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North Atlantic warming and declining volume of arctic sea ice

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Abstract

Long-term thinning of arctic sea ice over the last few decades has resulted in significant declines in the coverage of thick multi-year ice accompanied by a proportional increase in thinner first-year ice. This change is often attributed to changes in the arctic atmosphere, both in composition and large-scale circulation, and greater inflow of warmer Pacific water through the Bering Strait. The Atlantic Water (AW) entering the Arctic through Fram Strait has often been considered less important because of strong stratification in the Arctic Ocean and the deeper location of AW compared to Pacific water. In our combined examination of oceanographic measurements and satellite observations of ice concentration and thickness, we find evidence that AW has a direct impact on the thinning of arctic sea ice downstream of Svalbard Archipelago. The affected area extends as far as Severnaya Zemlya Archipelago. The imprints of AW appear as local minima in sea ice thickness; ice thickness is significantly less than that expected of first-year ice. Our lower-end conservative estimates indicate that the recent AW warming episode could have contributed up to 150–200 km^3 of sea ice melt per year, which would constitute about 20 % of the total 900 $km^3 yr^{-1}$ negative trend in sea ice volume since 2004.

1 Introduction

Two branches of Atlantic Water (AW) penetrate the Arctic Ocean. The Fram Strait branch (FSBW) enters the Arctic Ocean through the Fram Strait. The Barents branch enters through the Barents–Kara seas and undergoes significant transformation (cooling and freshening) before it enters the Arctic through St. Anna Trough, where the two branches converge (Schauer et al., 2002). FSBW is conventionally defined as a layer of water at a temperature above 0 °C (Schauer et al., 2004). Traditionally this water mass is considered to be insulated by a thick surface layer, especially far downstream from the point where AW enters the Arctic Ocean (Rudels et al., 1994). This concept is

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justified by the fact that joint effects of vertical winter convection (Steele et al., 1995), dense water cascading from adjoining shelves (Ivanov et al., 2004), and freshwater input from Siberian rivers (Rudels et al., 1996) create the so-called "cold halocline layer" (CHL), a cold high-gradient layer in salinity which effectively impedes vertical mixing and consequently high heat fluxes from the AW layer towards the Arctic sea ice. However, a well-developed CHL has not always been observed within the Arctic Ocean. For a period of about 10 yr the CHL was absent from the Amundsen basin between Svalbard and the North Pole (Steele and Boyd, 1998; Björk et al., 2002). Further to the east, e.g. in the Laptev Sea and in the Canada Basin the CHL has been more permanently observed (EWG report, Timmermans et al., 2008).

The CHL in the Atlantic sector of the Arctic Ocean (between Svalbard and Severnaya Zemlya Archipelago) seems not to be a permanent feature (Rudels et al., 1994; Björk et al., 2002; Rudels et al., 2004). In some years winter convection can therefore reach as deep as 100 m (Rudels et al., 1994, 2004). Hence, the key question is: can this relatively deep convective mixing affect the under-ice water layer and the ice cover? Historically, it was considered that the surface mixed layer to the east of Svalbard contains Polar surface water which moves generally towards Fram Strait, opposing the FSBW inflow. Because this water is lighter than FSBW, it overlays the latter; in consequence FSBW sinks beneath the surface mixed layer (Nikiforov and Shpaikher, 1980). Extensive field studies in the 1990s and 2000s provided new data, especially from long-term observational programs deploying moored instruments including the Nansen and Amundsen Basins Observational Program (NABOS; http://nabos.iarc.uaf.edu) that challenged this traditional view. These data confirmed the hypothesis, initially suggested by Rudels et al. (1994), that the surface mixed layer originates directly from the upper part of the inflowing AW, which cools through heat loss to the ice cover and atmosphere and freshens due to mixing with water from melted ice. It also appears that FSBW temperature exhibits a strong seasonal cycle, which is advected eastwards by the boundary current and can be detected even in the Laptev Sea (Ivanov et al., 2009). As a result, a substantial fraction of AW heat (stored within at least the upper 100 m)

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seasonally penetrates under the pack ice and is released upwards via convective mixing, contributing to the heat and salt budget of the under-ice water layer and the ice cover (Polyakov et al., 2010).

Energy stored in AW is enough to melt all the arctic sea ice several times. Attempts have been made to assess the effect of AW warming on pan-Arctic-scale sea ice thinning (Zhang et al., 2010; Polyakov et al., 2010). The observed thinning of the ice cover from 1980–2009 (Kwok and Rothrock, 2009) is equivalent to roughly 1 $\mathrm{W\,m^{-2}}$ applied directly to the ice (equivalent to 0.1 m of ice melt $\mathrm{yr^{-1}}$), or an increase in ocean heat flux of $>4\,\mathrm{W\,m^{-2}}$ from a nominal value of 2–4 $\mathrm{W\,m^{-1}}$ (Kwok and Untersteiner, 2011).

Long-term trend in arctic sea ice over recent few decades includes a dramatic decrease in the summer extent and a significant decline in the proportion of the multi-year thick ice (Rothrock et al., 1999; Kwok et al., 2009). This change is often attributed to changes in the arctic atmosphere, both in composition (Francis and Hunter, 2007) and large-scale circulation (Wang et al., 2009), and greater inflow of warmer Pacific water through the Bering Strait (Shimada et al., 2006). The Atlantic Water (AW) was often considered less important compared to other processes. This article is trying to estimate the effect of the recent North Atlantic warming on the ice melting processes happening at the outlet of the Arctic Ocean near Fram Strait, Svalbard and Franz Joseph Land.

2 Results

The AW temperature in Fram Strait has been monitored for an extended period of time by the international scientific community (Schauer et al., 2004; Lind and Ingvaldsen, 2011). The AW temperature time series presented in Fig. 1 was generated from the oceanographic database collected by and routinely updated at the Arctic and Antarctic Research Institute CTD data for temperature and salinity used in this study were taken during NABOS (Nansen and Amundsen Basins Observational System) campaigns and data were downloaded from NABOS archive (http://nabos.iarc.uaf.edu). The data had

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passed thorough quality control, and have been used in multiple published studies, see the reference list in (Polyakov et al., 2011).

Figure 1 clearly illustrates that the AW temperature has been increasing since the mid-1960s. The warming accelerated in the 2000s and this warming was observed both in Fram Strait, on the pathway along the continental shelf break, and as far away as the Laptev and East Siberian seas with the maximum recent observed warming in 2006–2007 (Polyakov et al., 2011). This warming was proposed as one of the mechanisms responsible for the overall thinning of arctic sea ice (Polyakov et al., 2010). Even though strong stratification in the eastern Arctic is often quoted as the main reason why AW has had little or no impact on sea ice, we argue that recent warming may have changed this.

After entering the Arctic Ocean through Fram Strait, the warm AW near the surface effectively prevents sea ice formation north of Svalbard in a location historically called Whalers Bay. This area is often ice-free during winter (Fig. 2), and multi-year (MY) ice is generally not present here.

This AW signal propagates far downstream of Fram Strait along the continental slope north of Svalbard in counter-clockwise direction around the Arctic Ocean. A series of transects taken at 31° E, 81° N in the fall of 2004, 2006, and 2008 as a part of the NABOS campaigns (Fig. 1) shows that AW in these sections is in actual contact with sea ice and therefore directly contributes to the sea ice heat budget. This is illustrated in Fig. 3 which presents images of sea ice thickness (SIT) from Ice, Cloud, and land Elevation Satellite (ICESat) campaigns in late winter from 2004–2008.

The shown ice thickness fields are monthly means for February–March for 2004, 2005, 2006 and 2008, and March–April for 2007 Uncertainty of ICESat products at 25 km length scale is ~0.5 m based on assessment with submarines and upward looking sonars. Averaging over the larger area reduces the uncertainty in the overall noise; therefore, we argue that the uncertainty is significantly smaller than the observed anomalies.

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In Fig. 3, curious minima in SIT around Svalbard/Franz Joseph Land are clearly present. Are these features a signature of AW impact on sea ice? A first order factor that could explain this thinning is a change in the atmospheric circulation and associated changes in ice transport and surface heat budget. Figure 3 shows two-monthly mean ice motion vectors (Kwok et al., 1998), and the sea ice edge on the mid date of the same time period (1 March in 2004–2006 and 2008 or 1 April in 2007). Generally the direction of the ice motion is similar for 5 yr with drift from the Arctic Ocean and the Kara Sea towards the Barents Sea. In 2004 an anomaly is visible with drift towards the north between Svalbard and Franz Josef Land. In 2004 consequently probably winds from the south favored formation of polynyas north of Svalbard and Franz Joseph Land. Yet, in all years an ice thickness minimum is located far away from the sea ice boundary in the interior of the sea ice pack. In addition, these anomalies are located right above the continental slope where AW propagates eastward. Moreover, in all four years beginning in 2005 SIT anomalies east of Franz Joseph Land are located downstream (in terms of the direction of ice drift) of completely ice-covered ocean. We therefore argue that these minima in ice thickness are a result of bottom melt because of AW.

Simulations using a global fully coupled model, the Norwegian Earth System Model (NorESM, Bentsen et al., 2012) as a part of CMIP5 experiment (Taylor et al., 2012) provide a qualitatively consistent picture for the bottom melt of sea ice in the vicinity of Svalbard (Fig. 4). NorESM is a state of the art global Earth System Model with reasonably high resolution in the Svalbard region (∼ 50 km). The sea-ice model in NorESM is the original CICE4 version used in Community Climate System Model 1 Version 4 (CCSM, Gent et al., 2011). Many other parts of the model system are the same as in CCSM, but the ocean component is an isopycnic coordinate ocean general circulation model (Bentsen et al., 2012). NorESM standard historic simulations according to CMIP5 protocol show good results for Arctic sea ice in general (Langehaug et al., 2012). The annual cycle (including March and September sea ice extent) is simulated reasonably well similar to the other five CMIP5 models (models that presently made the detailed sea ice output available), with a correlation above 0.99. The model's Fram

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Strait sea ice area export is the best of the models in comparison (Langehaug et al., 2012), and simulations in this sector of the Arctic Ocean should therefore particularly useful.

NorESM fields are shown here to illustrate that a fairly large band of effective melting is possible, given the good quality of NorESM simulations in this region (Langehaug et al., 2012). The climatic mean (1980–2000) melt rates show that melting in this sector is much higher than in other regions of the Arctic Ocean, and that this relates to the AW inflow. Further evaluation of the NorESM ocean heat transport is presently ongoing, but outside the scope of this paper.

The simulated NorESM sea ice in the sector north of Svalbard of the Arctic Ocean is between 2 and 3 m thick in February, while thicker ice is found further west and north of Greenland (Fig. 4a). Many of the other CMIP5 models (Taylor et al., 2012) have a too low sea ice thickness in this sector (not shown). Effective bottom melting of sea ice is visible in Fig. 4b) and is clearly driven by AW inflow. While bottom melting during mid winter (Febrary) is almost zero elsewhere in the Arctic Ocean, values north of Svalbard over a ~ 100 km wide area range between 10–20 mm day^{-1}. The bottom melt in this area remains high throughout the year while the February field is representative for the period from January through April. This indicates a presence of a permanent source of heat below the sea ice that is not related to the strong radiative annual cycle at the surface.

Another way of estimating the direct effect of warm AW temperatures anomalies on sea ice melting is to use the approach presented in (McPhee et al., 2003: Table 1) for calculating the ocean heat flux. A melting rate can be estimates from:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{Q}{\rho_{\mathrm{ice}} L} \tag{1}$$

where the mean ocean heat flux (Q) is estimated at $10.5 \pm 2.3\,\mathrm{W\,m^{-2}}$ for an ocean layer under the ice that has a temperature of 0.08 ± 0.01 K above the freezing point (McPhee et al., 2003). From Eq. (1) it follows that $10\,\mathrm{W\,m^{-2}}$ of extra heat applied to the ice from

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below will melt additional 3 mm of ice per day. The melt rates of $\sim 20\,\mathrm{mm\,day^{-1}}$ shown in Fig. 4b thus compares to a heat flux from AW of $\sim 67\,\mathrm{W\,m^{-2}}$. The shallow location of the AW warm core (Fig. 1) suggests that the temperature directly underneath the ice in September 2006 and October 2008 could be well above the freezing point. This is about 500 km downstream of the AW inflow region in Fram Strait. An ocean heat flux of $\sim 100\,\mathrm{W\,m^{-2}}$ is therefore a realistic value for this sector. On the other hand the average ice motion across the pathway of AW flow estimated at $1.32 \pm 1.12\,\mathrm{km\,day^{-1}}$. This is a mean value over all surveys shown in Fig. 3 within area 15–90° E, 80–85° N. The average width of the AW warm core should be of the order of the baroclinic Rossby radius and therefore is expected to be between 5 and 15 km (Aksenov et al., 2011). This gives us an estimate of 3–11 days for the period when the drifting ice could be directly affected by enhanced ocean heat flux from below.

These estimated melt rates might seem high, but one ice drift station that drifted across the AW inflow area calculated maximum heat fluxes towards the ice from observations of under-ice turbulence and bursts between 50–100 $\mathrm{W\,m^{-2}}$ lasted for a day or three (McPhee et al., 2003), while the general level of heat flux towards the ice in this area was found to be 10–2 $\mathrm{W\,m^{-2}}$. The simulated melt rates from the NorESM therefore seem plausible, and that such levels of high melting can affect areas of several km also seems likely. In order to see if factors other than ice drift played a role in creating the SIT minima in Fig. 3 we calculated anomalies in the surface heat budget.

Warmer air temperature and more water vapor in the air would generally be the result from large areas of open water during wintertime. The downwelling longwave (DLW) anomaly calculated from National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) Reanalysis, NCEP2 (Kanamitsu et al., 2002) for February–March 2008 at the surface is shown in Fig. 5. The anomaly is probably generated by the large open water area in the north eastern Barents Sea localized south of the DLW anomaly. In addition, the shape of the anomaly above the continental shelf break cannot explain the spotty picture of SIT anomalies. The shapes and magnitude of DLW anomalies in 2006 and 2007 are very similar to what was observed in 2008, but are significantly smaller in 2004–2005 (not shown here). We picked only the DLW component of the surface heat budget because it will reflect the effect of changes in the atmosphere better than, e.g. sensible or latent heat fluxes. The latter will primarily be a function of current sea ice concentration and not very indicative of remotely induced forcing. The shortwave flux plays a minor role in this part of the Arctic at this time of year.

Snow on ice can thermodynamically influence SIT. It can also affect the accuracy of satellite products. These snow-on-ice anomalies (at least large anomalies) should, in principle, be reasonably collocated with DLW anomalies because both strongly depend on the amount of precipitable water in the atmosphere. We estimated total accumulated snowfall from ERA Interim Reanalysis (Dee et al., 2011) assuming a snow density of 0.25, and that snowpack starts developing in September. The snow depth anomaly for February–March 2008 that would have developed if the ocean surface were able to hold it is also shown in Fig. 5. A maximum snowfall in the northeastern Barents Sea is clearly related to more open water there. This snowfall impacts a relatively wide area north and east of the open water in the Barents Sea, creating a deeper snowpack with typical values of about 5 cm for the anomaly in the region of interest. The climatological value for snow depth is around 25–30 cm according to the ERA interim reanalysis. Again, we can see from our simple estimates that the shape of the snow depth anomaly indicates that the extra snowfall is not a likely mechanism responsible for the ice thickness anomalies in 2008. A similar conclusion could be reached for other years (not shown). One potential caveat of this analysis is that the thin ice anomalies (Fig. 3) could be advected in from elsewhere. However, the prevailing motion around Svalbard and Franz Joseph Land is the transpolar drift from north east. The ice is thicker upstream of the thinner ice cover.

Physical processes are quite different in the Barents Sea. Here AW clearly impact the sea ice cover (Årthun et al., 2012), and there is a general lag of about a year or two between anomalies in AW heat transport and the sea ice response. However, apart from a few events of large ice drift into the Barents Sea as occurred in 2002/2003 (Kwok, 2009) the Barents Sea ice response to AW heat is plainly that it is not forming. Two

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pairs of years, 2005, 2006 and 2004, 2008, have very similar wind patterns especially near Novaya Zemlya Archipelago, but the distribution of ice is absolutely different. The deep tongues of open water reaching the northern tip of Novaya Zemlya in between 2006 and 2008 (Fig. 3) is likely a result of AW heat preventing sea ice formation, as anomalies in the AW heat transport was reached as high as ~30 TW in these years (Årthun et al., 2012). Sea ice anomalies in the central Arctic Ocean could probably be explained by a combination of factors: atmospheric dynamics, more open water in the previous summer, and inflow of warmer Pacific water. However, ice dynamics outside the focus area is not a topic of the present study.

Between 2004 and 2008 anomalies in sea ice thickness occurred in the same area and increased in strength. We argue that this cannot be explained by ice drift anomalies or heat flux anomalies from the atmosphere. How much ice that likely melted as a consequence of warm temperature anomalies of the AW near Svalbard/Franz Joseph Land can be estimated from Fig. 4. For our estimates we assume first-year (FY) ice to be between 1.8 and 2.2 m thick. Ice thinner than FY ice in the area of interest was considered to be a result of an AW effect, as we have already demonstrated that other factors (e.g. wind) cannot explain this thinning. Just as a reminder, our model estimates also give climatological values greater than 2 m for thicknesses of ice not affected by AW.

We will only consider an area of about 600 000 km^2 bounded by 15° E–90° E and 80° N–85° N. A rough estimate of ice being 1m thinner than the climatological mean at the end of the winter will result in an ice volume anomaly of about 600 km^3. Mean ice thickness anomalies averaged over this area calculated using five different estimates of FY ice thickness, from 1.8 m to 2.2 m, are shown in Fig. 6. The most conservative estimate for 2008 according to this simple analysis yields an anomaly of about 130 km^3

3 Discussion

Warmer Pacific water inflow through Bering Strait and accelerating global warming in recent years has already been identified as important processes responsible for the overall thinning of Arctic sea ice. This thinning means a dramatic reduction in the proportion of MY ice. The prevailing wind pattern favoring the transpolar drift brings significant amounts of ice to the area north of Svalbard where AW is still close to the surface. Evidence presented here suggests that the strong AW warming of the mid-2000s is a major factor responsible for significant ice thinning observed in 2005–2008 by the ICESat missions. The anomalies are located east of Svalbard, right above the AW pathway along the continental slope. Atmospheric heat flux anomalies and/or ice transport mechanisms seem unlikely to provide an explanation for the satellite-observed anomalies in ice thickness. Intensification of melt by warmer AW is put forward here as a primary mechanism responsible for the thinning in this area. One very important consequence is the potential contribution of this meltwater to the increased freshwater export from the Arctic Ocean in the form of liquid water rather than as ice. This local melt, upstream of Fram Strait, will affect the freshwater transport, and transfer mass from the sea ice to the liquid freshwater portion.

Presence of AW in the Arctic Ocean was first discovered by Fridtjof Nansen during his historic drift (Nansen 1901), and the possibility of a significant AW influence on sea ice in the Arctic has been suggested before (Timofeev, 1962). The authors of the present study have participated in cruises in the area and have personal experience with the ice there. In particular, a NABOS cruise conducted in late October 2008 found the whole area generally covered with young and relatively thin ice (40–50 cm). The ice presence delayed mooring recovery until, quite unexpectedly, the expedition entered an open water area where surface water measured about 1 to 2 °C while the outside air temperature was −10 to −15 °C. Ocean temperature reached almost 5 °C at 100 m depth (Fig. 1). The warming in the 2000s was unprecedented. The earlier warming in

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the mid-1990s was weaker than the most recent warming, but unfortunately no precise measurements of ice thickness from satellites are available from that time.

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References

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., and Kristjánsson, J. E.: The Norwegian Earth System Model, NorESM1-M. Part 1: Description and basic evaluation, in review, 2012.

Björk, G., Söderkvist, J., Winsor, P., Nikolopoulos, A., and Steele, M.: Return of the cold halocline layer to the Amundsen Basin of the Arctic Ocean: implications for the sea ice mass balance, Geophys. Res. Lett. 29, 1513, doi:10.1029/2001GL014157, 2002.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Holm, E. V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., and Thepaut, J. N.: The Era-Interim reanalysis: configuration and performance of the data assimilation system, Q. J Roy. Meteor. Soc., 137, 553–597, 2011.

Environmental Working Group, Arctic Climatology Project. Arctic Meteorology and Climate Atlas, edited by: Fetterer, F. and Radionov, V., Boulder, CO: National Snow and Ice Data Center, USA CD-ROM; also available from http://www.aari.ru/, 2000.

Francis, J. A. and Hunter, E.: Changing fabric of the arctic blanket, Environ. Res. Lett., 2, 045011, doi:10.1088/1748-9326/2/4/045011, 2007.

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The Community Climate System Model 1 version 4, J. Climate, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, 2011.

Ivanov V. V., Shapiro, G. I., Huthnance, J. M., Aleynik, D. M., and Golovin, P. N.: Cascades of dense water around the World Ocean, Prog. Oceanogr., 60, 47–98, 2004.

Ivanov, V. V., Polyakov, I. V., Dmitrenko, I. A., Hansen, E., Repina, I. A., Kirillov, S. A., Mauritzen, C., Simmons, H., and Timokhov, L. A., Deep Sea Res. Pt. I, 56, 1–14, 2009.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S. K., Hnilo, J. J., Fiorino, M., and Potter, G. L.: NCEP-DOE AMIP-II reanalysis (R-2), B. Am. Meteorol. Soc., 83, 1631–1643, 2002.

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

Kwok, R. and Rothrock, D. A.: Decline in Arctic sea ice thickness from submarine and ICEsat records: 1958–2008, Geophys. Res. Lett., 36, L15501, doi:10.1029/2009GL039035, 2009.

Kwok, R. and Untersteiner, N.: The thinning of Arctic sea ice, Phys. Today, 64, 36–41, 2011.

Kwok, R., Schweiger, A., Rothrock, D. A., Pang, S., and Kottmeier, C.: Sea ice motion from satellite passive microwave data assessed with ERS SAR and buoy data, J. Geophys. Res., 103, 8191–8214, 1998.

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, J. Geophys. Res., 114, C07005, doi:10.1029/2009JC005312, 2009.

Langehaug, H. R., Geyer, F., Smedsrud, L. H., and Gao, Y.: Arctic sea ice decline and ice export in the CMIP5 historical simulations, Ocean Model., in press, 2012.

Lind, S. and Ingvaldsen, R. B.: Variability and impacts of Atlantic water entering the Barents Sea from the north, Deep-Sea Res. Pt. I, 62, 70–88, 2011.

McPhee, M. G., Kikuchi, T., Morison, J. H., and Stanton, T. P.: Ocean-to-ice heat flux at the North Pole environmental observatory, Geophys. Res. Lett., 30, 2274, doi:10.1029/2003GL018580, 2003.

Nansen, F. The Norwegian North Polar Expedition 1893–1896, Vol II, Publishers: London, New York: Longmans, Green and co.; Christiania: J. Dybwad, Available online from: http://archive.org/details/norwegiannorthpo13nans, 1901.

Nikiforov, Ye. G. and Shpaikher, A. O.: Features of the Formation of Hydrological Regime Large-Scale Variations in the Arctic Ocean, Gydrometeoizdat, Leningrad, 269 pp., 1980 (in Russian).

Polyakov, I. V., Timokhov, L. A., Alexeev, V. A., Bacon, S., Dmitrenko, I. A., Fortier, L., Frolov, I. E., Gascard, J. C., Hansen, E., Ivanov, V. V., Laxon, S., Mauritzen, C., Perovich, D., Shimada, K., Simmons, H. L., Sokolov, V. T., Steele, M., and Toole, J.: Arctic Ocean warming contributes to reduced polar ice cap, J. Phys. Oceanogr., 40, 2743–2756, doi::10.1175/2010JPO4339.1, 2010.

Polyakov, I. V., Alexeev, V. A., Ashik, I. M., Bacon, S., Beszczynska-Moller, A., Carmack, E. C., Dmitrenko, I. A., Fortier, L., Gascard, J. C., Hansen, E., Holemann, J., Ivanov, V. V., Kikuchi, T., Kirillov, S., Lenn, Y. D., McLaughlin, F. A., Piechura, J., Repina, I., Timokhov, L. A., Walczowski, W., and Woodgate, R.: NOWCAST: fate of early-2000's Arctic warm water pulse, B. Am. Meteorol. Soc., 92,5, 561–565, 2011.

Rothrock, D. A., Yu, Y., and Maykut, G. A.: Thinning of the Arctic ice cover, Geophys. Res. Lett., 26, 3469–3472, 1999.

Rudels, B., Jones, E. P., Anderson, L. G., and Kattner, G.: On the intermediate depth waters in the Arctic Ocean, in: The Polar Oceans and their Role in Shaping the Global Environment, edited by: Johannessen, O. M., Muench, R. D., and Overland, J. E., AGU Geophys. Monograph 85, Washington, 33–46, 1994.

Rudels, B., Anderson, L. G., and Jones, E. P.: Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean, J. Geophys. Res., 101, 8807–8821, 1996.

Rudels, B., Jones, P. E., Schauer, U., and Eriksson, P.: Atlantic sources of the Arctic Ocean surface and halocline waters, Polar Res., 23, 181–208, 2004.

Schauer, U., Rudels, B., Jones, E. P., Anderson, L. G., Muench, R. D., Björk, G., Swift, J. H., Ivanov, V., and Larsson, A.-M.: Confluence and redistribution of Atlantic water in the Nansen, Amundsen and Makarov basins, Ann. Geophys., 20, 257–273, doi:10.5194/angeo-20-257-2002, 2002.

Schauer, U., Fahrbach, E., Osterhus, S., and Rohardt, G.: Arctic warming through the Fram Strait: oceanic heat transport from 3 years of measurements, J. Geophys. Res., 109, C06026, doi:10.1029/2003JC001823, 2004.

Shimada, K., Kamoshida, T., Itoh, M., Nishino, S., Carmack, E., McLaughlin, F., Zimmermann, S., and Proshutinsky, A.: Pacific Ocean inflow: influence on catastrophic reduction of sea

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ice cover in the Arctic Ocean, Geophys. Res. Lett., 33, L08605, doi:10.1029/2005GL025624, 2006.
Steele, M. and Boyd, T.: Retreat of cold halocline in the Arctic Ocean, J. Geophys. Res., 103, 10419–10435, 1998.
Steele, M., Morison, J. H., and Curtin, T. B.: Halocline water formation in the Barents Sea, J. Geophys. Res., 100, 881–894, 1995.
Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.
Timofeev, V. T.: Influence of deep Atlantic water on formation and melting of ice in the Laptev Sea, Okeanologiya, 2, 219–225, 1962.
Untersteiner, N.: On the mass and heat balance of Arctic sea ice, Arch. Meteor. Geophys. Bioclimatol., A12, 151–182, 1961
Wang, J., Zhang, J. L., Watanabe, E., Ikeda, M., Mizobata, K., Walsh, J. E., Bai, X. Z., and Wu, B. Y.: Is the dipole anomaly a major driver to record lows in Arctic summer sea ice extent? Geophys. Res. Lett., 36, L05706, doi:10.1029/2008GL036706, 2009.
Zhang, J. L., Steele, M., and Schweiger, A.: Arctic sea ice response to atmospheric forcings with varying levels of anthropogenic warming and climate variability, Geophys. Res. Lett, 37, L20505, doi:10.1029/2010gl044988, 2010.

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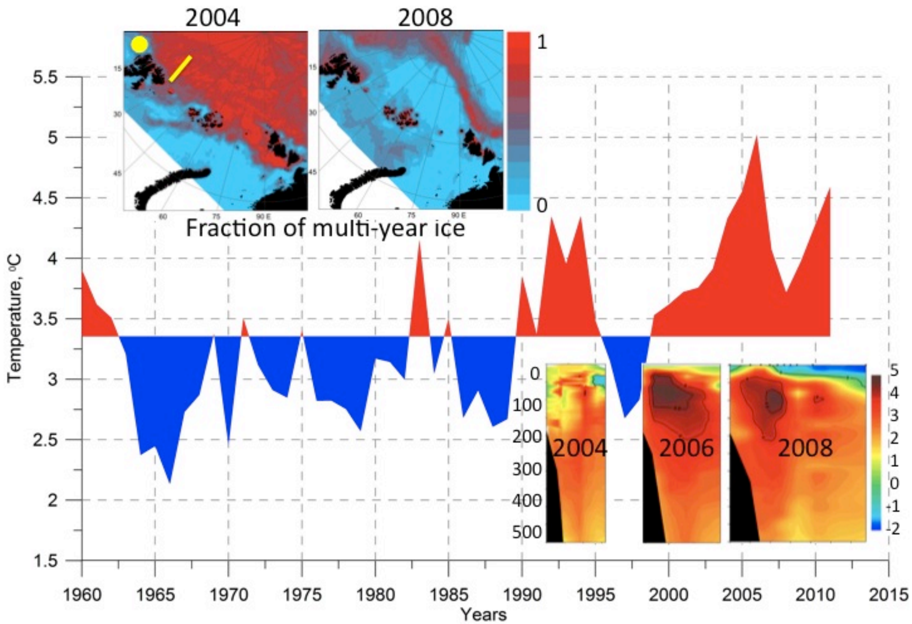

Fig. 1. Concentration of multi-year ice in 2004 and 2008 (two upper insets). Temperature in the AW core (main graph) measured in Fram Strait (yellow circle, upper left inset) and from transects of different extent (three lower insets) made in September 2004, 2006, and October 2008 at 31° E, 80° N (location marked by yellow line in the upper left inset).

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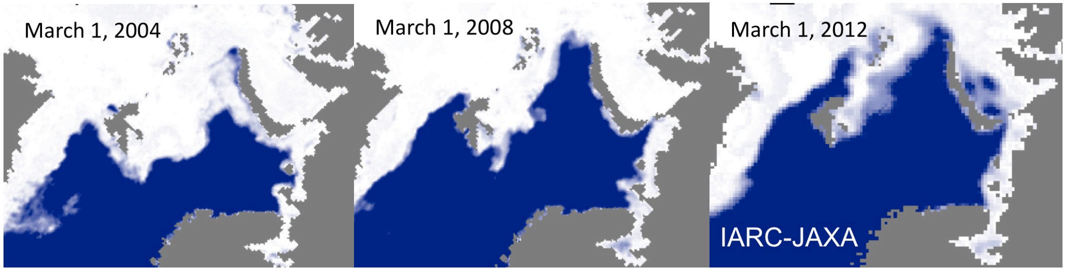

Fig. 2. AMSR-E and AMSR2 sea ice concentrations on 1 March in 2004, 2008, and 2012 (Advanced Microwave Scanning Radiometer for EOS (AMSR-E), Advanced Microwave Scanning Radiometer 2 (AMSR2), http://www.ijis.iarc.uaf.edu) (IARC: International Arctic Research Center, University of Alaska Fairbanks. JAXA: Japan Aerospace Exploration Agency).

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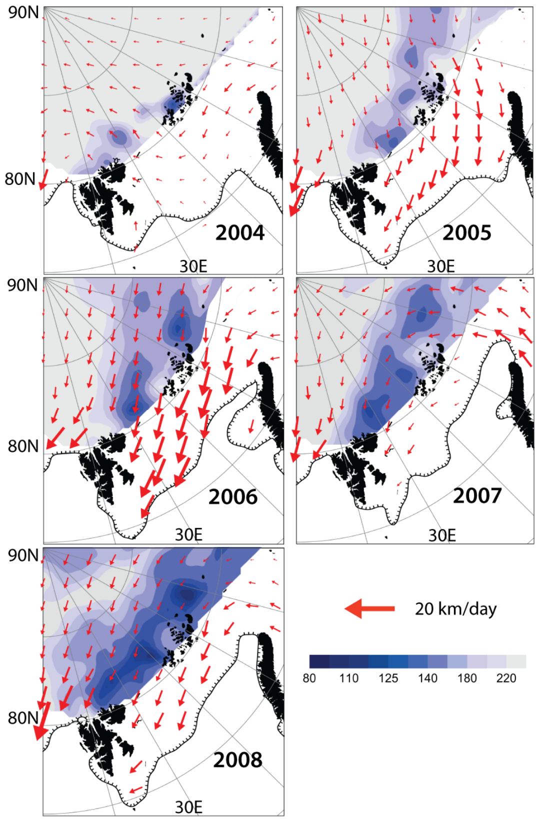

Fig. 3. ICESat winter sea ice thickness and ice motion vectors. Ice thickness is showed in color shading [cm], and ice motion as vectors [km day^{-1}]. The ice edge is drawn at 15 % sea ice concentration.

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a)

b)

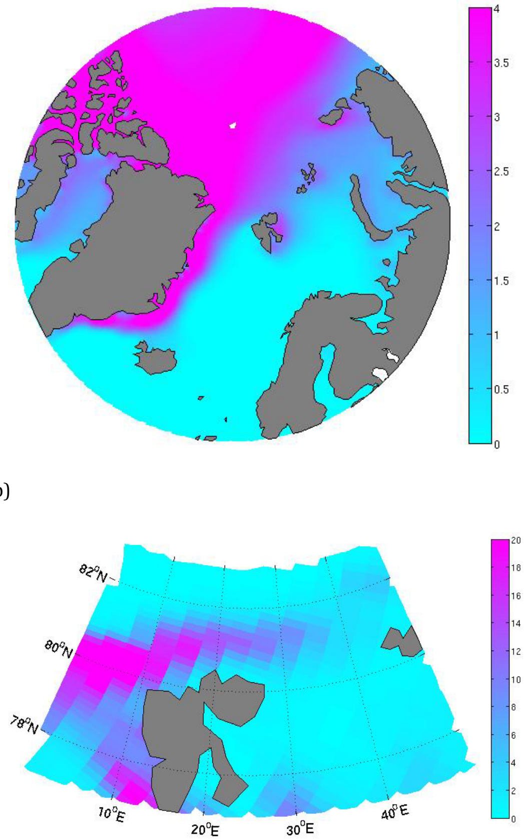

Fig. 4. NorESM historical CMIP5 simulations (1980–2000 means are shown). **(a)** February ice thickness [m]. **(b)** Bottom melt [mm day^{-1}] for the sector around Svalbard. The cells' sizes visible on the picture indicate model resolution.

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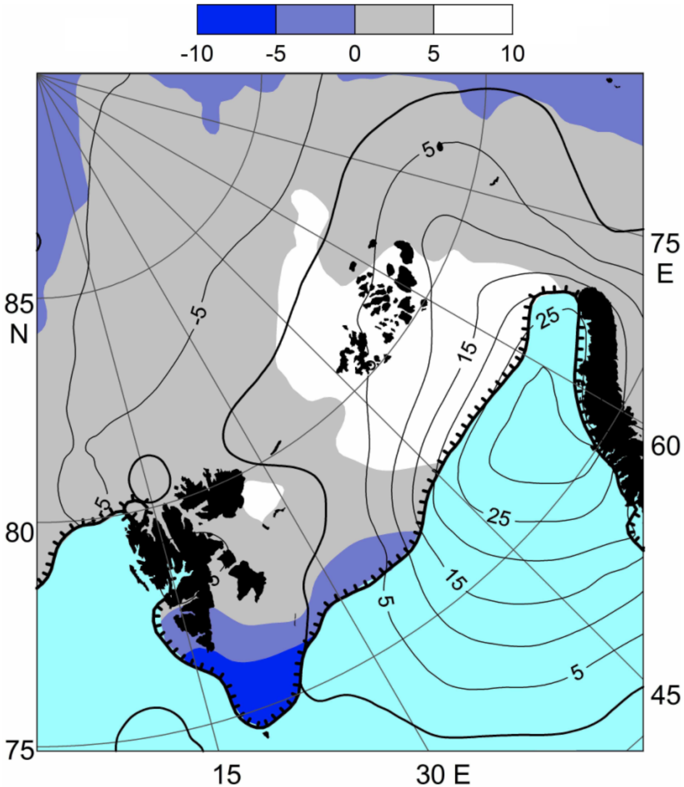

Fig. 5. Downwelling longwave anomaly (contour lines, February–March 2008, W m^{-2}), calculated from NCEP/DOE Reanalysis, snow depth anomaly estimated from European Re-analysis Agency (ERA) Interim Reanalysis (Dee et al., 2011) (color shading, cm), and sea ice edge based on a 15 % concentration threshold.

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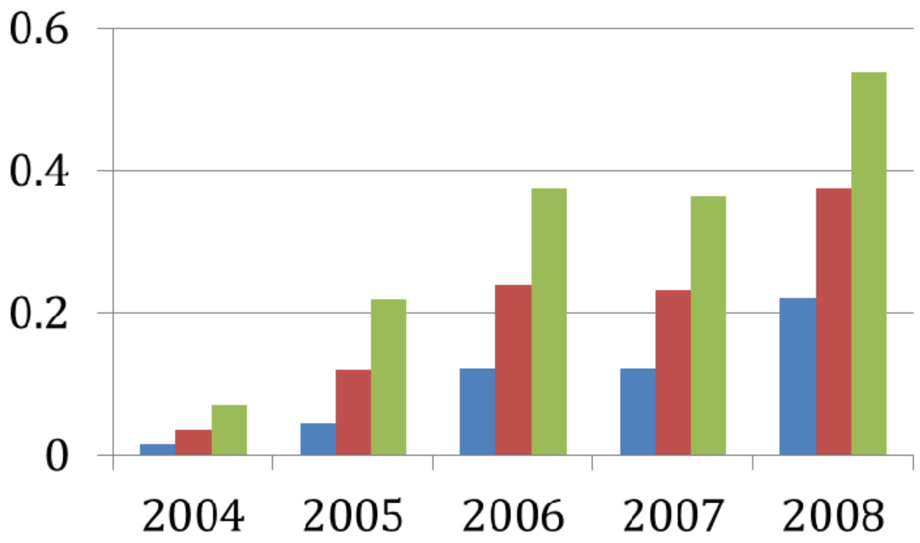

Fig. 6. Mean of absolute ice thickness anomaly (m) of ice thinner than 2.2 m (green) 2 m (red) and 1.8 m (blue) as a function of time averaged over an area bounded by 15° E–90° E and 80° N–85° N.

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