (Tomczak and Godfrey 1994). In these regions the dense water sinks and is replaced by surface water from other areas and the continuation of this process is one of the drivers of the Meridional Overturning Circulation; the sinking of these waters is compensated by upwelling at other sites (Talley et al. 2011). On the other hand, sea ice constitutes a source of relatively fresh water (with an average salinity ranging from 2 to 7 (Thomas and Dieckmann 2010)) and when it melts it decreases the density of the water directly underneath, creating a stable surface layer. Changes in the water density at the deep convection sites may alter mixing

and convection processes. Hence, the presence of sea ice strongly modulates interactions between ocean and atmosphere, namely heat, mass, and momentum transfers.

In addition to all physical aspects, sea ice acts as a key component also for the Arctic ecosystem, it also determines marine transportation and offshore activities, and is of crucial societal importance. A detailed description of these aspects is beyond the scope of the present review, but we refer to the Arctic Climate Impact Assessment – Scientific Report (ACIA 2004) for a more thorough perspective.

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## Arctic – Subarctic Atmosphere

### Atmospheric Circulation: Why Does It Matter?

The polar regions are the world's heat sink: at low latitudes the amount of incoming solar radiation (shortwave) exceeds the emitted infrared radiation (longwave), whereas there is an annual energy deficit at the poles, where more heat is emitted than absorbed. The surplus of energy is then transported from the equatorial region towards the poles in the atmosphere and ocean. In the atmosphere, this manifests as global circulation cells, which, due to turbulent interactions, transfer energy to smaller processes of regional and local importance forcing climate and weather patterns. The latter play a very important role in the coupling with ocean and sea ice, which on the other hand also force changes on the atmospheric circulation. Therefore, global climate and weather are highly dependent on these interactions between the components of the earth system (Taylor 2009).

Though temperatures have been increasing in polar and equatorial regions, it has been amplified at high latitudes, especially over the Arctic (Serreze and Barry 2011). This amplification is attributed to several feedback mechanisms (Taylor et al. 2013) and, even though the ice-albedo feedback is often cited as primary contributor, some studies suggest that other interactions, like the warming of the lower atmosphere might play a bigger role (Pithan and Mauritsen 2014). Serreze and Barry (2011) provide a thorough synthesis of research on Arctic amplification.

The fact that the temperature increase over the Arctic has been happening at a faster rate than the global average, decreases the overall meridional temperature gradient over the globe, which in turn may affect the atmospheric circulation pattern locally as well as remotely (Barnes and Screen 2015). The scientific community has been broadly concerned with possible changes over mid-latitude weather such as, e.g., the occurrence of extreme weather events and the weakening and shifting of the westerly winds (Overland 2016). These winds are strongly coupled to the track and intensity of storm systems travelling at mid-latitudes, hence it is expected that changes in the position and strength of the jet

stream leads to noticeable changes in the northern hemispheric daily weather (e.g., Barnes and Screen 2015; Serreze and Barry 2011).

The particular role and responses of the atmosphere in a warming climate are beyond the scope of this work. Thus, for more comprehensive understanding we refer here to several studies which review and investigate responses of large-scale atmospheric circulation to changes in sea ice cover over the Arctic (Budikova 2009; Bader et al. 2011; Vihma 2014; Semmler et al. 2016). Nevertheless, an overview on the background characteristics of the Arctic atmospheric system are given next.

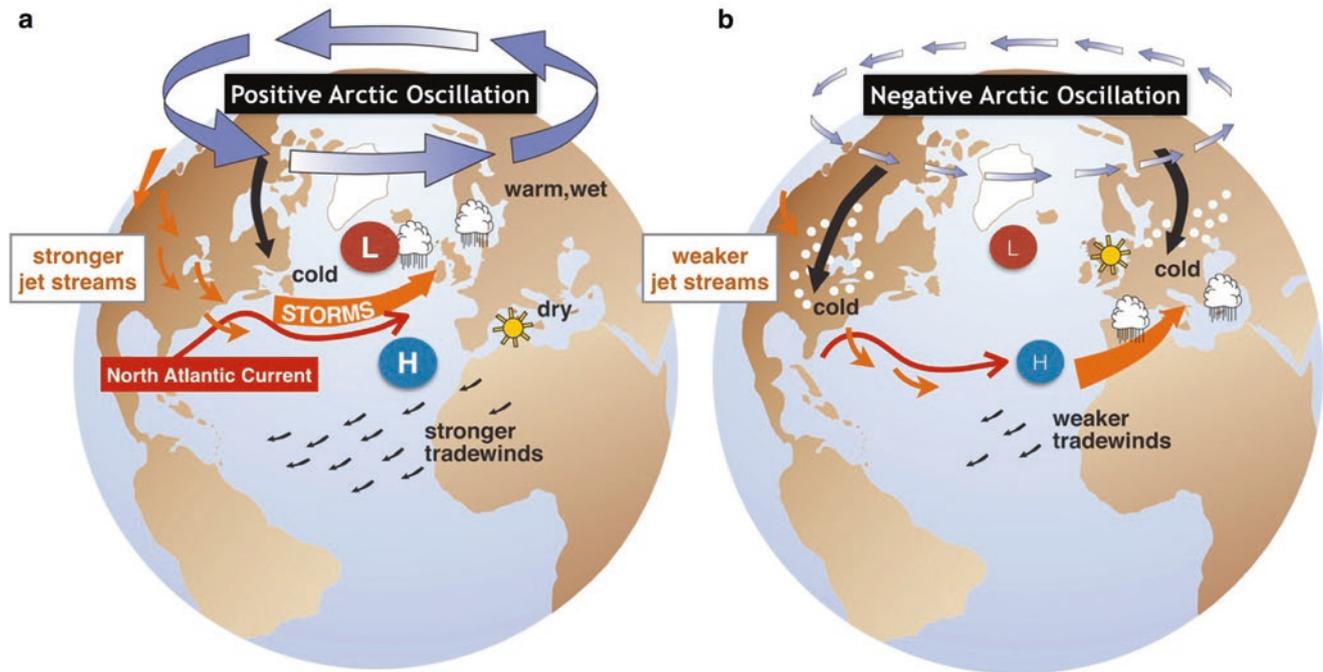
### Major Modes of Atmospheric Circulation in the Arctic

As explained above, atmospheric circulation and weather are linked to gradients. The system has an intrinsic seasonal variability upon which these gradients oscillate. To characterize the major atmospheric modes over the Arctic, a brief illustration on its climatology is given in terms of sea level pressure.

The prevailing atmospheric circulation over the Arctic is anticyclonic, which results from an average high-pressure system that spawns winds over the region. Although prevalent, the circulation regime may shift to cyclonic on the time scales of 5–7 years (Proshutinsky et al. 2009). Shifts from one regime to another are forced by changes in the location and intensity of the pressure systems described below. This oscillatory mode is part of the Arctic system's natural variability and may help to explain the significant, basin-scale changes of the Arctic atmosphere-ice-ocean system (Polyakov and Johnson 2000; Proshutinsky et al. 2009, 2015).

The two semi-permanent centers of low pressure, the oceanic Aleutian and Icelandic Lows, and the continental Siberian High, which extends into the Arctic as the Beaufort High, are observed as pronounced features during winter. In summer, the gradients of the polar and subpolar regions are relatively weak, and sea level pressure distribution is dominated by the subtropical, the Azores and the Pacific Highs (McBean et al. 2005). To describe the main states of the atmospheric circulation, indices were created. Based on a surface variable and obtained through statistical analysis, these are used to characterize complex climate processes and explain past variability.

The major mode of variability in the Arctic is the Arctic Oscillation (AO), and is characterized by the relation between the surface pressure anomaly in the Arctic and in mid-latitudes (Thompson and Wallace 1998). When the AO is in its positive phase, surface pressure in the polar region is low. This mode manifests as the strengthening of the zonal westerly winds



**Fig. 3** Schematic of the Arctic Oscillation and its effects (adapted from AMAP 2012, with permission). Positive Arctic Oscillation (a) and negative Arctic Oscillation (b) Accordingly, the centres of low (red encircled L) and high (blue encircled H) pressure systems over the North Atlantic indicate the corresponding North Atlantic Oscillation phases (a: positive, b: negative)

which act to confine colder air over the high latitudes. On the other hand, in the negative phase of the AO, surface pressure is high in the Arctic, acting to weaken the atmospheric circulation, and thus, allowing an easier escape of the cold polar air masses towards the mid-latitudes (Fig. 3).

The regional manifestation of the AO in the North Atlantic is the North Atlantic Oscillation (NAO). It is given by the correlation of the main pressure centers in the North Atlantic, namely the Icelandic Low and the Azores High (Fig. 3). Oscillations between positive and negative phases are tied to shifts in storm tracks and associated patterns of precipitation and temperature.

For more detailed information we refer to Serreze and Barry (2014) and Turner and Marshall (2011).

## Ocean

### Geography of the Arctic Mediterranean

The Arctic Mediterranean consists of two major parts: the Arctic Ocean and the Nordic Seas. The Arctic Ocean is the northernmost part of the Arctic Mediterranean which is enclosed by North America, the Eurasian continent, Svalbard, and Greenland (Fig. 1). The Nordic Seas are enclosed by Svalbard, Norway, Iceland, Scotland and Greenland and include the Greenland Sea, Norwegian Sea, and Iceland Sea (also called the GIN Seas). The Arctic Ocean connects to the

Nordic Seas via the Fram Strait (between Greenland and Svalbard, ~2600 m deep) and the Barents Sea Opening (between Svalbard and Norway, ~200 m deep). Other gateways are the narrow channels through the Canadian Arctic Archipelago (Islands North West of Greenland, ~150–230 m deep) and the Bering Strait (~45 m deep and only 50 km wide), which is the only connection to the Pacific Ocean. Towards the Eurasian Continent the Arctic Ocean consists of wide, shallow shelves (<50–300 m deep), which make up almost half of the entire Arctic Ocean and comprise five marginal seas: Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea and Chuckchi Sea. At the coasts of North America and Greenland the shelves are much narrower. The deep basins in the center of the Arctic Ocean are divided into two major parts, the Amerasian Basin and the Eurasian Basin. They are separated by the Lomonosov Ridge, which is approximately 1600 m deep. The Eurasian Basin consists of the Nansen Basin and the Amundsen Basin, which are separated by the Gakkel Ridge. The Mendeleev Ridge and Alpha Ridge divide the Amerasian Basin into the Makarov Basin and the Canada Basin. With approximately 4500 m depth, the Amundsen Basin is the deepest, while the Canada Basin is by far the largest. The boundary of the Nordic Seas to the North Atlantic is Denmark Strait (~500–700 m deep) and the Iceland-Scotland-Ridge (~300–850 m deep). There are two fracture zones in the center of the Nordic Seas: the Greenland Fracture Zone and the Jan Mayen Fracture Zone. The shelves along the Greenland coast are wide and shallow with a steep shelf break.

## Arctic Ocean Circulation and Hydrography

Since the Arctic Ocean is a largely enclosed ocean, there are only two water masses that enter the basin from other oceans: Pacific Water (PW) and Atlantic Water (AW). The low-salinity PW is transported through the Bering Strait (Fig. 4) and is mainly advected at the surface into the Amerasian Basin and adjacent shelf regions. In addition to continental runoff and precipitation, the low salinity PW is an important Arctic fresh water source. Due to relatively small differences in temperature throughout the water column of the Arctic Ocean, the stratification is mainly determined by salinity changes (Fig. 5). Thus, the fresh (light) waters stay in the upper ocean and build the so called Polar Mixed Layer. Large parts of the Arctic Ocean are covered by sea ice which is built from these fresh surface waters at near-freezing temperatures. By sea ice formation and melt, freshwater is concentrated at the surface.

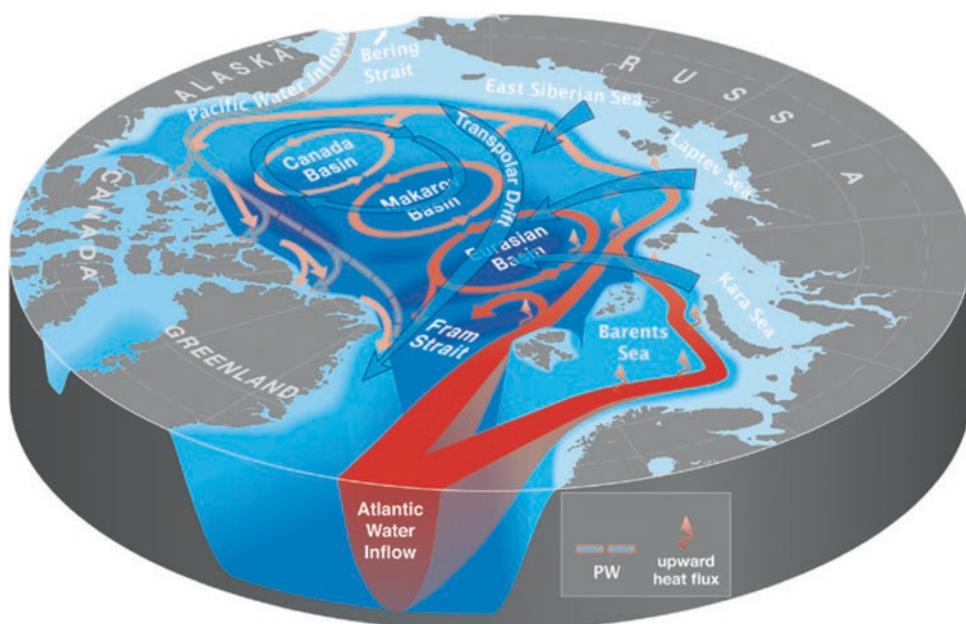
The AW is warmer but saltier than PW and Meteoric waters comprising continental run-off and net precipitation. Thereby, it is denser and can be found deeper in the water column. The significant difference in salinity creates a strong halocline between the Polar Mixed Layer and the AW layer establishing a strong permanent stratification in the deep basins (Fig. 5). The halocline, which is defined by high vertical salinity gradients ( $32.5 < S < 34.5$ ), is thickest in the Canada Basin (200–250 m) and thinnest in the Nansen Basin (100–150 m). The temperatures of the halocline remain close to the freezing point. Due to heat loss and mixing with shelf waters there are many modifications of AW at intermediate depths. Just below the halocline, temperatures are highest in the Nansen Basin and decrease towards the Canada Basin

(Fig. 5). The densest waters are formed on the shelves of the Barents Sea, where the AW subsequently releases heat to the atmosphere and is mixed with brine rejected from newly formed sea ice before it sinks down the shelf break into the Nansen Basin (Fig. 4). This Arctic bottom water is the densest water of the world ocean, but can only be found in the Arctic region (Tomczak and Godfrey 1994). Only a small part is able to flow over the sill of the Fram Strait into the Nordic Seas balancing the bottom/deep water formation on the Arctic shelves (e.g., Bönisch and Schlosser 1995).

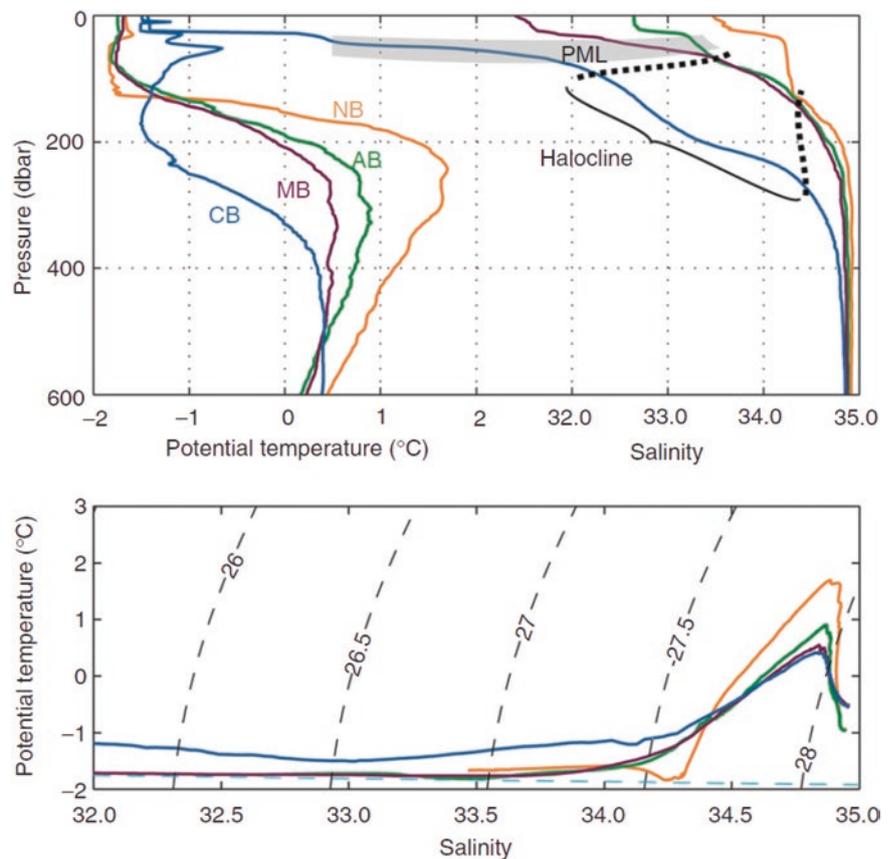
The surface circulation in the central Arctic Ocean mainly comprises two features: the Beaufort Gyre and the Transpolar Drift (Fig. 4). The Beaufort Gyre is an anticyclonic circulation in the Canada Basin that is forced by a high pressure system in the lower atmosphere, the so called Beaufort High. Fresh surface waters from the shelves and from the Pacific accumulate in the interior of the gyre and leave the Arctic through the Canadian Arctic Archipelago or the Fram Strait. The Transpolar Drift is a wind-driven current that directs sea ice and waters from the Siberian shelves and the Bering Strait to the Fram Strait, where they exit the Arctic Ocean into the Nordic Seas and subpolar North Atlantic.

The relatively warm and saline AW, which is the main water source of the entire Arctic Ocean, enters the Nordic Seas from the south. The Norwegian Atlantic Current carries the AW through the Nordic Seas at the surface and splits into two main branches. One branch enters the Arctic Ocean through the Barents Sea Opening, the other, which then is called West Spitsbergen Current, flows through the Fram Strait. Only a part of the West Spitsbergen Current propagates further north into the Arctic Ocean, the other part recirculates close to the Fram Strait. The AW dives underneath

**Fig. 4** Schematic of the Arctic Ocean circulation (reproduced from Carmack et al. 2015, American Meteorological Society, used with permission). Blue arrows indicate the surface circulation, pink-blue arrows show the main pathways of the Pacific Water at intermediate depths and red arrows show the Atlantic Water circulation. GIN Seas: Greenland-Iceland-Scotland Seas, usually called the “Nordic Seas”



**Fig. 5** Upper Arctic Ocean hydrography (reproduced from Rudels 2009, with permission from Elsevier). Potential temperature and salinity of the upper Nansen Basin (NB, orange), Amundsen Basin (AB, green), Makarov Basin (MB, purple), and Canada Basin (CB, blue). PML Polar Mixed Layer



the sea ice when reaching it North of Fram Strait and later meets the other cooled AW branch, which flows down the Barents Sea shelf slope into the Nansen Basin. Steered by the topography, the AW flows along the shelf breaks and spreads all over the Arctic Ocean forming counterclockwise circulations in all deep basins (Fig. 4).

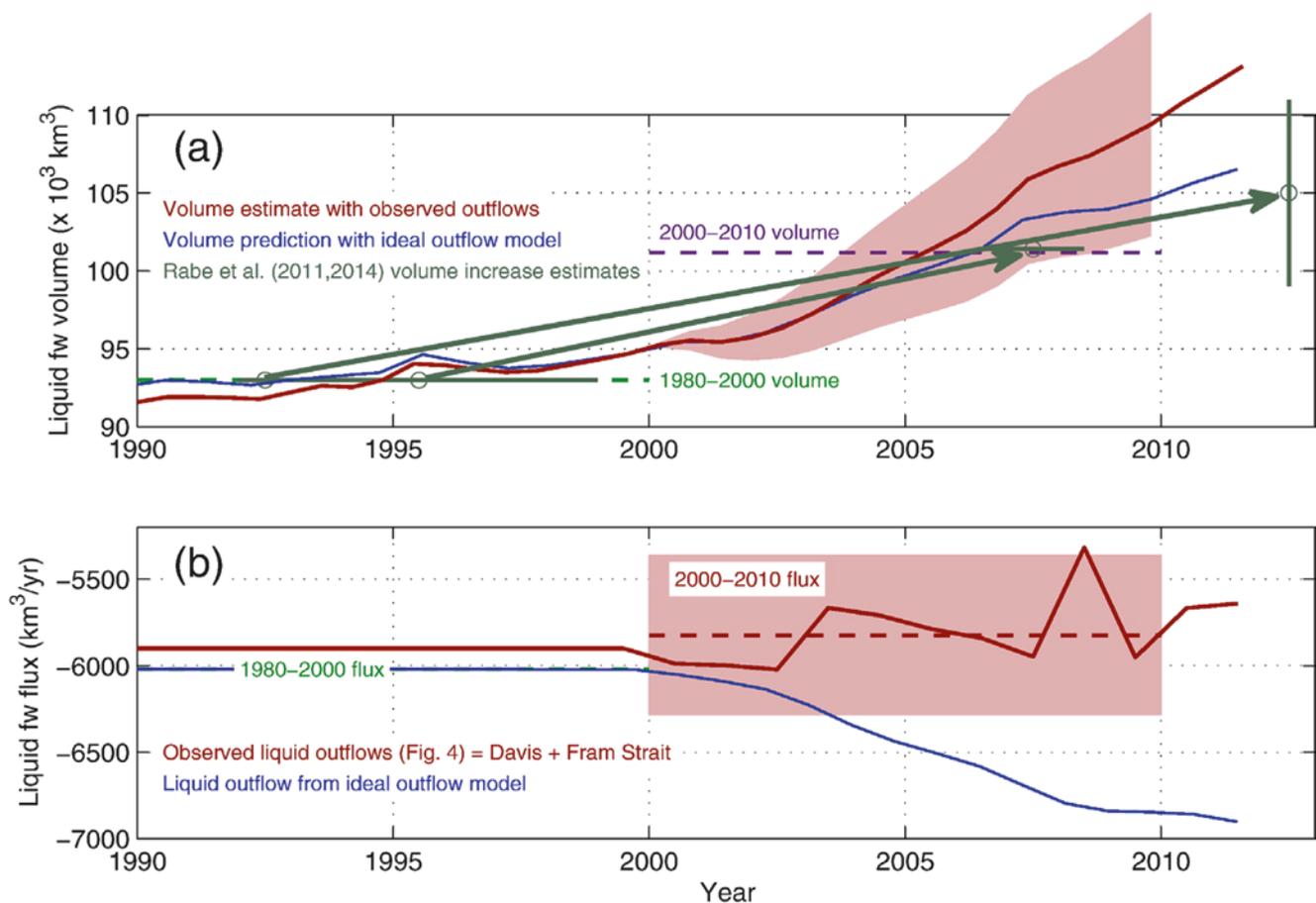
For more details on the Arctic Ocean hydrography and circulation see Rudels (2009).

### Fresh water

As salt is mainly conserved in the present-day oceans, the only way to change ocean salinity, which determines the stratification in the Arctic Ocean, is by removing or adding fresh water. Therefore, fresh water, both liquid and stored in sea ice, plays a key role in many physical processes in the Arctic. It is of high relevance for local and global climate and the thermohaline circulation, as the fresh surface layer in the Arctic Ocean limits the upward heat transfer from the AW layer to the atmosphere and sea ice and as a freshening of the upper Nordic Seas and subpolar North Atlantic may decrease deep convection due to higher stratification (e.g. Aagard and Carmack 1989; Haak et al. 2003; Häkkinen 1999; Yang et al. 2016).

By freshwater content or oceanic freshwater transport, we understand an equivalent amount of fresh water that is required to dilute water with a reference salinity to obtain the observed salinity. For the Arctic Ocean most studies use a reference salinity of 34.8 as it is approximately the average salinity of the Arctic Ocean (e.g., Aagard and Carmack 1989; Serreze et al. 2006; Holland et al. 2007; Haine et al. 2015). Others choose the reference salinity 35 as it is approximately the salinity of the AW inflow (e.g., Rabe et al. 2011, 2014). With a changing climate and related ocean changes, the estimates of the average Arctic Ocean salinity and AW inflow salinity might need to be adjusted. However, there is a starting discussion amongst scientists on the sensible choice of the reference salinity, challenging the common way to calculate freshwater content and transport (Tsubouchi et al. 2012; Bacon et al. 2015).

More than 100,000 km<sup>3</sup> of fresh water with respect to a reference salinity of 34.8 are stored in the Arctic Ocean (Haine et al. 2015) (Fig. 6). About 95,000 km<sup>3</sup> are stored as liquid freshwater and about 15,000 km<sup>3</sup> in sea ice (Haine et al. 2015). Liquid fresh water is added to the Arctic Ocean by precipitation, continental run-off, glacier/ice sheet/sea ice melt, and PW inflow and is removed by evaporation, sea ice formation and advection to the North Atlantic. All these sources and sinks are affected by the recent climate change



**Fig. 6** Arctic freshwater variability (adapted from Haine et al. 2015, with permission from Elsevier). (a) Arctic liquid freshwater volume (Arctic Ocean, Canadian Arctic Archipelago and Baffin Bay) and (b)

export flux (through Davis and Fram Strait) from observations (red) and an ideal outflow model (blue). The arrows indicate estimates from Rabe et al. (2011, 2014)

influencing the freshwater budget of the Arctic Ocean and adjacent seas.

### River Runoff and Atmospheric Fluxes

The major source of liquid fresh water in the Arctic Ocean is the continental runoff. The rivers discharge approximately  $3300 \text{ km}^3 \text{ year}^{-1}$  fresh water to the upper Arctic Ocean, which accounts for 11% of the total global river discharge (Fichot et al. 2013). Considering that the upper Arctic Ocean only makes up 0.1% of Earth's total ocean volume, this is a remarkable contribution. Net precipitation (precipitation minus evaporation) over the Arctic is estimated to  $2200 \text{ km}^3 \text{ year}^{-1}$  (Haine et al. 2015).

Syntheses of Arctic river discharge data revealed an increase of 7–10% in the last 30 to 60 years correlated with the NAO and global mean surface air temperature (Peterson et al. 2002; Overeem and Syvitski 2010). Niederdrenk et al. (2016) showed in a model study that a strong Icelandic low promoting warmer and wetter conditions over Eurasia leads to increased precipitation and thus enhanced river runoff to the Arctic Ocean. This mechanism is proposed to be respon-

sible for the most of the Arctic river runoff variability. Although Déry and Wood (2005) found a 10% decrease in annual river discharge from Canadian rivers into the Arctic Ocean and North Atlantic, the total river discharge into the Arctic Ocean increased by  $5.6 \text{ km}^3 \text{ year}^{-2}$  during the second half of the twentieth century (McClelland et al. 2006). There is evidence for an intensification of the global water cycle related to global warming (Huntington 2006) explaining the positive trends in precipitation and continental runoff.

### Arctic Glacier and Greenland Ice Sheet Melt

Due to the warming atmosphere and ocean, freshwater fluxes from both, the Greenland Ice Sheet and Arctic glaciers, increased significantly in the last few decades (Yang et al. 2016). The Greenland Ice Sheet mass-loss more than doubled from 2002 to 2009 (Velicogna 2009). Yang et al. (2016) estimated the acceleration of the trend to  $20 \text{ Gt year}^{-2}$ . Freshwater flux anomalies from surface meltwater and solid ice discharge from 1995 to 2010 sum up to about  $3000 \text{ km}^3$  (Bamber et al. 2012). Thereby, the highest freshwater flux with an increase of about 50% was released into the Irminger

Sea and the Labrador Sea (Bamber et al. 2012). This increased freshwater flux is mainly attributed to increased ice discharge from accelerated outlet glaciers in south Greenland (van den Broeke et al. 2009), which might be triggered by the warming of the waters at the glacier ice-ocean interface resulting in increased basal melting (e.g., Holland et al. 2008). Although the freshwater flux is highest in the South, there are also indications in the Northeast of Greenland that warm waters get close to the outlet glaciers and may initiate increasing glacier retreat and associated freshwater fluxes to the ocean (e.g., 79 North Glacier, Schaffer et al. 2017). Also the ice mass loss of glaciers in the Canadian Arctic Archipelago has sharply increased in recent years and almost tripled between 2004 and 2009 (Gardner et al. 2011; Lenaerts et al. 2013).

### Oceanic Transport of Sea Ice and Liquid Fresh water

About 2500 km<sup>3</sup> year<sup>-1</sup> of liquid fresh water (relative to a salinity of 34.8) enter the Arctic Ocean through the Bering Strait, while 3200 km<sup>3</sup> year<sup>-1</sup> and 2800 km<sup>3</sup> year<sup>-1</sup> exit the Arctic via the Canadian Arctic Archipelago and Fram Strait, respectively (Serreze et al. 2006; Haine et al. 2015). There are only small amounts of sea ice transported through the Bering Strait (140 km<sup>3</sup> year<sup>-1</sup>) and the Canadian Arctic Archipelago (160 km<sup>3</sup> year<sup>-1</sup>), whereas large amounts of sea ice are exported through Fram Strait (1900 km<sup>3</sup> year<sup>-1</sup> solid freshwater transport) (Serreze et al. 2006; Haine et al. 2015).

Observations presented by Woodgate et al. (2012) showed a slight increase in Bering Strait freshwater flux since 2001 due to increased volume fluxes, which can be explained by changes in the Pacific-Arctic pressure head and local winds. Although the liquid freshwater outflow through the Canadian Arctic Archipelago and the Fram Strait show large interannual variability, there is no significant long-term trend since the beginning of record (Haine et al. 2015). However, a new data record of Fram Strait sea ice area export, which was developed from satellite radar images and surface pressure observations across Fram Strait by Smedsrud et al. (2017), reveals a positive trend of about 5.9% per decade from 1979 to 2014. Ionita et al. (2016) related changes in the simulated Fram Strait sea ice export to atmospheric blocking events over Greenland, which block the winds over the Strait that mainly drive the sea ice transport. These Greenland blocking events are proposed to happen more frequently in recent years due to climate change (e.g., Hanna et al. 2016).

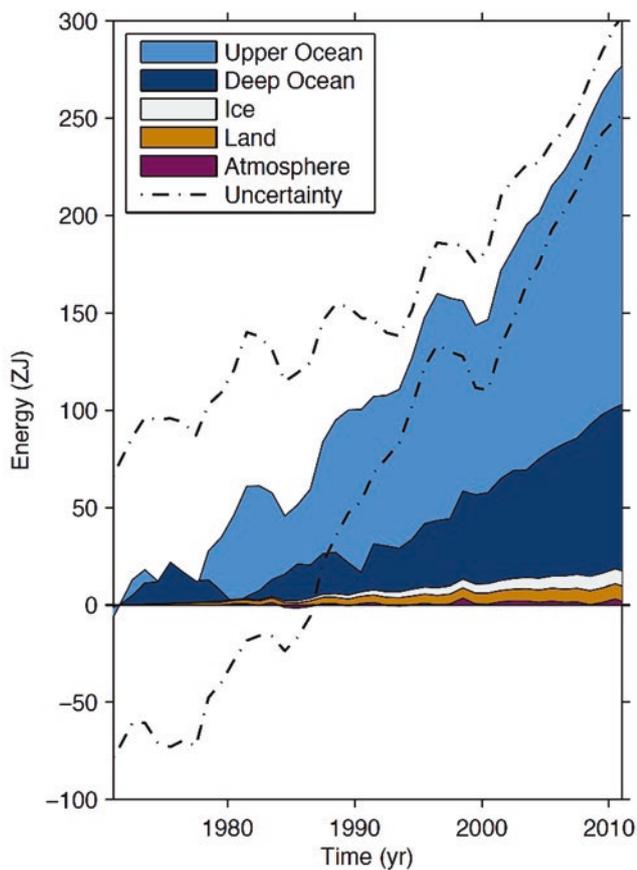
The freshwater export through the various channels of the Canadian Arctic Archipelago varies mainly due to volume flux anomalies governed by variations in the large-scale atmospheric circulation (Jahn et al. 2010a, b; Peterson et al. 2012) or driven by the sea surface height gradient across the strait (e.g., McGeehan and Maslowski 2012; Wekerle et al. 2013). Proshutinsky and Johnson (1997) identified two

wind-driven circulation regimes in the Arctic Ocean that either accumulate fresh water in the western Arctic Ocean (anticyclonic) or releases it to the North Atlantic (cyclonic). During anticyclonic circulation regimes, fresh water accumulates in the Beaufort Gyre north of the Canadian Arctic Archipelago due to a wind-driven spin-up as a response to anomalously high sea level pressure over the Arctic (low AO/NAO). During cyclonic regimes (high AO/NAO), the Beaufort Gyre slows down due to cyclonic winds and releases the accumulated fresh water (Proshutinsky et al. 2002; Giles et al. 2012). This fresh water mainly exits the Arctic via the Canadian Arctic Archipelago and partly via the Fram Strait. A tracer study by Jahn et al. (2010a) showed that the main sources of the freshwater export through the Canadian Arctic Archipelago is PW and North American runoff. Although the Arctic Ocean's circulation alternated between the cyclonic and anticyclonic pattern at 5–7 year-intervals in the past, it has remained in an anticyclonic mode for 17 years since 1997 (Proshutinsky et al. 2015). Proshutinsky et al. (2015) speculated that freshwater fluxes from the Greenland Ice Sheet to the North Atlantic interrupted an ocean-atmosphere feedback loop that previously lead to an automatic decadal alternation between cyclonic and anti-cyclonic circulation regimes (“auto-oscillatory system”).

The variability of liquid freshwater export through Fram Strait is driven by both, variations in the volume flux and changes in the salinity of the advected waters (e.g., Jahn et al. 2010b). The salinity of the waters exported through Fram Strait depends of the source water, which is mainly Eurasian runoff or PW (Jahn et al. 2010a). During years of an anticyclonic circulation anomaly (low AO) Eurasian runoff is released from the Eurasian Shelf (Jahn et al. 2010a) and directed towards Fram Strait by a strong Transpolar Drift (Morison et al. 2012). During a cyclonic circulation regime (high AO) the Eurasian runoff is kept by a cyclonic circulation in the Eurasian basin (Morison et al. 2012) and PW that is released from the Beaufort Gyre flows along the northern shelf of Greenland and penetrates into Fram Strait (Jahn et al. 2010a). In agreement with this, Karcher et al. (2012) found, from iodine-129 observations and modeling, changing contributions of AW and PW in the Fram Strait outflow to result from changes in the Arctic Ocean circulation as a response to the large-scale atmospheric circulation.

### Heat and Volume Fluxes in the Arctic Ocean

It is by now evident that changes in any of the components of the Earth system play a role in determining climate responses over high latitudes and consequent teleconnections. Therefore, it is expected that the interannual variability and recent decline trend of sea ice cover are not



**Fig. 7** Stored energy in the Earth climate system (modified from IPCC 2014). Discretisation of energy accumulation change in zeta joules (ZJ) in each component of the climate system relative to 1971 for periods as given. Ocean: upper ocean heat change (from surface to 700 m) in light blue; deep ocean (below 700 m, including below 2000 m estimates starting from 1992) in dark blue. Ice melt: glaciers and ice caps (light grey), Greenland and Antarctic ice sheet estimates starting from 1992, and Arctic sea ice estimate from 1979 to 2008. Land: continental warming (orange). Atmosphere: warming estimate starting from 1979 (purple). Uncertainty in the ocean estimate also dominates the total uncertainty (dot-dashed lines indicate the uncertainty from all five components at 90% confidence intervals)

only controlled by atmospheric heating and cooling, but also largely by heat flux from the underlying ocean. The oceans are the largest thermal reservoir of the Earth's climate system (Fig. 7). According to recent estimates, around 90% of the warming of the Earth's system over the last century has been stored in the oceans (e.g., Levitus et al. 2012; Riser et al. 2016). The biggest share of this amount is kept trapped in the upper ocean, hence being potentially available for atmosphere warming and sea ice melt. Thus, small changes in the pathways and amounts of heat carried and stored by the ocean currents could have a significant effect on present and future changes in Arctic coupled ocean-ice-atmosphere system. For an in-depth review and speculation on this topic see Carmack et al. (2015).

Shortwave radiation and sensible heat fluxes are the sources of net heat input in the upper ocean (Itoh et al. 2011). Most of the heat input to the upper ocean in summer is given off in autumn and winter as longwave radiation and turbulent sensible heat fluxes to the atmosphere cool the open water and the ice/snow surfaces (e.g., Serreze et al. 2009). Still, important observations indicated that a surplus of heat is preserved in the ocean during winter, potentially hindering the seasonal growth of sea ice (e.g., Timmermans 2015).

Another source of heat into the Arctic system is the relatively warm AW carried through the main gateways connecting the Arctic Ocean with the Atlantic Ocean: the Fram Strait and Barents Sea. There is also some exchange with the Pacific Ocean, but, according to up-to-date estimates reviewed in Beszczynska-Möller et al. (2012), the net volume and heat fluxes flowing from the Pacific Ocean into the Arctic through the Bering Strait are small, particularly when compared to those through Barents Sea (0.8 Sv and  $10^*$  to  $20^*$  TW, against 2.0 Sv and  $50^{**}$  to  $70^{***}$  TW, respectively<sup>1</sup>). In fact, the inflow of AW to the Barents Sea accounts for about half of the northward heat transport to the Arctic Ocean and the Barents Sea combined (Smedsrud et al. 2013). Notwithstanding, the heat carried by the AW into the Barents sea is lost to the atmosphere as latent, sensible, and long wave radiation (Smedsrud et al. 2010).

### Atlantic Water

Recent observations report a warming of the North Atlantic Ocean resulting in trackable changes in the Arctic Ocean. Since the 1990's, temperature and salinity have rapidly increased from the eastern North Atlantic subpolar gyre branch to the Fram Strait (Holliday et al. 2008). Furthermore, during the last decade, a net temperature increase of the incoming AW in the Fram Strait of 1 °C has been reported (Schauer et al. 2008; Polyakov et al. 2013). Over the period from 1997 to 2006, an increase of 1 °C was described for AW entering the Barents Sea (Beszczynska-Möller et al. 2012).

The warming of the AW is accompanied by estimates of volume transport increase into the Barents Sea, setting the so-called "Atlantification" of the basin (Årthun et al. 2012; Oziel et al. 2016; Smedsrud et al. 2013). Oziel et al. (2016) suggested that the increased inflow of AW into the Barents Sea would also cause the enhancement of the outflow of the dense modified AW mode (also called Barents Sea Water) into the intermediate layers of the Arctic. The reason to this is that more warm waters could initiate a sea ice melt-freeze

<sup>1</sup>Estimation of heat transport is dependent on a chosen reference temperature. For thorough understanding we refer to Schauer and Beszczynska-Möller (2009). Here:

\* referenced to freezing temperature

\*\* referenced to 0 °C

\*\*\* heat flux for closed volume budget

loop assuring a constant mixing and sinking of denser water. On the contrary, Rudels et al. (2013) state that under a regime of stronger inflow of the warm AW, no cooling to freezing temperature would occur. In this case, no brine-induced convection would occur, thus modulating the production of less dense Barents Sea Water. In either case, changes in the cooling and mixing of AW in the Barents Sea could impact the ventilation of the intermediate layer inside the Arctic, since 50–80% of the water occupying this layer is influenced by water mass originated on the Barents Sea basin (Schauer et al. 2002).

It has been hypothesized that the inflow of warm AW into the Arctic Ocean has a considerable influence on the decline and variability of sea ice extent and thickness (Årthun et al. 2012; Smedsrud et al. 2013; Carmack et al. 2015; Long and Perrie 2015). Roughly 20% of the total trend in sea ice volume loss since 2004 is related to observed episodes of AW warming (Ivanov et al. 2012).

In their study “*Is weaker sea ice changing the Atlantic Water circulation?*”, Itkin et al. (2014) try to understand and predict the effects of recent loss of sea ice on the overall intermediate circulation. It is presented that a thinner sea ice cover offers less hindrance to momentum transfer to the ocean, thus allowing a spin up of the Arctic circulation. The strengthening of the surface anticyclonic circulation results in the accumulation of water in the interior of the Beaufort Gyre, as a consequence of the enhanced Ekman convergence (Deser et al. 2014; Itkin et al. 2014; Long and Perrie 2015). Later, the stored water adds up to an increased outflow into the Atlantic Ocean, and is compensated by the increased inflow through the Barents Sea.

The Atlantification of the Arctic Ocean has been recently shown to extend even further into the Arctic Ocean as sea ice-ocean-atmosphere interactions change; at the same time the usual vertical stability of the Arctic Ocean is decreasing as the warm waters reach further upward and more heat is made available for inducing further melting of sea ice (Polyakov et al. 2017).

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## Outlook

Along with pronounced atmospheric warming, the summer Arctic sea ice has been projected to disappear by the second half of the twenty-first century (Overland and Wang 2013). How this will affect the atmosphere-sea ice-ocean interactions and influence the weather and variability in and beyond the Arctic boundaries has been more and more under discussion (Jung et al. 2014; Suo et al. 2017).

Model simulations predict that the hydrological cycle will further intensify and thereby increase the Arctic freshwater content, as well as the liquid freshwater export (e.g., Arzel et al. 2008; Holland et al. 2007). At the same time, the sea ice

volume will further shrink, which possibly results in a decreasing sea ice export as projected by Arzel et al. (2008).

Accelerating melt of the Greenland Ice Sheet and Arctic glaciers due to increasing air temperature provides even more freshwater to the North Atlantic with its deep water formation sites (Yang et al. 2016) and contributes to the projected increase in sea level rise (Rahmstorf 2007). Predictions on the impact of the increasing freshwater input to the North Atlantic are very diverse and range from almost no impact to a complete shutdown of the Atlantic Meridional Overturning Circulation (AMOC). Böning et al. (2016) argue from their model simulation that the accumulation of Greenland Ice Sheet melt water has not been large enough yet to have a significant impact on the AMOC. Though, they found that an accumulated freshwater runoff of about 20,000 km<sup>3</sup>, that could be reached by 2040 considering the current observed trend in runoff, would slowdown the AMOC by more than 5 Sv. Liu et al. (2017) even projected a complete collapse of the AMOC 300 years after an abrupt doubling of the atmospheric CO<sub>2</sub> concentration from the 1990 level. However, Behrens et al. (2013) showed how sensitive model simulations are to small variations in precipitation and the choice of sea surface salinity restoring to climatological values. From these small variations they found in their model simulation a variation of an accelerated AMOC of ~22 Sv to a nearly-collapsed state of ~6 Sv. Swingedouw et al. (2009) showed with their model experiment that the AMOC response to the freshwater input is not linear and depends on the mean state of the climate.

Changes in ocean characteristics and sea ice cover can have significant influence on the biogeochemical feedbacks and marine ecosystem (Bates and Mathis 2009; Johannessen and Miles 2011). The reduction of the sea ice cover allows for more light to reach and warm the ocean surface, promoting an increase in primary production (Slagstad et al. 2015). This, in turn, is intrinsically related to an expected increase CO<sub>2</sub> uptake by the ocean (Bates and Mathis 2009). Still, some controversy exists with indications that the ocean may soon enough saturate, and loses its CO<sub>2</sub> uptake capacity (Cai et al. 2010).

Indeed, fundamental questions on the pathways and time scales in which the ocean drives and responds to changes in the coupled system still remain unresolved, hence still demanding much effort in order to better understand the role of the northern seas in the context of a changing climate.

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## Appendix

This article is related to the YOUMARES 8 conference session no. 9: “The Physics of the Arctic and Subarctic Oceans in a Changing Climate”. The original Call for Abstracts and the abstracts of the presentations within this

session can be found in the appendix “Conference Sessions and Abstracts”, chapter “2 The Physics of the Arctic and Subarctic Oceans in a Changing Climate”, of this book.

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