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Thin Ice on Top of a Warm Ocean – the Changing Arctic Ocean*

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Abstract: While the most prominent, and through remote sensing easy to observe, signal of Arctic change is the decrease of sea-ice extent in summer, there is increasing evidence that also ice thickness is declining. The ice extent is recovering through winter, but the thickness is not and this has been shown to facilitate further shrinking of the extent. Less or thinner ice cover allows the ocean to absorb more insolation and both less sea-ice and warmer ocean surface enables higher heat flux from the ocean to the atmosphere. This sets positive feedbacks through anomalies in the atmospheric heat and pressure distribution. Other feedbacks are expected for the ocean, like an increase in water exchange with the North Atlantic as a consequence of less ice and thus more liquid fresh water export. Advection of considerably warmer water from the North Atlantic has only regional effect to the sea-ice in displacing the ice edge in the Barents Sea and north of Svalbard. On the other hand it leads to warming of large parts of the interior Arctic Ocean. This paper provides a brief review of current understanding of the processes affecting Arctic sea-ice and the possible consequences of the retreating sea-ice cover. The review is based both on observations and model simulations.

Zusammenfassung: Das prominenteste Signal für den Klimawandel in der Arktis ist die Abnahme der Meereisausdehnung im Sommer. Weit weniger leicht zu messen als jene ist die Dicke des Meereises, aber auch hier mehren sich die Zeichen für eine generelle Abnahme. Zunehmend dünneres Eis auch im Winter ist eine der Voraussetzungen für eine weitere Reduzierung der Ausdehnung im folgenden Sommer. Weniger und dünneres Eis ermöglicht auch, dass mehr Sonneneinstrahlung im Ozean absorbiert wird, und gleichzeitig, dass die vermehrte Wärme des Ozeans leichter an die Atmosphäre abgegeben werden kann, was wiederum zu Verschiebungen der Luftdruck- und -temperaturverteilung führt. Weitere positive Rückkopplungen werden für den Ozean erwartet, etwa ein möglicher Anstieg des Austauschs mit dem Nordatlantik als Folge von verringertem Eis- und damit erhöhtem Süßwasserexport. Auch das einströmende Wasser aus dem Nordatlantik war in den letzten Dekaden erheblich wärmer als zuvor. Aufgrund der Isolierung durch die starke Dichteschichtung ist der Effekt auf das Meereis regional begrenzt auf die Barentssee und nördlich von Svalbard und sonst vermutlich zu vernachlässigen. Stattdessen verbleibt die Wärme im Ozean und zeigt sich als großskalige Erwärmung im Nordpolarmeer. Basierend auf Beobachtungen und Modellsimulationen liefert dieser Artikel einen kurzen Überblick über das derzeitige Verständnis der Prozesse, die das arktische Meereis verändern und die über die möglichen Folgen des sich zurückziehenden Meereises.

INTRODUCTION

Global warming has a distinct latitudinal pattern and is largest in polar regions. The discussion about possible causes for the amplification in the Arctic reflects on the sea ice as key factor because of its radiative and isolating properties. Sea ice strongly reflects incoming short wave radiation and thus inhibits radiative warming of the ocean surface layers from where the atmosphere is warmed. At the same time, sea-ice shields the ocean from the atmosphere, inhibiting the exchanges of heat, water, substances, and momentum.

The position of the sea-ice edge in winter is governed by the heat supply through the ocean. That large parts of the Barents Sea and the Nordic Seas are ice-free in winter is due to the vicinity of the sea ice to the warm Atlantic waters of subpolar origin. In summer, however, the sea-ice edge retreats from the region of advected warm surface waters and a direct effect of the oceanic heat transport into the Arctic is not obvious. Actually, the cold halocline that underlies most of the sea ice in the Arctic Ocean prevents significant heat flux from warmer ocean layers to the surface even when wind generated turbulence should increase in the ocean as sea-ice retreats. For the future we anticipate a more pronounced stratification in the near surface Arctic Ocean because of increasing fresh water supply by a stronger hydrological cycle.

This paper gives an overview of recent findings from observations and from simulation of long-term developments and of the various feedbacks. In Chapter 1, we compile congruent findings of sea-ice thickness reduction from various observation platforms, Chapter 2 discusses the impact of the decline of both extent and thickness on the ocean and atmosphere as derived from model simulations and Chapter 3 considers the possible contribution of ocean heat to sea-ice reduction. Chapter 4 gives a summary and lists a number of open questions

Chapter 1: ARCTIC SEA-ICE RETREAT AND THINNING

Summer sea-ice extent has declined by around 40 % since the beginning of Arctic wide measurements of sea-ice concentrations from satellites. The record sea-ice extent reduction in recent years has boosted the downward trend in sea-ice extent to 11 % per decade. While the typical sea-ice extent in the 1980s was 7.5 million km^2, the ice extent in the summer of 2007 amounted to only 4.3 million km^2. Since then it has slightly recovered with the sea-ice extent minimum amounting to 4.6 million km^2 in September 2010 (FETTERER et al. 2009).

Summer sea-ice extent in the Arctic is varying strongly from year to year. The largest sea-ice extent in the satellite time series occurred in 1996. The main reason for that sea-ice extent maximum was a persistent low-pressure anomaly over the central Arctic in the months of July and August (HAAS & EICKEN 2001). The wind forcing distributed sea ice from the Arctic interior to its periphery. Likewise, the sea-ice extent minima of the years 2007 and the following years were promoted by anomalous but persistent sea-level pressure (SLP) anomalies over the Arctic Ocean. A persistent low-pressure anomaly over northern Siberia and the eastern Arctic Ocean drives sea ice from the eastern to the western Arctic,

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thus opening up the eastern Arctic while accumulating sea ice under a high SLP anomaly centred over northern Canada and Greenland. Sea-ice extent reacts sensitively to inter-annual variability in the wind.

Besides the retreat of the summer sea-ice cover, there are indications that also the sea-ice thickness has decreased substantially over the last decades. Indirect measurements based on surface backscatter (KWOK 2004) and sea-ice age calculated from backward trajectories (MASLANIK et al. 2007) show a loss of multiyear ice that tends to be thicker than first year ice. Submarine measurements of sea-ice draft indicate a wide spread thinning between the 1990s and the period 1958-1976 (ROTHROCK et al. 1999). Freeboard measurements from the ICESat satellite show a substantial decrease of sea-ice thickness between 2003 and 2008 (FARREL et al. 2009, KWOK et al. 2009). Direct measurements of sea-ice and snow thickness by EM-measurements north of Fram Strait (HAAS et al. 2008) show a decline in the thickness of the level ice category from over 2 m in the early 1990s to around 1 m in 2007. On the other hand, EM measurements in the thick sea-ice north of the Canadian Archipelago show a rather constant ice thickness (HAAS et al. 2009). Simulations with ocean – sea-ice models under realistic atmospheric forcing reproduce the variability of sea-ice concentration in the Arctic Ocean (e.g. KAUKER et al. 2003) and indicate a long-term declining trend in sea-ice volume (e.g. KÖBERLE & GERDES 2003)

A sequence of four years (2007–2010) with record low Arctic sea-ice extent are unprecedented and, according to long integrations with coupled climate models, highly unlikely to occur by chance (L. Kaleschke, pers. comm.). In a study investigating the sensitivities of summer sea-ice extent, KAUKER et al. (2009) identify sea-ice thickness at the end of winter as one of the most important factors besides wind stress in June and July and surface air temperature in September. This finding has been confirmed by ocean – sea-ice model experiments starting with different initial sea-ice thicknesses. When starting with conditions typical for the 1980s, the summer minimum sea-ice extent did not fall below 7 million km^2 under atmospheric forcing taken from the last 20 years. With the same atmospheric forcing but initial conditions typical for the first decade of the 21st century, the minimum summer sea-ice extent is around 4 million km^2 (Kauker et al. pers. comm.). Thus, it is possible that the recent dramatic reduction of sea-ice extent was caused ultimately by the long-term thinning of the sea ice.

Chapter 2: IMPACTS OF SEA-ICE DECLINE ON THE OCEAN AND ATMOSPHERE

Sea ice is an important component of the climate system in high latitudes. It influences the radiation balance and the ocean – atmosphere exchanges of heat and water. The surface conditions affect the pathways and intensity of storms. The fresh water transport by the sea ice impacts the ocean circulation through its effect on the stability of the water column in downstream regions. The fresh water transport with the sea ice is also an important part of the fresh-water balance of the Arctic Ocean. Changes in the sea-ice properties will thus potentially have an impact on ocean and atmosphere circulations. Through the regulation of light transmission into the ocean, the provision of a distinct habitat and through its influence on the upwelling of nutrient-rich water, sea ice also has an effect on the biological productivity in the Arctic Ocean. In the following, we will focus on the effect of Arctic sea ice and especially the decline of sea-ice area and volume on the oceanic and atmospheric circulations.

Relative to its surface area, the Arctic Ocean receives a disproportionate amount of freshwater, mainly through river run-off and precipitation. In equilibrium, the Arctic Ocean exports as much freshwater as it receives from various sources. Main export pathways are through Fram Strait and the Canadian Arctic Archipelago. Freshwater is exported both as liquid freshwater and as sea ice. A recent assessment of the Arctic Ocean freshwater balance can be found in SERREZE et al. (2006). Climate model scenario calculations show declining sea-ice export for the 21st century. This implies a larger need for liquid freshwater export and an intermittent increase in freshwater storage in the Arctic Ocean (HOLLAND et al. 2006). A new equilibrium requires a stronger oceanic exchange between the Nordic Seas and the Arctic Ocean. This brings in more saline Atlantic water and can lead to more saline conditions in parts of the Eurasian Basin. The recent decline in thickness of the ice exported through Fram Strait has perhaps already impacted the sea-ice export from the Arctic Ocean. Hindcasts with the ocean – sea-ice model NAOSIM under realistic atmospheric forcing show a reduction of the sea-ice export through Fram Strait of around one third since the early 1990s (Fig. 1). The decline in sea-ice thickness by almost 50 % could not be wholly compensated by the simultaneous increase in sea-ice drift speed. However, the simulated decline in sea-ice export exceeds estimates based on observations (SPREEN et al. 2009).

Since the mid-1990s, liquid freshwater has been accumulating in the Beaufort Gyre while the Eurasian Basin freshwater

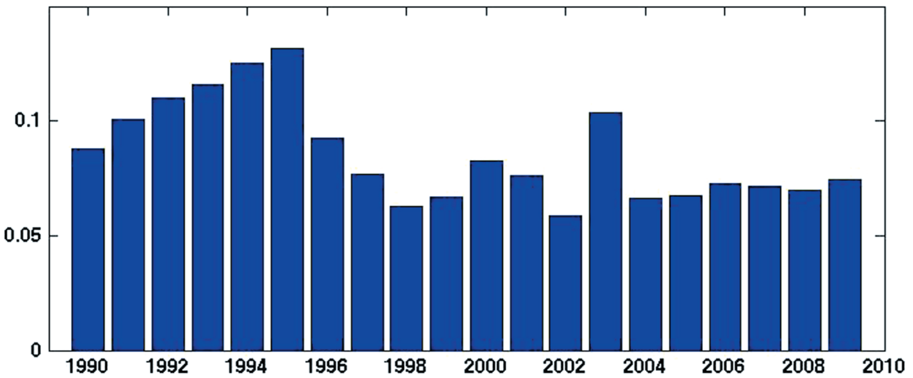

Fig. 1: Annual means (January through December) of sea-ice export from the Arctic Ocean as simulated in a NAOSIM hindcast for the period 1990–2009. The export is given as a volume flux in Sv ($10^6 m^3 sec^{-1}$).

Abb. 1: Jahresmittel (Januar bis Dezember) des Meereisexports aus dem Nordpolarmeer aus einer „hindcast“ Simulation von NAOSIM für den Zeitraum 1990–2009. Der Export ist als Volumenfluss in Sv ($10^6 m^3 sec^{-1}$) ausgedrückt.

content remained approximately constant (Fig. 2; RABE et al. in press). Model reanalysis exhibit large temporal changes in the Arctic Ocean freshwater content (KÖBERLE & GERDES 2007, GERDES et al. 2008, JAHN et al. 2010). GERDES et al. (2008) simulate a long-term decline from the late 1960s with intermittent maxima in the early and late 1980s as well as an increase since the late 1990s. The earlier fluctuations in liquid freshwater content were not associated with corresponding changes in the sea-ice export from the Arctic and were rather more directly driven by the wind stress. It remains an open question how strongly the recent changes in Arctic Ocean liquid freshwater content are connected to decreasing sea-ice export.

The effect of winter sea-ice concentration anomalies on the ocean-atmosphere heat exchange and the atmospheric circulation has been studied with a number of model experiments (among others ALEXANDER et al. 2004, MAGNUSDOTTIR et al. 2004). Sea-ice thickness changes can have a similar impact on the atmospheric circulation because smaller heat flux anomalies occur over much larger areas than those associated with the relatively small shifts in the position of the sea-ice edge in winter (GERDES 2006). Sea-ice thickness reduction in the central Arctic generated a positive NAO response in experiments with an atmospheric GCM. This suggested a positive feedback between the sea-ice state and the NAO as the sea-ice thickness reduction was thought of as a consequence of enhanced ice exports during strong positive NAO states (HILMER & JUNG 2000). However, the recent development was characterized by thin sea ice, negative NAO index, and low sea-ice export through Fram Strait.

The summer sea-ice extent anomalies of 2007 and 2008 represented a massive change in the lower boundary conditions for the atmosphere. Not only was the highly reflective snow and ice surface replaced by the dark ocean. The ocean mixed layer heated through the absorption of solar radiation and sea surface temperatures were 4 K higher than the long term mean in large areas of the Arctic Ocean. It is conceivable that such an anomaly has a significant impact on the atmospheric temperature and pressure distributions (FRANCIS et al. 2009, OVERLAND & WANG 2010). In nature, different effects are hard to distinguish. BLÜTHGEN (2009) applied the 2007 Arctic surface anomalies in the Arctic to an atmospheric general circulation model, which was integrated for more than 40 years to achieve a sufficiently large ensemble to eliminate internal variability unrelated to the change in boundary conditions. He found a warming of the lower atmosphere of several

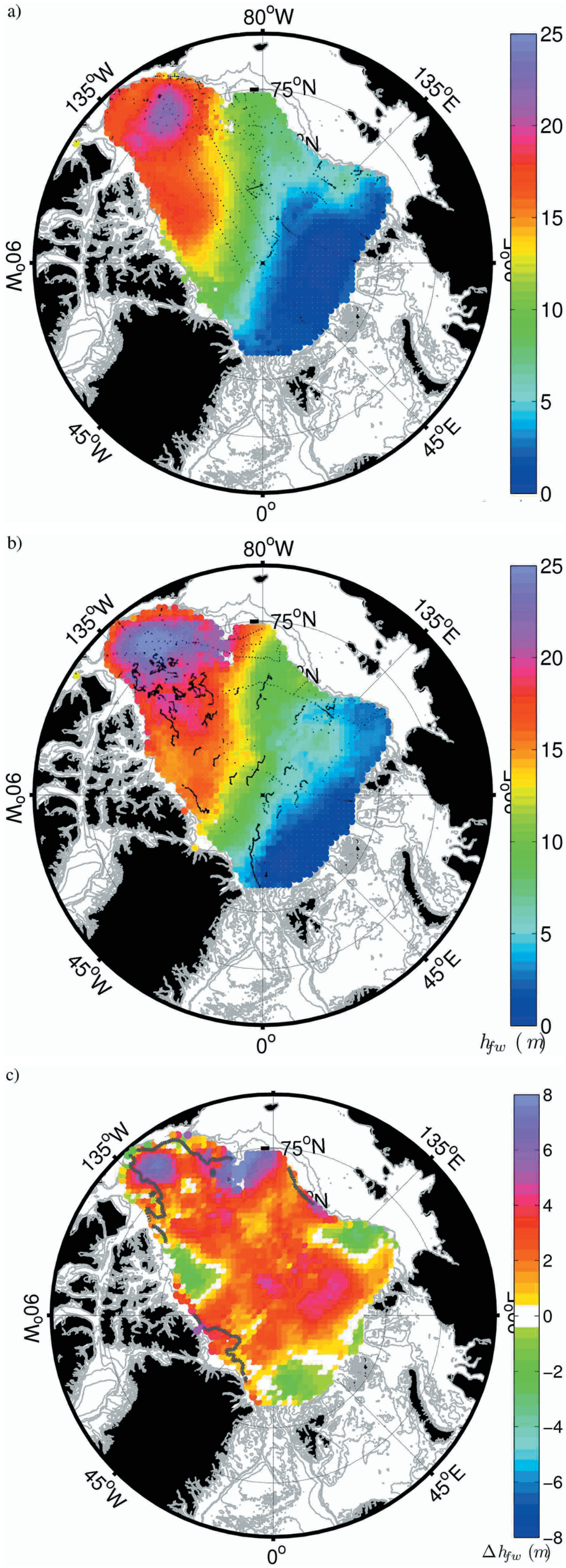

Fig. 2: Liquid freshwater inventory in the upper Arctic Ocean during July, August and September for the periods (a) 1992 to 1999 and (b) 2006 to 2008 derived from salinity observations. The inventory (unit metres) is the amount of freshwater per unit area above the 34-isohaline, which, combined with water of salinity 35, results in the observed salinity. The interpolation was performed through objective mapping. (c) Difference between the periods 2006-2008 and 1992-1999. The small black dots in (a) and (b) show the respective observation locations. After RABE et al. (in press).

Abb. 2: Süßwassergehalt im oberen Ozean bis zur 34-Isohaline aus Beobachtungen im zentralen Nordpolarmeer, interpoliert durch „objective mapping“ (a) für die Periode von 1992 bis 1999 und (b) für die Periode 2006 bis 2009. Der Süßwassergehalt ist bezogen auf einen Salzgehalt von 35. (c) Differenz des Süßwassergehalts zwischen beiden Perioden (spätere minus frühere). Die kleinen Punkte in (a) und (b) kennzeichnen die Positionen der Beobachtungen. Nach RABE et al. (im Druck).

degrees compared to the control experiment with climatological surface boundary conditions. A low-pressure system developed over northern Siberia and the eastern Arctic Ocean (Fig. 3). The low-pressure centre was accompanied by high-pressure anomalies over North America and the western Arctic Ocean. The latter signal, however, was not statistically significant. The response of the atmosphere thus was at least partially similar to the pressure pattern that persisted over the Arctic over several summer months in the record low sea-ice extent years. This is an indication of a possible positive dynamical feedback between atmospheric circulation and sea ice. Furthermore, due to the heat capacity of the oceanic mixed layer, the anomalous atmospheric state is more persistent and extends into the fall. In the numerical experiments, BLÜTHGEN (2009) could, however, not identify an effect lasting into the winter as has been conjecture based on correlations between observed fields (OVERLAND et al. 2010).

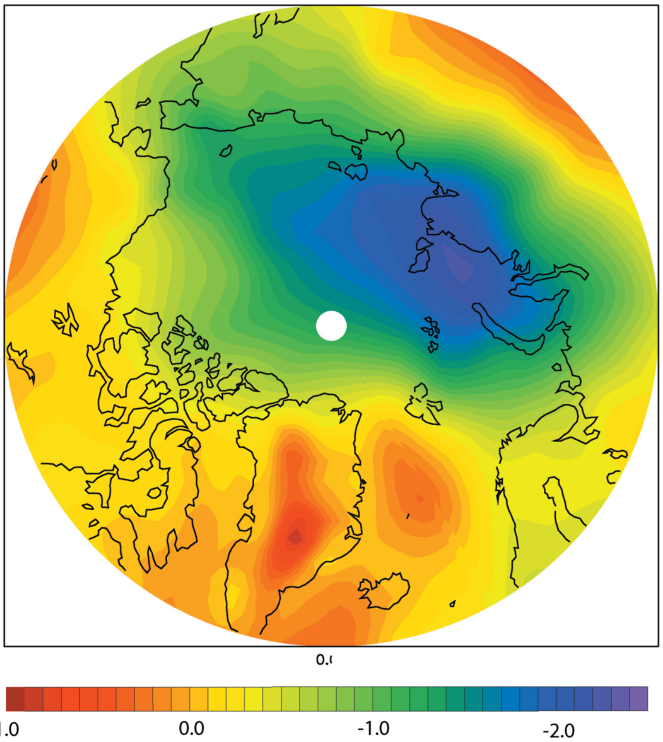

Fig. 3: Sea level pressure anomaly (hPa) in a numerical experiment where observed sea-ice concentration and sea surface temperatures for 2007 replace the climatological values as boundary conditions for the atmospheric general circulation model ECHAM5.

Abb. 3: Anomalie (in hPa) des Luftdrucks auf Meeresspiegelniveau in einem numerischen Experiment, in dem die beobachteten Meeresoberflächentemperaturen und Meereiskonzentrationen aus dem Jahr 2007 die klimatologischen Werte in den Randbedingungen des allgemeinen atmosphärischen Zirkulationsmodells ECHAM5 ersetzen.

Chapter 3: ROLE OF THE OCEAN IN ARCTIC SEA-ICE DECLINE

The Arctic Ocean takes part in the global ocean overturning circulation. It receives relatively warm and saline Atlantic Water near the surface and returns fresher and colder intermediate water to lower latitudes. The intermediate water leaves the Arctic Ocean through Fram Strait and is one of the main contributors to the overflow waters that cross the Greenland-Iceland-Scotland Ridge and form North Atlantic Deep Water. The Atlantic Water enters the Arctic Ocean through Fram Strait and the Barents Sea. Largest modifications of the Atlantic Water occur in the Barents Sea and in the immediate vicinity of Svalbard. Once a fresh layer has established at the surface through interaction with sea ice (RUDELS 1996) and further east through the input of the large freshwater supply from Siberian river runoff and from the Pacific, Atlantic Water in the Arctic is effectively isolated from the atmosphere. In the interior of the Arctic Ocean, the Atlantic Water occupies depths of 200 to 800 m. Further modification of Atlantic Water is possible through mixing with waters that were formed in the Barents Sea and in the Siberian shelf seas and that flow off the shelves into intermediate depths of the interior Arctic Ocean.

The temperature of the inflowing Atlantic Water varies with time. These variations are carried to the Arctic Ocean mostly by the branch that enters through Fram Strait. The Barents Sea branch looses much of any excess heat by interaction with the atmosphere within the Barents Sea region. Since 1997, the Norwegian Polar Institute and the Alfred Wegener Institute maintain a mooring array in Fram Strait that delivers temperature, salinity, and velocity time series at several locations within the West Spitzbergen Current (WSC). A time series for the mean temperature of the core of the WSC has been derived from the moorings and has been extended into the past using available hydrographic data (KARCHER et al. in press). This time series shows an increase by 1°C since around 1985 with shorter-term fluctuations superimposed (Fig. 4). Especially warm inflow periods occurred in the earlier 1990s and the first years of the 21st century. SCHAUER & BESZCZYNSKA-MÖLLER (2009) have calculated the heat transport of the Atlantic Water exchanged through Fram Strait. While the background heat transport is around 30 TW they find elevated heat transports of up to 50 TW between 2002 and 2007. This increased heat supply can either be balanced by increased loss to the atmosphere or lead to higher temperatures in the interior Arctic Ocean. More oceanic heat has been released to the atmosphere in the past decade north of Svalbard. This is the region where the Atlantic water currently subducts below the fresher Arctic waters and/or where salinity stratification is strongly increased by the freezing/ melting cycle. Further east and north the stratification dims the vertical exchange of water and thus of heat.

Since Atlantic Water has temperatures well above the freezing point when it enters the Arctic Ocean it is conceivable that it contributes to sea-ice melting. There is no doubt that the Atlantic Water is essential in pushing the sea-ice edge far north on the eastern side of the Nordic Seas, the Barents Sea, and north of Svalbard. However, due to its isolation from the sea ice in most parts of the Arctic Ocean by the 'cold halocline', its actual heat flux to the sea-ice away from the sea ice edge is very small. In numerical simulations, the Atlantic Water can be traced through the whole Arctic Ocean where modifications are only due to mixing with waters flowing from the shelves to intermediate depths (KARCHER et al. submitted). Available observations also show the spreading of the anomalously warm Atlantic Water throughout intermediate depth levels of the Arctic Ocean (POLYAKOV et al. 2005).

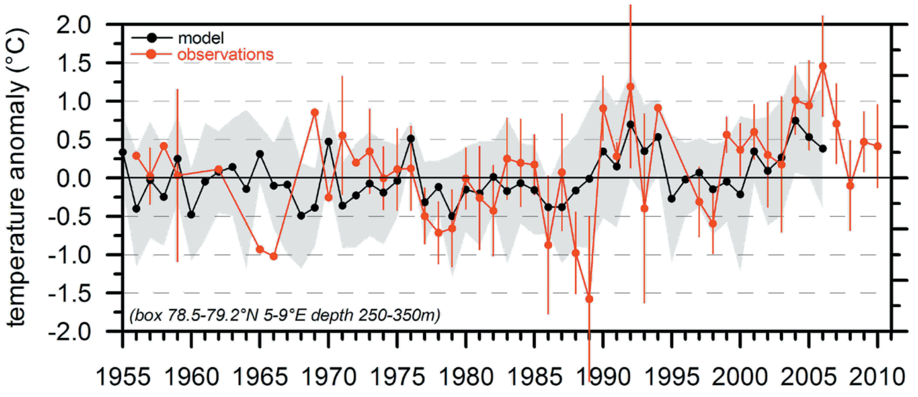

Fig. 4: Observed (red) and simulated by NAOSIM (black) temperature time series in the core of the West Spitzbergen Current (after KARCHER et al. in press)

Abb. 4: Beobachtete (rot) und von NAOSIM simulierte (schwarz) Zeitreihe der Temperatur im Kern des West-Spitzbergen-Stroms (nach KARCHER et al. im Druck).

Chapter 4: SUMMARY and OUTLOOK

Arctic sea ice is vanishing at an accelerating rate. Observational evidence includes a strong decreasing trend for the sea-ice extent of 11 % per decade and various indications of thinning sea ice. Thinner ice and comparatively small increases in sea-ice drift velocity imply a decreasing sea-ice export through Fram Strait. This is very well supported by ocean – sea-ice model hindcasts. The decreasing sea-ice export may have started to seriously affect the Arctic Ocean fresh water balance with consequences for oceanic circulation, sea level, and transport patterns of e.g. nutrients and contaminants. The impact on the subpolar seas has not yet been satisfactorily assessed. Retreating and thinning sea ice allows more solar radiation to be absorbed in the oceanic mixed layer. The stored heat is released to the atmosphere in fall and early winter with effects on the near surface temperature and the sea level pressure distribution. Positive feedbacks between sea ice and atmospheric circulation are possible with consequences for the climate in northern and central Europe.

Over the last ten years, Arctic sea ice has exhibited drastic changes with considerable impact on atmospheric and oceanic conditions. The impact on the biologic processes is not well known but it is conceivable that they also significant. The sea-ice changes of recent years are associated with certain developments in the atmosphere. One aspect is the increasing near surface air temperature that has surpassed the mid-century warming. We almost certainly see the combination of anthropogenic warming and the warm phase of the Atlantic multi-decadal oscillation. These effects have contributed strongly to the sea-ice decline. Besides an Arctic-wide temperature increase we observe the emergence of distinct surface pressure patterns that are likely to decrease the net-formation rate of sea ice within the Arctic Ocean. Both in winter and in summer, SLP is increasingly characterized by centres over northern Siberia and the Canadian Arctic. In winter, the Icelandic low seems to shift into the Barents Sea and even further east in recent years (ZHANG et al. 2009). In summer, persistent pressure dipoles over the Arctic increase meridional atmospheric flow with strong atmospheric heat transport to high latitudes. The SLP dipole also has dynamic consequences, in recent years a redistribution of sea ice from the eastern to the western Arctic. This effect made a strong contribution to dislocate the ice from the Eastern Arctic (KAUKER et al. 2009).

Open questions remain. Clearly, the oceanic mixed layer is an important storage medium for heat that prolongs the effects of the retreating sea ice on the atmosphere into late fall and perhaps early winter (OVERLAND & WANG 2010, FRANCIS et al. 2009). So far, the Atlantic Water and the increasing temperature of the Atlantic Water layer in the Arctic are of no consequence for the Arctic sea-ice volume. How will the Arctic cold halocline develop in the future? Will it thicken because of the increasing supply of fresh water from rivers and precipitation? Will it decrease at least in certain regions because of increasing exchanges between the Nordic Seas and the Arctic Ocean? Will this effect be strong enough to release substantial parts of the Atlantic Water layer heat content to the sea ice and thus accelerate its demise? Other open questions are related to the remaining amount of sea ice in the Arctic Ocean. Apparently, the sea-ice thickness decline has already affected the seasonal cycle of sea-ice extent with much lower sea-ice areas in summer. Will positive feedbacks, e.g. the interaction with the atmospheric circulation, finalize the demise of the multi-year sea ice in the Arctic? Will negative feedbacks, the higher thermodynamic growth rate from open ocean or regions covered with thin sea ice and the reduced ice export, allow the sea-ice volume to recover when atmospheric forcing is favourable? In this context, the development of the Atlantic multi-decadal oscillation is highly relevant. Will its current warm phase terminate quickly and thus allow stronger sea-ice growth? Will the current warm phase persist long enough that sea-ice volume will be reduced even more substantially and will this suffice that the Arctic will remain in a permanently low sea-ice state?

References

Alexander, M.A., Bhatt, U.S., Walsh, J.E., Timlin, M.S, Miller, J.S. & Scott, J.D. (2004): The atmospheric response to realistic Arctic sea-ice anomalies in an AGCM during winter.- J. Clim. 17: 890-905.
Blüthgen, J. (2009): The atmospheric response to the summer 2007 Arctic sea-ice extent minimum – simulations with the atmospheric circulation model ECHAM5.- B.Sc. thesis in Earth and Space Sciences, Jacobs University Bremen
Farrell, S.L., Laxon, S.W., McAdoo, D.C., Zwally, D.Yi & Zwally, H.J. (2009): Five years of Arctic sea-ice freeboard measurements from the Ice, Cloud and land Elevation Satellite.- J. Geophys. Res. 114, C04008, doi:10.1029/2008JC005074.
Fetterer, F., Knowles, K., Meier, W. & Savoie, M. (2002, updated 2009): Sea Ice Index. Boulder, CO: National Snow and Ice Data Center. Digital media.
Francis, J.A., Chan, W., Leathers, D.J., Miller, J.R. & Veron, D.E (2009): Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent.- Geophys. Res. Lett., doi 10.1029/2009GL037274.
Gerdes, R. (2006): Atmospheric response to changes in Arctic sea-ice thickness.- Geophys. Res. Lett. 33, L18709, doi:10.1029/2006GL027146.

Gerdes , R. & Köberle, C. (2007): Comparison of Arctic sea-ice thickness variability in IPCC Climate of the 20th Century experiments and in ocean – sea-ice hindcasts.- J. Geophys. Res. 112, C04S13, doi: 10.1029/2006JC003616.

Gerdes, R., Karcher, M., Köberle, C. & Fieg, K. (2008): Simulating the long term variability of liquid freshwater export from the Arctic Ocean, Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate.- In: B. Dickson, J. Meincke & P. Rhines (eds), Springer, 405-425.

Haas, C. & Eicken, H. (2001): Interannual variability of sea-ice thickness in the Siberian and central Arctic under different atmospheric circulation regimes. – J. Geophys. Res. 106: 4449-4462.

Haas , C., Pfaffling, A., Hendricks, S., Rabenstein, L., Etienne. J.-L. & Rigor. I. (2008): Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat.- Geophys. Res. Lett. 35, L17501, doi: 10.1029/2008GL034457.

Haas, C., Hendricks, S., Eicken, H. & Herber, A. (2010): Synoptic airborne thickness surveys reveal state of Arctic sea-ice cover.- Geophys. Res. Lett. 37, L09501, doi:10.1029/2010GL042652.

Hilmer, M. & Jung, T. (2000): Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea-ice.- Geophys. Res. Lett. 27(7): 989-992.

Holland, M.M., Finnis, J. & Serreze, M.C. (2006): Simulated Arctic Ocean freshwater budgets in the 20th and 21st centuries.- J. Clim. 19: 6221-6242.

Karcher, M., Beszczynska-Möller, A., Kauker, F., Gerdes, R., Heyen, S., Rudels, B. & Schauer, U. (in press): On Consequences of Arctic Ocean Warming for the Denmark Strait Overflow, J. Geophys. Res.

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, 3182, doi:10.1029/2002JC001573.

Kauker, F., Kaminski, T., Karcher, M., Giering, R., Gerdes, R. & Voßbeck, M. (2009): Adjoint analysis of the 2007 all time Arctic sea-ice minimum.- Geophys. Res. Lett. 36, L03707,doi: 10.1029/2008GL036323.

Köberle, C. & Gerdes, R. (2003): Mechanisms determining the variability of Arctic sea-ice conditions and export.- J. Clim. 16: 2843-2858.

Kwok, R. (2004): Annual cycles of multiyear sea-ice coverage of the Arctic Ocean: 1999–2003.- J. Geophys. Res. 109, C11004, doi: 10.1029/2003JC002238.

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

Magnusdottir, G., Deser, C. & Saravanan, R. (2004): The effects of North Atlantic SST and sea-ice anomalies on the winter circulation in CCM3: Part I. Main features and storm track characteristics of the response.- J. Clim. 17: 857-876.

Maslanik, J.A., Fowler, C., Stroeve, J., Drobot, S., Zwally, H.J., Zwally, D.Yi. & Emery, W. (2007): A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss.- Geophys. Res. Lett. 34, L24501, doi:10.1029/2007GL032043.

Overland, J.E. & Wang, M. (2010): Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea-ice.- Tellus 62A: 1-9.

Polyakov, I.V. (2005): One more step toward a warmer Arctic.- Geophys. Res. Lett. 32, doi:10.1029/2005GL023740.

Rabe, B., Karcher, M., Schauer, U, Krishfield, R., Toole, J., Pisarev, S., Gerdes, R., Kauker, F. & Kikuchi, T. (in press): An assessment of pan-Arctic Ocean freshwater content changes from the 1990s to the IPY period.- Deep-Sea Res. I.

Rothrock, D.A., Maykut, Y.Yu, & Maykut, G.A. (1999): Thinning of the Arctic sea_ice cover.- Geophys. Res. Lett. 26(23): 3469-3472.

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

Schauer, U. & Beszczynska-Möller, A. (2009): Problems with estimation and interpretation of oceanic heat transport – conceptual remarks for the case of Fram Strait in the Arctic Ocean.- Ocean Sci. 5: 487-494.

Serreze, M.C., Barret, A.P., Slater, A.G., Woodgate, R.A., Aagaard, K., R. Lammers, B., Steele, M., Moritz, R., Meredith, M. & Lee, C.M. (2006): The large-scale freshwater cycle of the Arctic.- J. Geophys. Res. 111, C11010, doi:10.1029/2005JC003424.

Spreen, G., Kern, S., Stammer, D. & Hansen, E. (2009), Fram Strait sea-ice volume export estimated between 2003 and 2008 from satellite data.- Geophys. Res. Lett. 36, L19502, doi:10.1029/2009GL039591.

Zhang , X., A. 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, L22701, doi: 10.1029/2008GL035607.