Water mass transformations and air-sea exchange in the Barents Sea

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And yet even today we hear people ask in surprise: What is the use of these voyages of exploration? What good do they do us? Little brains, I always answer to myself, have only room for thoughts of bread and butter.

Roald Amundsen

Acknowledgments

Many people have contributed directly and/or indirectly to my work and deserves recognition. My supervisors Corinna Schrum, Lars Henrik Smedsrud and Richard Bellerby; thank you for your support, constructive discussions, and for guiding me through the PhD maze. Discussions and cooperation with other "Barents Sea people" in Bergen, especially Randi Ingvaldsen, Tor Eldevik and Abdir Omar, have also been much appreciated.

Modeling can be a strange and lonely world, and help from the members of the small and exclusive HAMSOM/ECOSMO modeling group has been crucial. I also wish to thank Keith Nicholls and my new colleagues at the British Antarctic Survey for their flexibility, and for taking me out for some fresh Southern Ocean air when I needed it.

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My partners in crime and fellow PhD students at the Geophysical Institute have made the last years very enjoyable. From our own 3 o'clock coffee breaks where it is possible to get the latest news about Giulio's politicians, Sturla's new skis, or Mathew's girl(s) - to beer brewing in the basement. GFI has always been a good place to work! Christophe and Torleif deserve an extra thank you for their efforts as coffee makers, which is, as we all know, a key ingredient in good research.

Family and friends: Thank you for reminding me to think about the important things in life, such as country music and struggling football teams.

Iselin, in short; Du e ei goe kåna.

Marius Årthun
Bergen, June 2011

Abstract

Water mass transformation processes in the Barents Sea and their interannual to decadal variability are studied using a regional coupled ice-ocean model and observational data. Long-term data allows for assessment of temporal and spatial variability in water mass properties and distribution, and the influence on air-sea exchange of heat and CO_2.

The Barents Sea ocean climate shows substantial interannual to decadal variability between 1948 and 2007. Variations in ocean heat transport associated with the Atlantic inflow modulate both the Barents Sea mean temperature (heat content) and the sea-ice extent. An increasing ocean heat transport is largely responsible for the sea-ice retreat in the Barents Sea during recent decades. The increased open ocean area causes a larger heat loss to the atmosphere, which provides sufficient cooling to transform a majority of the warm Atlantic inflow into cold, dense water before it is exported into the deep Arctic Ocean. The Barents Sea is thus an effective ocean cooler, and the dense outflow into the Arctic Ocean displays large variability, corresponding to variations in the Atlantic inflow.

Variability of water mass transformation processes related to changes in surface heat loss, sea-ice growth and corresponding salt fluxes, and the surface salinity before winter, also leads to substantial variations in the thermohaline properties of dense water. In the southern Barents Sea this is associated with the Atlantic inflow and thus the regional climate, whereas variable preconditioning of surface waters by ice melt and fresh coastal waters are more important in the northern Barents Sea.

Oceanic heat loss and convective processes also favor an uptake of atmospheric CO_2. Calculated air-sea CO_2 fluxes for the period 2000-2007 identifies the southern Barents Sea as a particularly efficient sink of atmospheric CO_2. Temporal and spatial variability of water mass properties and sea-ice extent are important to the CO_2 uptake, although wind speed is the major driver of variability.

Contents

1 Outline

The thesis consists of an introductory part and a collection of four papers. The introduction provides a general scientific background (Section 2), including the regional oceanographic setting and circulation in the Barents Sea. Objectives and methods are described in Section 3, and main results and perspectives are given in Section 4 and Section 5, respectively. The manuscripts included in this thesis are listed below.

PAPER I
Ocean surface heat flux variability in the Barents Sea[1]
Årthun, M. and Schrum, C. (2010)
Journal of Marine Systems, **83**, 88-98

PAPER II
Barents Sea ice cover reflects Atlantic inflow
Årthun, M., Eldevik, T., Smedsrud, L. H., Skagseth, Ø.
Manuscript

PAPER III
Dense water formation and circulation in the Barents Sea
Årthun, M., Ingvaldsen, R. B., Smedsrud, L. H., Schrum, C.
Accepted for publication in Deep-Sea Research I

PAPER IV
Air-sea CO_2 fluxes in the Barents Sea as determined from empirical relationships
Årthun, M., Bellerby, R. G. J., Omar, A. M., Schrum, C.
Submitted to Journal of Marine Systems

[1]Reproduced with permission of the publisher

2 Scientific background and Motivation

One of the driving mechanisms of the Atlantic meridional overturning circulation is deep water formation in high latitudes (Kuhlbrodt et al., 2007) where waters become denser and sink. The dense water masses formed in Arctic and Antarctic shelf seas contribute to the deepest branches of the overturning circulation (Meincke et al., 1997). In the Arctic, substantial densification of water masses takes place in the Barents Sea (e.g. Nansen, 1906; Midttun, 1985; Schauer et al., 2002a), one of the largest shelf seas and also the deepest (230 m). Its boundaries are defined by Norway and Russia in the south, Svalbard and Frans Josef Land in the north, Novaya Zemlya in the east, and the continental slope toward the Norwegian Sea in the west (Fig. 1). The Barents Sea is one of two pathways in which warm Atlantic Water (AW) reaches the Arctic Ocean (Fig. 1). Upon entering the Barents Sea the mean AW temperature is 5.3°C (Skagseth et al., 2008). However, the heat transported by the Barents Sea branch of the Norwegian Atlantic Current (NwAC) is effectively lost through intense ocean-atmosphere heat exchange (Häkkinen and Cavalieri, 1989), and more than 50% of the winter Arctic Ocean heat loss occurs here (Serreze et al., 2007). Thus, temperatures of the main outflow between Frans Josef Land and Novaya Zemlya (Fig. 1) are mostly below 0°C (Schauer et al., 2002a; Gammelsrød et al., 2009). The high salinities (>34.5; Gammelsrød et al., 2009) of the outflow make it sufficiently dense to be a source of intermediate and deep waters of the Arctic Ocean (e.g. Rudels et al., 1994; Schauer et al., 2002a). The properties of the outflow also strongly influence the characteristics of the Arctic Ocean Boundary Current (Schauer et al., 1997), and observed warming events in the Arctic Ocean can be attributed to variable AW modification during its translation through the Barents Sea (Gerdes et al., 2003; Dmitrenko et al., 2009). Variability in water mass transformation processes in the Barents Sea is thus of major importance to the Arctic region as a whole. This thesis will improve the understanding of how the warm Atlantic inflow is transformed into colder water masses before entering the Arctic Ocean.

2.1 Circulation and water masses in the Barents Sea

The circulation in the Nordic Seas (Fig. 1) is dominated by warm, saline AW in the southern and eastern part of the basin, and cold, fresh Polar Water (PW) in the northern and western part (e.g. Hansen and Østerhus, 2000; Blindheim and Østerhus, 2005). AW is carried northwards by the NwAC in two branches (Orvik and Niiler, 2002), whereas PW is mainly transported southwards by the East Greenland Current (Hansen and Østerhus,

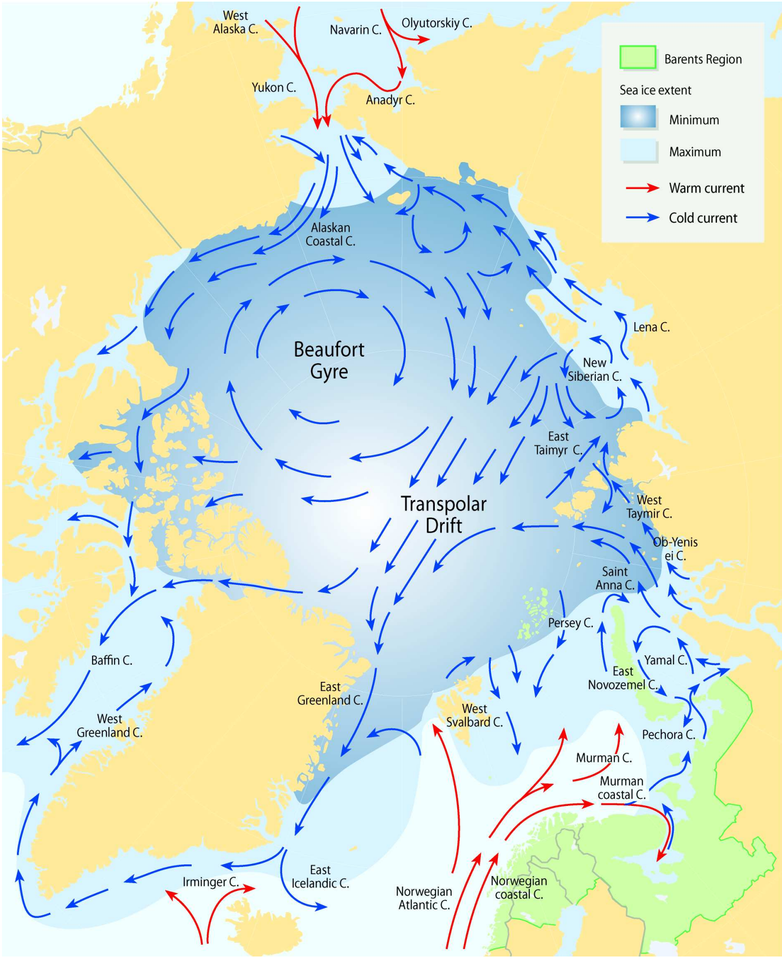


Figure 1: Ocean currents and sea-ice extent in the Arctic Ocean and adjacent shelf seas. *From Philippe Rekacwwicz, UNEP/GRID-Arendal Maps and Graphics Library, http://maps.grida.no/.*

2000). At ~70°N the NwAC bifurcates; One branch enters the Barents Sea as the North Cape Current (NCaC, Loeng et al., 1997) between Norway and Bjørnøya (Fig. 2), often called the Barents Sea Opening (BSO). The other branch continues north as the West Spitsbergen Current, but extensive recirculation in Fram Strait results in only a fraction of the AW entering the Arctic Ocean north of Svalbard (Walczowski et al., 2005).

Based on current meter observations between 1997 and 2007 the mean AW inflow through BSO is 2.0 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) (Smedsrud et al., 2010). This is augmented by 1.2 Sv in the Norwegian Coastal Current (NCC) which carries warm, low salinity water along the Norwegian coast and into the Barents Sea (Skagseth et al., 2011), and 1.2 Sv leaving the Barents Sea via the Bear Island Trench (Skagseth, 2008) and in the Bear Island Current (Blindheim, 1989), yielding a net eastward flow of 2.0 Sv. Higher transport during winter than summer is most common and is related to local atmospheric forcing (Ingvaldsen et al., 2004).

Upon entering the Barents Sea the NCaC splits into two main branches; one following the Norwegian/Russian coast parallel to the NCC, while the other flows north into the Hopen Deep (Fig. 2). The former branch is also known as the Murmansk Current. The northern core continues either north toward the Great Bank or flows north of the Central Bank and into the Eastern Basin (Ozhigin et al., 2000; Aksenov et al., 2010). Here it joins the northward flowing Western Novaya Zemlya Current (WNZC) and eventually exits the Barents Sea between Novaya Zemlya and Frans Josef Land (Maslowski et al., 2004; Gammelsrød et al., 2009; Aksenov et al., 2010). Some of the AW also recirculates within the Hopen Deep (Gawarkiewicz and Plueddemann, 1995; Skagseth, 2008). The fresher Norwegian/Murmansk Coastal Current flows eastward and either enters the Kara Sea south of Novaya Zemlya or continues to the north along the Eastern Basin. The low salinity of this water also reflects freshening due to river discharge in the southern part of the Barents Sea.

During its passage through the Barents Sea the AW loses heat to the atmosphere. Heat loss during winter can reach over 500 W m^{-2}, cooling the eastward flowing water by 4-5°C within a couple of months (Häkkinen and Cavalieri, 1989). Further modifications occur through mixing with lower salinity waters and seasonal ice formation and subsequent brine release (Schauer et al., 2002a).

The circulation in the northwestern Barents Sea is dominated by cold and fresh Arctic Water (ArW) transported southward by the East Spitsbergen Current and the Persey Current (Mosby, 1938; Pfirman et al., 1994). A branch of AW also enters the Barents Sea between Svalbard and Frans Josef Land. The separation between the Atlantic influenced southern Barents Sea and the Arctic waters in the north is denoted the Polar Front. The front is topographically trapped in the western Barents Sea by the barotropic circulation of AW (Harris et al., 1998), but the location is not stationary and varies in phase with the Barents Sea climate due to changes in the wind field (Ingvaldsen, 2005).

Cold and dense bottom water is also formed during winter in the Barents Sea by cooling and salt input from ice formation. This was postulated by Nansen (1906) based

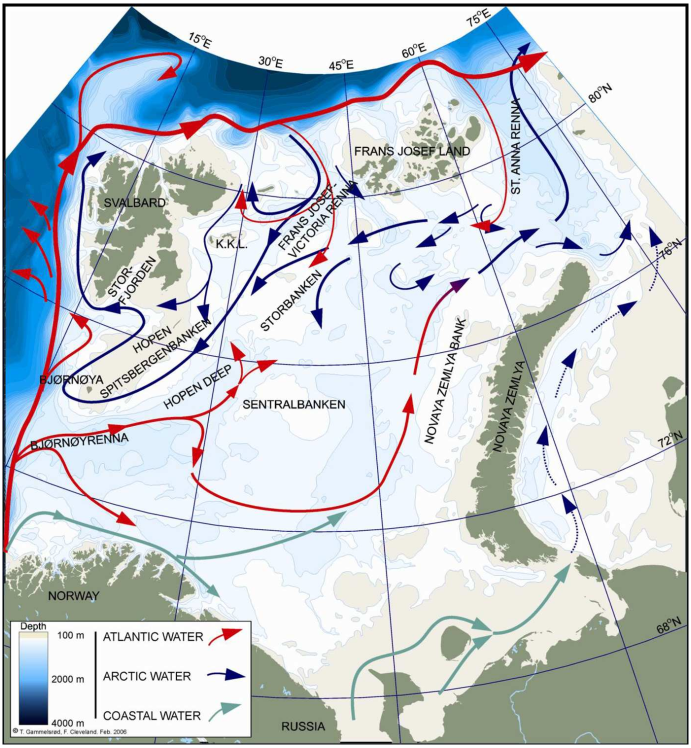


Figure 2: Bathymetry and general current system in the Barents Sea. Courtesy of Frank Cleveland and Tor Gammelsrød.

on observations from the north-eastern Barents Sea shelf, and later confirmed by Midttun (1985). Dense water has also been observed in the central- and western Barents Sea (Quadfasel et al., 1992; Steele et al., 1995; Maus, 2003), and in Storfjorden (e.g. Schauer, 1995; Skogseth et al., 2004). Dense water formation is faster in shallow areas where convection reaches the bottom. During favorable conditions (Ivanov and Shapiro, 2005) the dense water will descend down the slope and fill the deeper basins. When flowing off the banks substantial mixing with the surrounding water takes place and mixing will also occur en route from the bank to the outflow area (Schauer et al., 2002a; Fer and Ådlandsvik, 2008).

The dense water masses mainly exit the Barents Sea and flow into the Arctic Ocean through St. Anna Trough (Fig. 2). Dense water formed in the western Barents Sea mainly descends into the Norwegian Sea south of Svalbard (Quadfasel et al., 1988; Schauer, 1995; Fer and Ådlandsvik, 2008). The Barents Sea branch and Svalbard branch then meet and partly merge north of the Kara Sea and are modified as they continue further eastward (Schauer et al., 1997, 2002b; Rudels et al., 2004). However, the Barents Sea branch is still distinguishable in the Canada Basin (Woodgate et al., 2007). The deep water eventually exits the Arctic Ocean through the western Fram Strait (Aagaard et al., 1985; Meincke et al., 1997) and contributes to the deepest branches of the overflow across the Greenland-Scotland ridge (e.g. Mauritzen, 1996; Rudels et al., 1998; Hansen and Østerhus, 2000), and thus to variability of the Atlantic meridional overturning circulation.

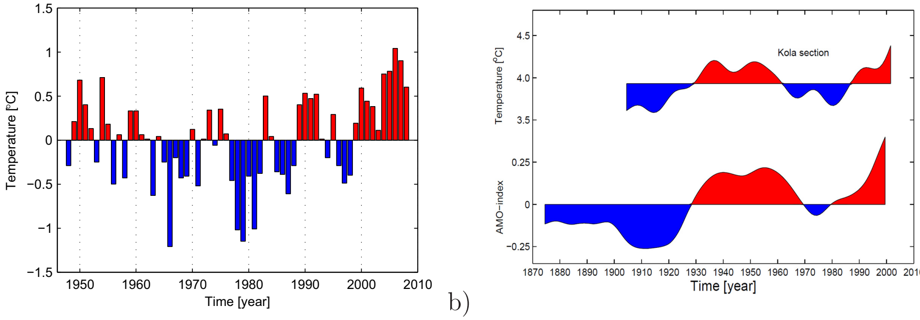
In order to understand the variability observed downstream it is necessary to establish the processes most important to dense water formation within the Barents Sea. This thesis presents multidecadal time series of observed and simulated dense water characteristics, and identifies the dominant drivers of variability.

2.2 Ice-Ocean variability

The Barents Sea climate fluctuates between a warm and cold state on interannual to decadal time scales (Fig. 3a). Variations are largely determined by the properties and strength of the AW inflow to the Barents Sea (Helland-Hansen and Nansen, 1909; Ådlandsvik and Loeng, 1991; Furevik, 2001; Ingvaldsen et al., 2003; Skagseth et al., 2008). The inflow is sensitive to large scale climate variations, evident from the importance of the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) to climate variability in the North Atlantic and Barents Sea (e.g. Dickson et al., 2000; Ingvaldsen et al., 2003; Sandø et al., 2010). Modulation of the AW inflow during a positive NAO phase is a result of anomalous southerly winds, increased winter storminess, and a narrowing of the NwAC towards the Norwegian coast (Ingvaldsen et al., 2003, and references therein). The influence of a negative NAO is weaker (Ingvaldsen et al., 2003; Dickson et al., 2000). The manifestation of larger-scale climate fluctuations is also expressed by the Atlantic Multidecadal Oscillation (mean sea surface temperature in the region 0-60°N and 7.5-75°W) and its correlation to sub-surface temperatures in the Barents Sea (Fig. 3b; Skagseth et al., 2008; Levitus et al., 2009).

Variations in atmospheric forcing and the ability to modulate advection of oceanic heat anomalies from the North Atlantic also influence the Barents Sea ice extent (Kauker et al., 2003; Sorteberg and Kvingedal, 2006; Francis and Hunter, 2007). Anomalous decrease in wintertime sea-ice cover in the Barents Sea may trigger a dynamic atmospheric response with consequences for climate in the northern continents (Honda et al., 2009; Petoukhov and Semenov, 2010). Furthermore, the atmospheric circulation tends to become more cyclonic when the sea-ice cover shrinks due to increased oceanic heat loss (Ikeda, 1990;

Ådlandsvik and Loeng, 1991). This forces an increased inflow to the Barents Sea and higher temperatures, which could maintain a given climatic state through internal feedbacks in which the atmospheric response to the anomalous heat flux reinforces the initial temperature anomaly related to the oceanic heat transport.



a) b)

Figure 3: a) Annual mean temperature anomalies from the Kola section (70.5-72.5°N, 33.5°E). Data are from PINRO, Russia. b) Kola section mean temperature and the Atlantic Multidecadal Oscillation (AMO) index. From Skagseth et al. (2008).

2.3 Air-sea CO_2 exchange

The ocean is important to the global carbon cycle, and acts to remove carbon from the atmosphere. Currently, the ocean absorbs ∼25% of the CO_2 emitted to the atmosphere by human activities (Le Quéré et al., 2010). Solubility for all gases increases with decreasing temperature, and heat fluxes from the ocean to the atmosphere thus drive an oceanic uptake of atmospheric CO_2. As the direct link between the atmosphere and sub-surface water masses, dense water formation and convection are also important to air-sea CO_2 uptake. Consequently, the North Atlantic and the adjacent marginal seas are considered to be significant sinks of atmospheric CO_2 (e.g. Olsen et al., 2003; Skjelvan et al., 2005; Borges et al., 2006), and shelf seas may contribute substantially to the global uptake of atmospheric CO_2 (Thomas et al., 2004).

Observations show that the surface waters across the Barents Sea are undersaturated with respect to atmospheric CO_2 (Kelley, 1970; Omar et al., 2003; Nakaoka et al., 2006; Omar et al., 2007), indicating a strong potential for significant uptake of CO_2 from the atmosphere. The transformation of AW into colder and denser water masses means that the carbon contained in these waters is sequestered for decades to hundreds of years when the waters exit into the neighboring deep basins of the Nordic Seas and Arctic Ocean

(Anderson et al., 1998). A recent carbon budget for the Barents Sea suggests that ∼70% of the carbon exported to the Arctic Ocean is in subsurface water masses (Kivimäe et al., 2010). Thus, understanding of water mass distribution and transformations also has implications for estimates of biogeochemical fluxes.

Estimates of regional oceanic CO_2 uptake are limited in time and space due to scarcity of observed carbon parameters. This thesis seeks to contribute in filling this gap by investigating the oceanic CO_2 uptake in the Barents Sea using a regional ice-ocean model together with a carbon system module with algorithms for the CO_2 system based on hydrography. This will not allow for integrated climate studies as there is no feedback to atmospheric CO_2, but dominant drivers of potential change in the Barents Sea carbon system can be identified.

3 This study

3.1 Objectives

This PhD-thesis is part of the project BIAC (Bipolar Atlantic Thermohaline Circulation), whose objective has been to study mechanisms, manifestation and impacts of intermediate and bottom water formation originating from the bipolar Atlantic Ocean shelves, with special emphasis on the Barents Sea. The aim of this thesis has thus been to investigate air-ice-sea interactions in the Barents Sea on interannual to decadal timescales, and thereby improve the understanding of the interaction between ocean circulation (heat distribution), ocean-atmosphere heat fluxes, changes in the ice cover, and their implications for dense water formation rates and biogeochemical fluxes.

More specifically, the main objectives are:

- Analysis of variability and trends in air-sea heat fluxes.
- Impact of Atlantic inflow properties on the Barents Sea ice extent.
- Identify the dominant processes controlling variability in dense water formation.
- Provide regional estimates of air-sea CO_2 fluxes and assess main drivers of variability.

3.2 Data and Methods

In a remote region such as the Barents Sea, the northern area especially, a numerical model is the most realistic method to address the questions posted in this thesis. Provided realistic forcing numerical models can be used to reproduce the history of ocean and sea-ice variables that are scarce in space and time, and several ice-ocean models have previously been successfully applied to the Barents Sea (e.g. Maslowski et al., 2004; Budgell, 2005; Sandø et al., 2010). The strength of a modeling based approach is that it allows for integration on a regular grid over a long period and hence accounts for variability on different time and spatial scales. Potential errors from undersampling are thus avoided.

All models are, however, exposed to limitations inherent in the applied forcing, and in trade-offs in terms of computational efficiency, spatial and temporal resolution, and choice of numerical schemes. Thus, model results always need to be critically evaluated and their realism determined. Due to the remoteness of the Barents Sea observations are limited, especially during winter time. However, when and where available, long-term observations, some previously unpublished, are used to supplement and evaluate model results.

3.2.1 Numerical model

In this thesis the coupled ice-ocean model HAMSOM (Hamburg Shelf Ocean Model), which has been developed at the Institute of Oceanography, University of Hamburg, Germany (e.g. Pohlmann, 1996; Schrum and Backhaus, 1999), is used. The model configuration for the Barents Sea (Fig. 4) has a horizontal resolution of 7 $\times$ 7 km and 16 vertical z-levels. The model has previously been set up for the Barents Sea and model sensitivity studies and assessment of the model's capability of investigating water mass transformation processes in the Barents Sea have been performed (Harms et al., 2005; Schrum et al., 2005). The manuscripts included in this thesis include further comparison between simulated parameters and observations from different sources.

In Paper I the original setup is used for a long term simulation (1958-1997) to study heat exchange and the thermodynamic state of the Barents Sea. For Papers II-IV an improved setup is applied. In Paper I boundary conditions for sea surface elevation and sea-ice properties are based on the global model C-HOPE (Marsland et al., 2003), while in Papers II-IV boundary values are taken from the Miami Isopycnic Coordinate Ocean Model (MICOM, Bleck, 1998; Sandø et al., 2010). The reason for this change is an underestimated Atlantic inflow in C-HOPE. In addition, the extended simulation period in Papers II-IV necessitated new forcing data.

A new advection scheme was also employed for Papers II-IV. In Paper I transport equations for temperature and salinity are discretized using an upstream scheme. This is conditionally stable and monotonic (preserves max/min properties). However, this

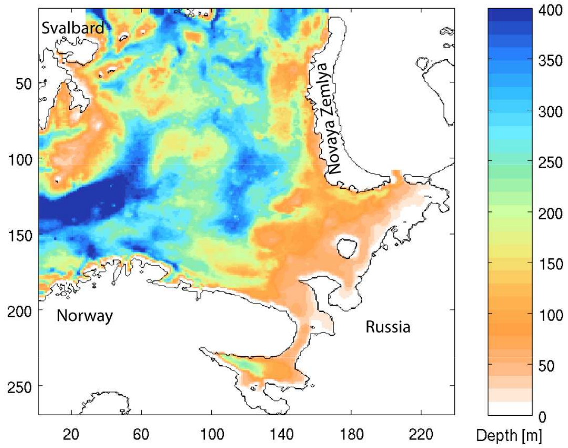


Figure 4: Model domain (7 × 7 km) and bathymetry. Axis labels show model gridpoints. Bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson, 2002).

method also introduces numerical diffusion, which will act to break down gradients or fronts. To overcome this problem a TVD scheme (total variance diminishing; Sweby, 1984) was implemented in the model. Properties of the TVD scheme guarantee that the total variation of the solution of an equation will not increase as the solution progresses in time, and it has very low numerical diffusion. Description and evaluation of the scheme are provided in Barthel et al. (2011, manuscript in preparation).

In Paper IV a carbon system routine was also added to the model. This exploits the relationships that exist between various CO_2 system variables and hydrographic variables (Millero et al., 1998; Olsen et al., 2003; Bellerby et al., 2005; Nondal et al., 2009). Knowledge of two of the four carbon system variables (dissolved inorganic carbon, total alkalinity, partial pressure of CO_2 (pCO_2), and pH) then allows for the calculation of the remaining CO_2 system variables through thermodynamic equations (Zeebe and Wolf-Gladrow, 2001). The net air-sea flux of CO_2 can then be calculated by prescribing the atmospheric CO_2 concentration (fluxes are proportional to the partial pressure gradient across the interface), and estimating the gas transfer velocity. The latter is a function of the turbulence in the atmosphere-ocean boundary layer, but is most often parameterized as a function of wind speed as this has the dominant effect (Wanninkhof et al., 2009). A more detailed description, including model equations and evaluation of empirical relationships, is given in Paper IV.

3.2.2 Observations

Observations used in this thesis are from various sources, and only a brief outline is given here. A more detailed description of the datasets is given in the manuscripts and references therein. Hydrographic data from regularly sampled sections were provided by the Institute of Marine Research, Norway (IMR) and PINRO, Russia. Previously unpublished bottom water temperature and salinity from 1970-2007 were also provided by IMR. In addition, hydrographic data were obtained from the International Council for the Exploration of the Sea (ICES) and from the Geophysical Institute, University of Bergen. Sea-ice data is available from the National Snow and Ice Data Center, USA. Arctic sea-ice concentrations on a 25 $\times$ 25 km grid have been generated from 1979 from brightness temperature data derived two different satellites (Cavalieri et al., 1999).

4 Summary of papers

4.1 Paper I: Ocean surface heat flux variability in the Barents Sea

Paper I investigates the variability and trends in the Barents Sea heat content, air-sea heat fluxes and sea-ice extent using a model run for the period 1958-1997. The heat input by ocean advection and shortwave radiation is lost through air-sea heat exchange mainly in the southern Barents Sea, and the northern Barents Sea thus receives little heat. The ocean heat transport displays large interannual to decadal variability which is reflected in the mean Barents Sea temperature (heat content) and oceanic heat loss. Largest heat flux variability is found in the marginal ice zone in the central Barents Sea due to fluctuations in sea-ice cover, and, hence, the area over which the cooling occurs. Periods of high heat transport are mainly related to increased volume transport and influenced by external forcing represented by the Arctic Oscillation. Due to increased heat transport, increased solar radiation, and less sea-ice, sea surface temperatures in the Barents Sea increased between the 1960s to the 1990s, in the north-east by as much as 1.0°C.

4.2 Paper II: Barents Sea ice cover reflects Atlantic inflow

Using available observations of AW inflow properties and model results Paper II presents an up-to-date analysis of sea-ice variability in the Barents Sea and the role of oceanic heat anomalies. In the eastern Barents Sea the ice edge has retreated about 240 km and the sea-ice area reduction between 1979 and 2010 is 45% based on the linear trend. The decrease in sea-ice area reflects observed variability in the Atlantic inflow, both interannually and for long-term trends.

Based on the heat budget from the regional ice-ocean model it is argued that ocean heat transport into the western Barents Sea sets the boundary of the ice-free Atlantic domain and, hence, the sea-ice extent. Recent sea-ice loss is thus largely caused by an increasing Atlantic inflow. The heat content and heat loss to the atmosphere also reflect the relative extent of the Atlantic domain in the Barents Sea, i.e., they are largely set by the ice free area. A simple prognostic model based on this scaling and on the Atlantic heat source explains 58% of the variance in the sea-ice area. This puts the findings from Paper I in the context of recent changes in the Barents Sea climate, and might have some implications for a potential recovery of the Barents Sea winter ice extent.

4.3 Paper III: Dense water formation and circulation in the Barents Sea

Paper III describes the processes and factors involved in determining the interannual variability of dense water (T<0°C and S>34.75) on shallow banks in the Barents Sea (Spitsbergen Bank, Central Bank, Great Bank, Novaya Zemlya Bank) as well as the general cooling of the AW throughflow, using both long-term hydrographic observations (1970-2007) and model data (1948-2007). These waters condition the intermediate waters of the Arctic Ocean (e.g. Rudels et al., 1994), and understanding the variability and processes involved are therefore of great interest.

Dense water formation is investigated with respect to the initial autumn surface salinity, atmospheric cooling, and sea-ice growth (salt flux). On the southern banks (Spitsbergen Bank and Central Bank) variability is associated with advection of Atlantic Water, which modifies the initial (November) surface salinity and oceanic heat loss. The high salinities on Central Bank imply that atmospheric cooling is enough to produce dense waters, but initial salinities have a strong influence on the variability through the effect on water column stability. Strong tidal currents also influence heat loss and salt input on Spitsbergen Bank. Initial salinity is also most important to anomalies in dense water formation on the northern banks (Great Bank and Novaya Zemlya Bank), and variability is associated with freshwater contributions from ice melt and fresh coastal waters, respectively.

The net dense water outflow to the Arctic Ocean is 1.6 Sv. The mean density of the outflowing dense water between Frans Josef Land and Novaya Zemlya is 1028.07 kg m^{-3}, which compares to observed densities below 1000 m in the Arctic Ocean. Compared to the total outflow 1/3 of the dense water originates from the banks, representing 9% of the Barents Sea area. Formation on the banks is more important when the Barents Sea is in a cold state (less AW inflow, more sea-ice). During warm periods with high throughflow more dense water is produced broadly over the shelf by general cooling of the northward flowing AW, making it the most important driver of dense water export to the Arctic Ocean. However, our results indicate that during extremely warm periods (1950s and late 2000s) the total export of dense water to the Arctic Ocean becomes strongly reduced.

4.4 Paper IV: Air-sea CO_2 fluxes in the Barents Sea as determined from empirical relationships

Paper IV investigates air-sea CO_2 fluxes in the Barents Sea and the dominant drivers of variability using a carbon system model based on hydrography coupled to the hydrodynamic model. The strong thermohaline control on the surface ocean CO_2 system allows for estimates of alkalinity and seawater pCO_2 based on simulated temperature and salinity. Compared to available measurements the use of temperature and salinity data to reconstruct spatial and temporal variability of carbon system variables in the Barents Sea is shown to be reasonable.

The Barents Sea is an annual sink for atmospheric CO_2 in all areas. The mean air-sea flux is 40 g C m^{-2}, corresponding to 0.061 Gt C yr^{-1}. This identifies the southern Barents Sea as an efficient, although globally very small, sink of atmospheric CO_2. Higher fluxes are found in waters of Atlantic origin in the south, whereas less gas exchange takes place in the seasonally ice covered northern Barents Sea. Due to the combined effect of a large concentration gradient across the air-sea interface (ΔpCO_2) and high wind speeds, the largest CO_2 uptake occurs in September and October. Interannualy, the fluxes vary by $\pm 12\%$ of the mean oceanic uptake, mostly driven by variations in wind speed.

The approach presented in Paper IV shows that with the assumptions that salinity is the foundation for the CO_2 system, and that on top of that there is a seasonal CO_2 cycle that can be constrained by sea surface temperatures, wind and redfieldian biological production, then one can get a reasonable representation of the annual cycle and its interannual variability. This is thus a useful approach for the purpose of understanding regional variability of contemporary air-sea fluxes in a region with few measurements.

5 Perspectives and Outlook

The importance of the inflowing AW is established throughout the thesis. Strong Atlantic inflow and higher temperatures (heat content) are compensated by an increase in the open ocean area (less sea-ice) and larger oceanic heat loss (Papers I-II, Fig. 5), establishing the Barents Sea as an adjustable and robust ocean cooler. Cooling of the AW throughflow is an important processes for the water mass transformation within the Barents Sea and thus to the properties of the water entering the Arctic Ocean. In Paper III it is shown that ~70% of the warm inflow is transformed into cold, dense water which is exported into the deep Arctic Ocean. However, during anomalously warm periods like the recent decade cooling of the AW throughflow has not been sufficient and the temperature of the outflowing waters has increased. This might have a profound impact on the heat transport to the Arctic Ocean, and temperature anomalies from the Barents Sea have previously been reported to be responsible for warming events in the Arctic Ocean (Gerdes et al., 2003). Future observations of the Atlantic inflow and dense outflow should therefore remain a high priority to follow the ongoing changes.

The increased ocean temperatures during the last decades have also lead to a reduced sea-ice cover in the Barents Sea (Papers I-II), i.e. an "Atlantification" of the region. The reduced ice cover in Barents Sea has been the largest decrease in the Arctic (Parkinson and Cavalieri, 2008). In Paper II it is discussed how much of this sea-ice retreat can be traced to the AW inflow using both observations and model results. The results from Paper II thus complement on the heat budget discussion presented in Paper I, and relates these findings to recent changes in the regional climate.

Temperature changes and sea-ice retreat also influence ecosystems and carbon fluxes (Bates and Mathis, 2009; Mueter et al., 2009). Sea-ice loss will expose additional surface waters to air-sea gas exchange. Higher ocean temperature has the opposite effect as solubility of gases decrease with increasing temperature. It is therefore to be expected that the long-term variability in the Barents Sea climate (Papers I-III) is reflected in the uptake of atmospheric CO_2. Changes in climate and circulation not only influence the hydrography and sea-ice. For instance; increased light exposure at previously ice-covered areas of the Barents Sea will increase primary production and lead to a further increase in net CO_2 uptake (Bates and Mathis, 2009). To capture the complex interactions between physics, biogeochemistry and ecology in the ocean, a fully coupled model (hydrodynamics, ecosystem dynamics and carbon chemistry) needs to be used. However, the approach presented in Paper IV provides a useful tool for assessing the sensitivity and dominant drivers of the carbon system, and results from Paper IV create a base for comparison

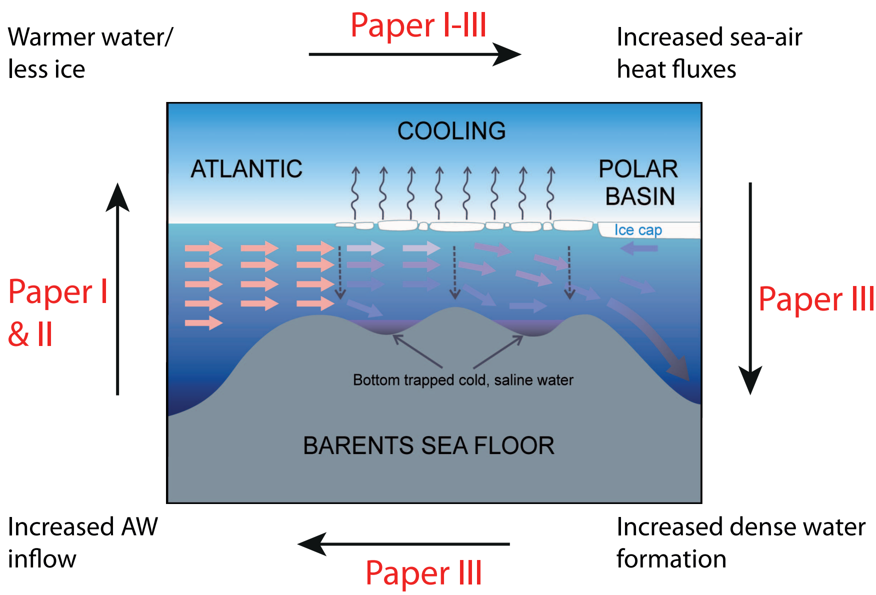


Figure 5: Schematic of water mass transformation processes in the Barents Sea (courtesy of Frank Cleveland and Tor Gammelsrød). Warm Atlantic Water enters the Barents Sea in the south-west (left) where it is subject to atmospheric cooling. Further cooling initiates ice growth and corresponding brine rejection. These processes produce dense water which eventually exits the northern Barents Sea (right) and descends into the Arctic Ocean. A potential positive feedback on the Atlantic inflow is also outlined with references to manuscripts included in this thesis. See text for discussion.

which can be used to evaluate developments in CO_2 uptake.

The influence of fluctuations in the Barents Sea climate between warm and cold states is well documented in the thesis. The persistence of a given state and the forcing of regional climate shifts are, however, not addressed in much detail. Large scale external forcing which affects the AW inflow to the Barents Sea has been identified by several authors (e.g. Dickson et al., 2000; Skagseth et al., 2008; Sandø et al., 2010). In addition, two potential internal feedbacks on the Atlantic inflow exist; a wind driven and a thermohaline feedback. The latter is related to the dense outflow which requires a compensatory inflow. Results from this thesis adds new insight about individual processes included in this feedback loop (Fig. 5). The wind driven feedback is based on the atmospheric response to an anomalous oceanic heat loss, leading to a low pressure anomaly over the Barents

Sea and therefore increased westerly winds and Atlantic inflow (Ådlandsvik and Loeng, 1991; Bengtsson et al., 2004). However, Petoukhov and Semenov (2010) found that the atmospheric circulation response to sea-ice decrease (more heat loss) in the Barents Sea is highly nonlinear and changes between an anomalous cyclonic and anticyclonic circulation depending on the sea-ice reduction. Changes in the Barents Sea ice extent can therefore play an important role in atmospheric circulation realignment over the European Arctic. To further address the importance of the Barents Sea on Arctic/sub-Arctic climate more detailed analysis should be performed using coupled climate models.

The Barents Sea is currently in a warm state associated with anomalously high temperatures in the ocean (Levitus et al., 2009) and in the air (Serreze et al., 2011). However, the Barents Sea climate is characterized by large multidecadal variability, and similar temperature anomalies were observed during the 1930-1950s (Bengtsson et al., 2004; Levitus et al., 2009) and proxy records indicate temperature variability of larger amplitude during the last 11,000 years (Risebrobakken et al., 2010). Understanding of local and remotely forced variability is required to predict future response and feedbacks of the surface ocean and ice formation to climate change. The observations and long-term model simulations presented in this thesis helps to improve the understanding of the natural scale of variability and dominant drivers of the Barents Sea climate system.

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