Barents Sea ice cover reflects Atlantic inflow

M. Årthun[a,b,*], T. Eldevik[a,b], L. H. Smedsrud[c,b], Ø. Skagseth[d,b]

[a]*Geophysical Institute, University of Bergen, Bergen, Norway*
[b]*Bjerknes Centre for Climate Research, Bergen, Norway*
[c]*Uni Research AS, Bergen, Norway*
[d]*Institute of Marine Research, Bergen, Norway*

Abstract

The recent Arctic winter sea-ice retreat is most pronounced in the Barents Sea. Using available observations of the Atlantic inflow to the Barents Sea and results from a regional ice-ocean model we assess the role of inflowing heat anomalies on sea-ice variability. Between 1979 and 2008 the reduction of annual sea-ice area was 15% decade^{-1}, and in the eastern Barents Sea the winter ice edge retreated about 240 km. The interannual variability and decrease in sea-ice area reflects observed variability in the Atlantic inflow. The heat budget of the model is used to elucidate further how Atlantic inflow anomalies influence the sea-ice area. 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. The regional heat content and heat loss to the atmosphere scales with the area of open ocean as a consequence. Recent sea-ice loss is thus largely caused by an increasing "Atlantification" of the Barents Sea. A simple prognostic model based on this scaling – and the Atlantic heat source – explains 58% of the variance in sea-ice area.

Key words: Barents Sea, Sea-ice, Atlantic water, Heat transport

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*Corresponding author. Now at: British Antarctic Survey, National Environment Research Council, Cambridge, UK.

Email addresses: marun@bas.ac.uk (M. Årthun), Tor.Eldevik@gfi.uib.no (T. Eldevik), Lars.Smedsrud@uni.no (L. H. Smedsrud), oystein.skagseth@imr.no (Ø. Skagseth)

1. Introduction

The Arctic sea-ice cover is a sensitive indicator of climate variability and change (Serreze et al., 2007). In the Barents Sea (Fig. 1), winter sea-ice extent has decreased since 1850 (Shapiro et al., 2003), and the retreat observed during the recent decades has been the largest decrease in the Arctic (Parkinson and Cavalieri, 2008). Variations in the Barents Sea ice extent have been attributed to a number of processes, including large-scale atmospheric circulation anomalies (Maslanik et al., 2007; Deser and Teng, 2008; Zhang et al., 2008), cyclone activity (Sorteberg and Kvingedal, 2006; Simmonds and Keay, 2009), local winds and ice import from the Arctic Ocean (Hilmer et al., 1998; Koenigk et al., 2009; Kwok, 2009), and oceanic heat anomalies either advected into the Barents Sea (Vinje, 2001; Kauker et al., 2003; Francis and Hunter, 2007) or generated locally (Schlichtholz, 2011).

The Barents Sea has a seasonal ice cover with minimum ice in September and maximum in March/April (Fig. 1; Kvingedal, 2005). Since the majority of the ice is formed locally during winter, Helland-Hansen and Nansen (1909) argued that the sea-ice extent in spring is highly dependent on the quantity of heat contained in the water masses of the Barents Sea during winter, and less dependent on variations in air temperature. Anomalous oceanic heat input can thus be reflected downstream by a retreating ice edge (Smedsrud et al., 2010). Interannual variability in Barents Sea ice cover, as well as the decreasing trend, can therefore be understood as a manifestation of the Arctic-ward extension of the Atlantic domain, i.e. the area where seasonal sea-ice formation does not occur (Fig. 1).

The inflow of Atlantic water between Norway and Bear Island (Barents Sea Opening, BSO; e.g., Skagseth et al., 2008) is the Barents Sea's main oceanic heat source. The inflow consists of several branches (Fig. 1; Loeng, 1991), but mainly follows a counter-clockwise circulation before exiting the Barents Sea between Novaya Zemlya and Frans Josef Land

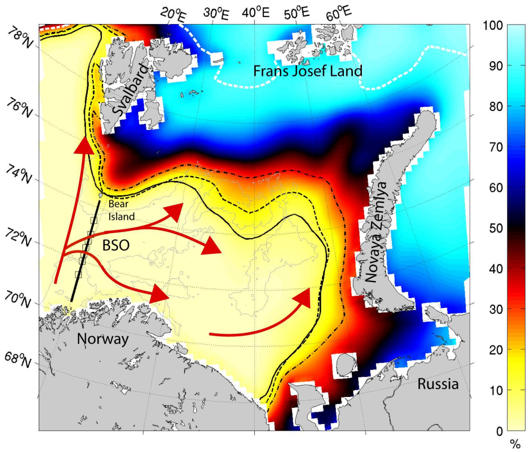
(Schauer et al., 2002). During its passage through the Barents Sea, the Atlantic water gives up its heat to the Arctic atmosphere (Häkkinen and Cavalieri, 1989; Årthun and Schrum, 2010), and the heat transport through the northern exit is consequently small (Gammelsrød et al., 2009). It is well established that thermohaline anomalies are advected from the North Atlantic Ocean towards the Arctic, the Barents Sea included (Furevik, 2001; Skagseth et al., 2008; Holliday et al., 2008). In support of ocean advection as a potential driver of sea-ice extent variability in the Barents Sea, Vinje (2001) found observed temperature anomalies in the central Norwegian Sea to be significantly correlated to the Barents Sea ice extent with a mean lag of two years.

In this paper we assess the influence of ”Atlantic heat” on the Barents Sea ice cover. Observational time series of ocean heat transport through BSO are for the first time considered in light of observed sea-ice retreat. The observation-based description is subsequently supported and generalized by analyzing model output from a regional ice-ocean model.

2. Data

Sea-ice area from 1979 to 2010 is estimated from passive microwave satellite data (NSIDC, Cavalieri et al., 1996; Meier et al., 2006) on a 25 $\times$ 25 km grid. The data are derived from two multichannel microwave sensors, SMMR and SSMI. Description of the sea-ice algorithms and the method used to derive a consistent dataset from the two sensors is described in Cavalieri et al. (1999) and references therein. Results considered herein is based on the area between 15-60°E and 70-81°N.

To describe the properties of the inflowing Atlantic Water (AW; T>3°C, S>35, Skagseth et al., 2008) north of Norway we use hydrographic data from a section between Norway and Bear Island (BSO; 20°E, 71.5–73.5°N; Fig. 1) which has been sampled since 1977 by the Institute of Marine Research, Norway (IMR). Current meter moorings have



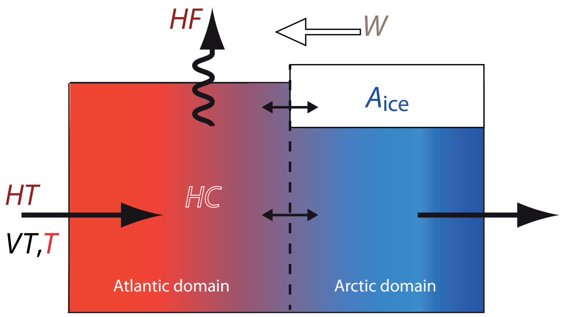


Figure 1: a) Satellite derived (NSIDC) winter (November-April) ice concentration between 1979-2010. Winter ice extent (15% concentration) during the 1980s (solid line), 1990s (dashed) and 2000s (dash-dotted) is also shown. White dashed line is the mean September ice extent during the 1990s. Red arrows indicate main paths of Atlantic water and black squares show mooring locations used to calculated volume and heat transport between Norway and Bear Island (Barents Sea Opening; BSO). b) Schematic of the Barents Sea and factors related to a variable sea-ice area (A_{ice}). HT, VT and T are the heat transport, volume transport, and temperature of Atlantic inflow, respectively. HC is integrated heat content, HF net heat flux to the atmosphere, and W is the meridional wind. The sea-ice extent defines the boundary between the Atlantic and Arctic domain.

also been operated by IMR since 1997 allowing for calculation of AW volume and heat transport through BSO.

To consider how winds influence the sea-ice extent, we use the meridional wind component from NCEP/NCAR reanalysis data (Kalnay et al., 1996) averaged over the Barents Sea. A comparison between annual NCEP wind speeds and observed wind speed at the meteorological station on the island Hopen (25.0°E, 76.5°N; eklima.no) shows similar variability (1979–2009; r=0.70).

We utilize a 1948–2007 simulation from the regional ice-ocean model Hamburg Shelf Ocean Model (HAMSOM, e.g. Schrum and Backhaus, 1999; Harms et al., 2005) to elucidate further the mechanisms influencing the Barents Sea ice cover . The setup for the Barents Sea has a horizontal resolution of 7 × 7 km. Atmospheric forcing is based on NCEP/NCAR reanalysis data, except for turbulent heat fluxes which are calculated by the model using standard bulk formulae. Detailed descriptions of the model setup and evaluation with respect to water mass transformation processes and climatic variability in the Barents Sea are given in Årthun and Schrum (2010) and Årthun et al. (2011). The model was found to produce realistic results for the Barents Sea in general, and essentially to reproduce the observed sea-ice cover from 1979 to 2007 in particular.

3. Results

The average observed AW heat transport (HT) through the BSO between 1997 and 2008 is 47 TW with respect to 0°C, ranging from 31 TW in 2001 to 61 TW in 2005. Positive (negative) annual heat anomalies coincide with reduced (increased) sea-ice area (A_{ice}; Fig. 2a). Changes in volume transport (VT) is the major contributor to observed heat transport variability (Fig. 2a). AW temperatures (T) have much less influence on interannual variations in heat transport during this period. Temperature is still linked to heat transport variability (r = 0.50), and is also strongly correlated to sea-ice area between

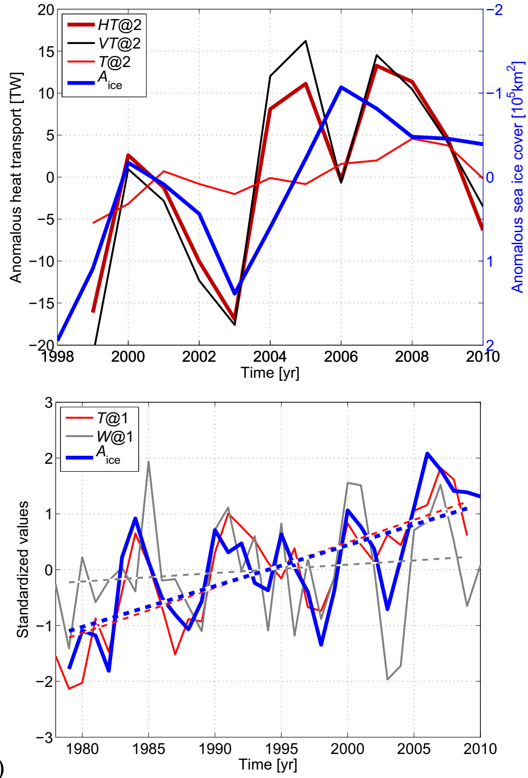
1979 and 2008 (Fig. 2b, Tab. 1; Schlichtholz, 2011). Note that correlations relating to observed HT and VT are considered indicative due to the shortness of the time series.

Linear trends (1997–2008) in observed inflow properties and sea-ice area are also comparable. The trend in sea-ice area corresponds to a reduction of $1.8{\cdot}10^5$ km^2 decade^{-1} (55% of the $3.8{\cdot}10^5$ km^2 1997 sea-ice area). During the same period the heat transport through BSO increased by 12 TW decade^{-1}, caused by trends in volume transport ($\Delta VT = 0.7$ Sv decade^{-1}) and temperature ($\Delta T = 0.7$°C decade^{-1}). The longer term (1979-2008) trend in sea-ice area is $-0.6{\cdot}10^5$ km^2 decade^{-1} (-15% decade^{-1}), and the observed temperature trend is 0.4°C decade^{-1} (Fig. 2b).

Apart from transporting anomalous atmospheric heat to the Barents Sea, winds can influence the ice extent mainly by three processes: 1) stronger northerly winds increase sea-ice transport into the Barents Sea from the Arctic Ocean (Kwok, 2009); 2) stronger winds in general increase turbulent heat fluxes at the surface; 3) stronger winds from the south-west increase the Atlantic inflow through the BSO (Ingvaldsen et al., 2004).

Most notably, there is only a relatively weak trend in the meridional wind speed (W) in the Barents Sea (Fig. 2b). The interannual correlation between wind and ice is still high (Tab. 1). E.g., an event of high annual inflow of sea-ice between Svalbard and Frans Josef Land occurred in 2002-2003 ($1.4{\cdot}10^5$ km^2) associated with a deep atmospheric low over the eastern Barents Sea (Kwok, 2009), and thus anomalous strong northerly winds (Fig. 2b). This significantly increased the relative contribution of ice export from the Arctic, from 12% based on the 1979–2007 average ($0.4{\cdot}10^5$ km^2) to 37%.

The distinct trend in BSO heat transport (Fig. 2a) and temperature (Fig. 2b) and the more modest trend for the local Barents Sea winds, suggests that ocean heat transport is the major player of the two in driving the observed sea-ice reduction. The influence of anomalous Atlantic heat on the Barents Sea ocean climate and sea-ice area can be further evaluated using the regional ocean model. Consistent lead/lag relationships between ob-



a)

b)

Figure 2: a) Observed annual time series of anomalous BSO heat transport (HT; dark red) leading the response in sea-ice cover (A_{ice}, inverted; blue) by two years. The black and red lines are the contributions to HT from anomalous BSO volume transport (VT) and temperature (T), respectively. The scaling of A_{ice} associates a heat loss of 100 W m^{-2} with an anomalously ice-free sea-surface. b) Standardized observed BSO temperature, southerly winds (W; gray), and sea-ice area (inverted). Temperature and wind lead by 1 year.

servations and model results (Tab. 1) provide confidence in that the model can be used to explain to what extent anomalous inflow properties are manifested in the interior Barents

Sea downstream.

4. Discussion

The influence of anomalous inflow properties on the Barents Sea ocean climate and sea-ice area is evaluated by the simulated heat budget. The Atlantic heat to the Barents Sea is essentially provided through the BSO. Heat transport through the other gateways is more than an order of magnitude less, and BSO heat transport carries 80% of the variance in the advective heat convergence in the Barents Sea. Positive BSO heat transport anomalies are associated with an increased Barents Sea mean temperature (heat content) and a reduced ice cover (Fig. 3). Higher ocean heat transport into the Barents Sea also leads to a larger heat loss to the atmosphere (HF_{out}: sum of turbulent heat fluxes and longwave radiation), but primarily not through stronger heat loss per area of open water. What changes is the area over which this cooling is applied, there is less ice, and thus more open water where cooling occur; illustrated in Fig. 3 by scaling the anomalous sea-ice area by the representative net heat loss q_0; cf. Appendix). Both heat content and heat loss to the

Table 1: Maximum lagged correlations between annual mean sea-ice cover (15–60°E, 70–81°N), and observed and modeled potential drivers of variability. A positive lag (@years) means that sea-ice lags. Correlations were done after removing linear trends. Observed correlations are based on available data (see Fig. 2), whereas the simulated correlations are for the years 1948 to 2007. Correlations are significant at the 95% confidence level (p = 0.05), except for (*) where p = 0.11. Autocorrelation has been taken into account by adjusting the effective number of independent observations (Chelton, 1983).

	HT	VT	T	W	HC	HF_{out}
Observations	-0.57@2*	-0.49@2*	-0.73@1	-0.60@1	-	-
Model	-0.56@1	-0.52@1	-0.70@1	-0.52@1	-0.85@0	-0.54@0

atmosphere consistently reflect the area of open ocean at no lag (Tab. 1). The co-variability between heat loss and sea-ice area is weaker in the beginning of the simulation period, possibly related to stronger atmospheric influence and prevailing northerly winds (Vinje, 2001).

The linear trend in modeled sea-ice area between 1979 and 2007 ($1.5 \cdot 10^5$ km^2 lost) corresponds to an 11% increase in open ocean area (relative to the total Barents Sea area of $14 \cdot 10^5$ km^2). The concurrent increase in heat content is 0.9°C in terms of mean temperature, and associated with a heat transport increase of 20 TW (Fig. 3). This is consistent with Smedsrud et al. (2010) who, using a column model, estimated that an increased oceanic heat transport of 13 TW and 0.8°C warming compared to a 10% increase in the open ocean area. The modeled increase in heat transport is partitioned into a 2.0°C warming of the inflowing water and a 0.4 Sv increase in volume transport, corresponding to 53% and 42% of the heat transport increase, respectively (the residual stems from eddy heat transport; $VT' \cdot T'$). Interannually, temperature and volume transport explains 36% and 56% of the total variance in heat transport.

The model results differ from the observed heat transport variability (Fig. 2a) which is essentially carried by the volume transport. However, the correlation between modeled BSO heat transport and temperature between 1997 and 2007 is also low and insignificant compared to that for the full simulation period. The difference can also partly be due to sampling. In the model the interannual variability of the net ocean heat transport to the Barents Sea can be calculated in a consistent way. This is not entirely the case for the observations as the moorings do not cover BSO completely.

The majority of the sea-ice loss has occurred east in the Barents Sea (Fig. 1). At 40°E the ice edge has retreated about 240 km (Fig. 1). In this area a warmer ocean column takes longer to cool to the freezing point during autumn, and the area where winter sea-ice cover does not develop has thus increased. The western Barents Sea, on the other hand, is to a

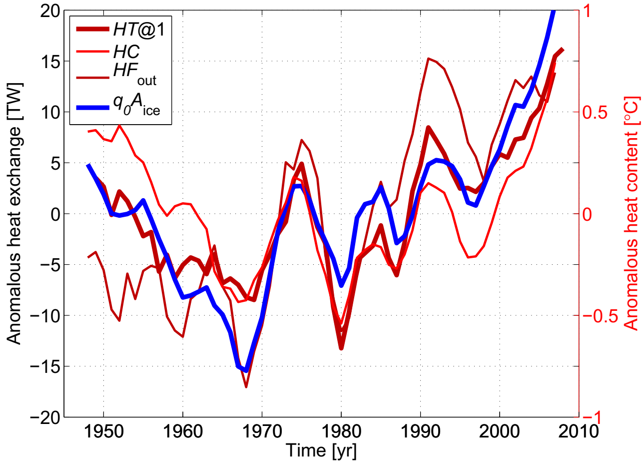


Figure 3: The modeled lagged response of Barents Sea ice cover (A_{ice}; inverted), HC (quantified as a mean temperature), and oceanic heat loss (HF_{out}) to BSO HT. Time series are 5-year running averages, and q_0 is a constant scaling factor (cf. Appendix). Note that HF_{out} does not include solar radiation.

larger extent influenced by southward flowing Arctic waters (Pfirman et al., 1994). This leads to higher sea-ice concentrations due to ice transport, but also due to fresher water residing beneath the sea-ice, protecting it from the warmer and saltier inflowing AW. In this marginal ice zone AW is cooled and freshened by further heat loss to the atmosphere and also by melting sea-ice (Steele et al., 1995). Ice melt is due to heat loss at the ice-ocean interface and by heat added to the ocean and the ice by radiation in summer. Following Rudels et al. (1999), the fraction of heat loss that goes into ice melt is proportional to the temperature of the water. A direct effect of a warmer inflow is thus to increase sea-ice melt and thereby the area of open water. This adds to the temperature contribution via heat transport, consistent with the relatively high correlation between T and A_{ice} (Tab. 1; see also Schlichtholz, 2011).

Similar warming trends as observed in BSO (Fig. 2b) have been observed both downstream in the West Spitsbergen Current (Walczowski and Piechura, 2006) and upstream in the Norwegian Atlantic Current (Orvik and Skagseth, 2005; Skagseth et al., 2008), consistent with an advective signal (Holliday et al., 2008). Oceanic heat anomalies in the Barents Sea can also be generated locally by air-sea interaction (Schlichtholz and Houssais, 2011). However, we find that the ocean heat transport through BSO consistently leads the air-sea fluxes (Fig. 3), indicating advection as a major factor in driving recent sea-ice reduction.

The causal role of Atlantic heat in setting the Barents Sea ice cover – including the consequent scaling of anomalous heat content and atmospheric heat flux with the variable ice area – can be put to test by applying the inferred scaling to the Barents Sea heat budget. The budget can be solved analytically as shown in the Appendix, and the result is an explicit expression for the anomalous sea-ice area (Eq. 4). The area at any given time is set by the previous heat input through BSO and the initial sea-ice area. The prognosis that results from using HAMSOM data as input is compared in Fig. 4 with the modeled sea-ice area (which is essentially the observed). The estimate explains 58% of the variance in sea-ice area, and 65% when including the trend. For the (model) parameters of the Barents Sea, the memory of the heat budget is about three years (cf. Appendix). Sea-ice anomalies in the Barents Sea can thus potentially be predicted from recent Atlantic heat input in agreement with the lagged response suggested by Table 1. Encouragingly, the physically based relation (Eq. 4) explains more of the sea-ice variance than any single correlation, including BSO temperature that was recently suggested as a predictor by Schlichtholz (2011).

The agreement is admittedly less striking (and less significant) for the corresponding comparison for the short observational record (12% of the variance is explained, 57% including the trend; not shown). It should, however, be noted that variance explained in the model data is reduced to 26% (67% with trend) when considering the period 1997–2007 only.

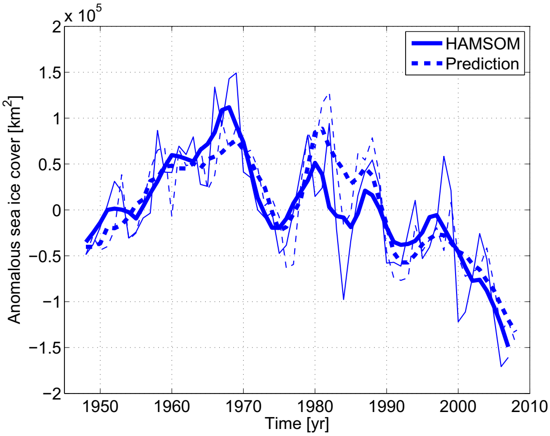


Figure 4: Simulated (HAMSOM) and predicted (Eq. 4) sea-ice area in the Barents Sea. Thin lines are annual values and thick lines are 5-year running averages.

5. Conclusions

The Barents Sea is a dominant area of Arctic sea-ice loss (Comiso, 2011). Sea-ice responds to anomalous heating both from below and above, and is therefore a sensitive indicator of ongoing climate change. The winter sea-ice cover in the eastern Barents Sea has retreated about 240 km during the last decades (Fig. 1). This decrease of sea-ice reflects variations in Atlantic inflow properties through the Barents Sea Opening (Fig. 2, Tab. 1), both interannually and for trends in the short observational record and the extended model period (Fig. 3).

Complementing the available observations, we have produced a consistent heat budget for the Barents Sea using a regional ice-ocean model. Keeping in mind that the retreating Barents Sea ice cover is more about the Arctic-ward expansion of the ice-free region (no wintertime freezing) than the melting of multi-year ice, our study supports the following simple relation between oceanic heat contributed by the Atlantic inflow and the sea-ice cover. The variable heat transport - ”the faucet” - maintains the Atlantic domain of the Barents Sea - ”the warm pool”. This is reflected in the extent of the ice-free region the following year, as corroborated by our simple prognostic relation between sea-ice area and Atlantic heat input.

The Barents Sea has been in a warm state during the last decades associated with high Atlantic inflow (Skagseth et al., 2008; Levitus et al., 2009). Inflow temperatures have, however, decreased since 2006 (Fig. 2b), 2009 and 2010 included (Anon, 2010). Consistently, the sea-ice area has slightly increased during the same period. This suggests that some recovery of the Barents Sea winter sea-ice area may occur in the short term, but if the general positive trend in Atlantic heat input remains, winter cooling will likely be insufficient to produce ice over an increasingly large area, leading to a further ”Atlantification” of the Barents Sea.

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Appendix

The integrated heat budget of the Barents Sea is

$$\frac{dHC}{dt} = HT - HF, \tag{1}$$

where the quantities in the present context should be understood as anomalies. We have suggested that both the anomalous heat content and heat loss to the atmosphere (relating to anomalous ocean heat transport through BSO) scales with the variable sea-ice area. We thus assume that

$$HC = -hc_0 A_{\mathrm{ice}}, \quad HF = -q_0 A_{\mathrm{ice}}, \tag{2}$$

where hc_0 and q_0 are constant scaling factors representing, respectively, the heat content and loss per area of the region of anomalous sea-ice cover. The heat budget then becomes a simple prognostic relation for the anomalous sea ice area,

$$\frac{dA_{\mathrm{ice}}}{dt} = -\frac{1}{\tau} A_{\mathrm{ice}} - \frac{1}{q_0 \tau} HT, \tag{3}$$

where $\tau = hc_0/q_0$ is the characteristic time scale for heat balance. Heat loss to the atmosphere acts as a relaxation toward no anomalous sea-ice cover, and ocean heat transport is the source that drives change.

The analytical solution of (3) is

$$A_{\mathrm{ice}}(t) = \left(A_0 - \frac{1}{q_0 \tau} \int_0^t HT(t) e^{\frac{t}{\tau}} dt \right) e^{-\frac{t}{\tau}}, \tag{4}$$

where A_0 is the initial sea-ice anomaly, and $t = 0$ could be, e.g., the year 1979. An objective quantification of the scaling factors is hc_0=std(HC)/std(A_{ice}), and q_0=std(HF)/std(A_{ice}), where std(X) is the standard deviation of the annual time series X. For HAMSOM time series, $hc_0 = 7.06 \cdot 10^9$ J, $q_0 = 138\ \mathrm{W\,m^{-2}}$, and consequently $\tau = 592$ days. The latter gives the e-folding of the exponential functions in (Eq. 4); the memory of the Barents Sea heat budget is thus about three years.

References

Anon, 2010. Survey report from the joint Norwegian/Russian ecosystem survey in the Barents Sea August-September 2010. IMR/PINRO Joint Report Series 4, 108 pp., ISSN 1502-8828.

Årthun, M., Ingvaldsen, R. B., Smedsrud, L. H., Schrum, C., 2011. Dense water formation and circulation in the Barents Sea, submitted to Deep-Sea Res. I.

Årthun, M., Schrum, C., 2010. Ocean surface heat flux variability in the Barents Sea. J. Mar. Syst. 83, 88–98.

Cavalieri, D., Parkinson, C., Gloersen, P., Zwally, H. J., 1996. Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I passive microwave data. Digital Media, updated 2008, National Snow and Ice Data Center, Boulder, Colorado.

Cavalieri, D. J., Parkinson, C. L., Gloersen, P., Comiso, J. C., Zwally, H. J., 1999. Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. J. Geophys. Res. 104 (C7), 15803–15814.

Chelton, D. B., 1983. Effects of sampling errors in statistical estimation. Deep-Sea Res. A 30 (10), 1083–1103.

Comiso, J. C., 2011. Large decadal decline of the Arctic multiyear ice cover, J. Clim, in press.

Deser, C., Teng, H., 2008. Evolution of Arctic sea ice concentration trends and the role of atmospheric circulation forcing, 1979-2007. Geophys. Res. Lett. 35 (2).

Francis, J. A., Hunter, E., 2007. Drivers of declining sea ice in the Arctic winter: A tale of two seas. Geophys. Res. Lett. 34 (17).

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

Gammelsrød, T., Leikvin, Ø., Lien, V., Budgell, W. P., Loeng, H., Maslowski, W., 2009.

Mass and heat transports in the NE Barents Sea: Observations and models. J. Mar. Syst. 75, 56–69.

Häkkinen, S., Cavalieri, D. J., 1989. A study of oceanic surface heat fluxes in the Greenland, Norwegian, and Barents Sea. J. Geophys. Res. 94, 6145–6157.

Harms, I. H., Schrum, C., Hatten, K., 2005. Numerical sensitivity studies on the variability of climate-relevant processes in the Barents Sea. J. Geophys. Res. 110, C06002.

Helland-Hansen, B., Nansen, F., 1909. The Norwegian Sea. Fiskdir. Skr. Ser. Havunders. 11 (2), 1–360.

Hilmer, M., Harder, M., Lemke, P., 1998. Sea ice transport: a highly variable link between Arctic and North Atlantic. Geophys. Res. Lett. 25, 3359–3362.

Holliday, N. P., Hughes, S. L., Bacon, S., Beszczynska-Möller, A., Hansen, B., Lavin, A., Loeng, H., Mork, K. A., Østerhus, S., Sherwin, T., Walczowski, W., 2008. Reversal of the 1960s to 1990s freshening trend in the northeast North Atlantic and Nordic Seas. Geophys. Res. Lett. 35 (3).

Ingvaldsen, R., Asplin, L., Loeng, H., 2004. Velocity field of the western entrance to the Barents Sea. J. Geophys. Res. 109 (C3).

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Met. Soc. 77, 437–471.

Kauker, F., Gerdes, R., Karcher, M., Köberle, C., Lieser, J. L., 2003. Variability of Arctic and North Atlantic sea ice: A combined analysis of model results and observations from 1978 to 2001. J. Geophys. Res. 108(C6), 3182.

Koenigk, T., Mikolajewicz, U., Jungclaus, J. H., Kroll, A., 2009. Sea ice in the Barents Sea: seasonal to interannual variability and climate feedbacks in a global coupled model. Clim. Dyn. 32 (7), 1119–1138.

Kvingedal, B., 2005. Sea-ice extent and variability in the Nordic Seas, 1967-2002. In: The Nordic Seas: An Integrated Perspective. Vol. 158 of Geophysical Monograph. American Geophysical Union, pp. 137–156.

Kwok, R., 2009. Outflow of Arctic Ocean sea ice into the Greenland and Barents Seas: 1979-2007. J. Clim. 22 (9), 2438–2457.

Levitus, S., Matishov, G., Seidov, D., Smolyar, I., 2009. Barents Sea multidecadal variability. Geophys. Res. Lett. 36.

Loeng, H., 1991. Features of the physical oceanographic conditions of the Barents Sea. Polar Res. 10 (1), 5–18.

Maslanik, J., Drobot, S., Fowler, C., Emery, W., Barry, R., 2007. On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions. Geophys. Res. Lett. 34 (3).

Meier, W., Fetterer, F., Knowles, K., Savoie, M., Brodzik, M. J., 2006. Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I passive microwave data, [2009-2010]. Digital Media, updated quarterly, National Snow and Ice Data Center, Boulder, Colorado.

Orvik, K. A., Skagseth, Ø., 2005. Heat flux variations in the eastern Norwegian Atlantic Current toward the Arctic from moored instruments, 1995-2005. Geophys. Res. Lett. 32 (14).

Parkinson, C. L., Cavalieri, D. J., 2008. Arctic sea ice variability and trends, 1979-2006. J. Geophys. Res. 113 (C7).

Pfirman, S. L., Bauch, D., Gammelsrød, T., 1994. The Northern Barents Sea: Water mass distribution and modification. In: The Polar Regions and Their Role in Shaping the Global Environment. Vol. 85 of Geophysical Monograph. American Geophysical Union, pp. 77–94.

Rudels, B., Friedrich, H., Hainbucher, D., Lohmann, G., 1999. On the parameterisation of oceanic sensible heat loss to the atmosphere and to ice in an ice-covered mixed layer in winter. Deep-Sea Res. II 46 (6-7), 1385–1425.

Schauer, U., Loeng, H., Rudels, B., Ozhigin, V. K., Dieck, W., 2002. Atlantic Water flow through the Barents and Kara seas. Deep-Sea Res. I 49, 2281–2298.

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

Schlichtholz, P., Houssais, M. N., 2011. Forcing of oceanic heat anomalies by air-sea interactions in the Nordic Seas area. J. Geophys. Res. 116.

Schrum, C., Backhaus, J. O., 1999. Sensitivity of atmosphere-ocean heat exchange and heat content in the North Sea and the Baltic Sea. Tellus 51 (4), 526–549.

Serreze, M. C., Holland, M. M., Stroeve, J., 2007. Perspectives on the Arctic's shrinking sea-ice cover. Science 315 (5818), 1533–1536.

Shapiro, I., Colony, R., Vinje, T., 2003. April sea ice extent in the Barents Sea, 1850-2001. Polar Res. 22 (1), 5–10.

Simmonds, I., Keay, K., 2009. Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979-2008. Geophys. Res. Lett. 36.

Skagseth, Ø., Furevik, T., Ingvaldsen, R., Loeng, H., Mork, K. A., Orvik, K. A., Ozhigin, V., 2008. Volume and heat transports to the Arctic Ocean via the Norwegian and Barents Seas. In: Dickson, R., Meincke, J., Rhines, P. (Eds.), Arctic Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate. Springer, New York, pp. 45–64.

Smedsrud, L. H., Ingvaldsen, R., Nilsen, J. E. Ø., Skagseth, Ø., 2010. Heat in the Barents Sea: Transport, storage, and surface fluxes. Ocean Sci. 6, 219–234.

Sorteberg, A., Kvingedal, B., 2006. Atmospheric forcing on the Barents Sea winter ice extent. Journal of Climate 19, 4772–4784.

Steele, M., Morison, J. H., Curtin, T. B., 1995. Halocline water formation in the Barents Sea. J. Geophys. Res. 100 (C1), 881–894.

Vinje, T., 2001. Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic Seas during the period 1864-1998. J. Clim. 14 (3), 255–267.

Walczowski, W., Piechura, J., 2006. New evidence of warming propagating toward the Arctic Ocean. Geophys. Res. Lett. 33 (12).

Zhang, X., Sorteberg, A., Zhang, J., Gerdes, R., Comiso, J. C., 2008. Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system. Geophys. Res. Lett. 35 (22).