# Impact of sea ice

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## 1. Introduction

The recent dramatic decline in summer sea ice extent in the Arctic Ocean has underlined the variability and the potential impact of sea ice variability on climate and weather in northern Europe and the Arctic itself. There are already apparent impacts of the retreating sea ice on Arctic marine ecosystems and human populations in the high north (ACIA, 2005).

Sea ice extent is a very variable indicator of Arctic changes. Year-to-year variability in the record of satellite observations is high compared to the long term trend. During the period of satellite observations, the year with the largest minimum ice extent was as recent as 1996. Sea ice extent increased from the 1995 value by almost 2 million km$^2$, an area that rivals the record reduction from the summer of 2006 to the summer of 2007. The increase in 1996 was due to a persistent low pressure anomaly over the central Arctic Ocean in July and August. Sea ice motion was out of the low pressure anomaly and sea ice stored in the central Arctic Ocean was distributed over the whole Arctic Ocean (Haas and Eicken, 2001). On the other hand, the dramatic decline in 2007 was at least in part forced by a persistent SLP distribution with a high pressure center over northern Canada and a low pressure center over Siberia. This pressure distribution was responsible for a large atmospheric heat transport from the North Pacific into the Arctic. It might also have triggered an increased flow of warm Pacific near surface waters into the Chukchi Sea and further over the Chukchi Cap and into the Beaufort Sea. Furthermore, the meridional winds from the Pacific to the Atlantic sector of the Arctic Ocean contributed to sea ice drift from the eastern into the western Arctic.

Thus, two pronounced anomalies in the Arctic sea ice cover were triggered by persistent anomalous atmospheric pressure distributions over the Arctic. May the decline in 2007 thus be viewed as a one-time event forced by a freak event in atmospheric circulation? Anyway, Arctic sea ice cover seems very much governed by atmospheric forcing. The feedbacks of the Arctic sea ice conditions onto the atmospheric circulation are less clear, especially for the summer months.

Here, I shall discuss the long term, large scale interactions between sea ice and atmosphere as they appear in coupled climate models and in stand-alone AGCMs or ocean-sea ice hindcasts. The second part of the abstract indicates sea ice processes that could be important for local to regional scales and relatively short term changes.

## 2. Role of forcing fields and initial conditions on the Arctic sea ice extent

At first sight, Arctic sea ice appears as a slave to atmospheric forcing. A more detailed analysis reveals that preconditioning, especially through the sea ice volume at the end of winter, is also an important factor. Thus, long term trends in sea ice formation and export from the Arctic become important for the sea ice development over the next several months.

To determine the sensitivity of the September 2007 sea ice extent on initial and boundary conditions, Kauker et al. (GRL, in press) have computed adjoint sensitivities for the NAOSIM (Karcher et al., 2003, Gerdes et al., 2005) ocean-sea ice model. Initializing the model with March 2007 results from a forward integration, four fields emerge as most important for the September 2007 sea ice extent. Among them is the September surface air temperature. However, the other most important fields are the wind stress in May and June as well as the initial March sea ice thickness. At the end of June, two-thirds of the difference between minimum ice extents in 2005 and 2007 were already determined. The importance of the early wind stress fields and of the initial condition hint at sea ice thickness being the single most important dynamic variable governing the development of sea ice cover until the late summer minimum.

In a probabilistic forecast of the sea ice extent minimum in 2008, Kauker et al. (2008, see 10_kauker_june_outlook.pdf under http://www.arcus.org/search/seaiceoutlook/downloads/monthly-reports/june/) have run NAOSIM with forcing from the 20 most recent summers, starting from June and July hindcasts for 2008. Although the extreme forcing of summer 1996 was included, the large sea ice extent of 1996 was not reproduced. This hints at the role of preconditioning of the minimum sea ice extent in September by the conditions in spring or early summer. Again, the sea ice thickness distribution in the Arctic and the total ice volume seemed to be especially important. In early summer 2008 there was apparently not enough sea ice left to be distributed over the whole Arctic Ocean by the extreme 1996 forcing.

## 3. Impact of sea ice anomalies on the large scale atmospheric circulation

The impact of sea ice extent anomalies on the atmospheric circulation has been investigated in a number of publications (Alexander et al., 2004; Magnusdottir et al., 2004). Sea ice extent anomalies associated with the positive phase of the NAO (large ice cover in the Labrador Sea, low sea ice cover in the Nordic Seas and the Barents Sea) seem to induce a response in sea level pressure that projects negatively on the NAO pattern. In these studies, SST anomalies in the northern North Atlantic are more important and can lead to a positive feedback with the NAO.

Given the importance of sea ice thickness for the sea ice extent development, it is interesting to determine the impact of sea ice thickness anomalies on the atmospheric circulation. Gerdes (2006) compared a control run and an experiment with sea ice thickness anomalies taken from an ocean-sea ice hindcast (Fig.1). The anomalies were chosen to represent maximum sea ice thickness conditions (mid-1960s) and relatively low sea ice thickness conditions (mid-1990s, after the ice export event of the winter 1994/95). These anomalies can also be thought of as NAO-related. The mid-1960s maximum was associated with relatively high atmospheric pressure over the central Arctic. The mid-1990s ice export event was related to favorable winds in Fram Strait associated with the strongly positive phase of the NAO. The atmospheric response to the sea ice anomalies consisted of a large scale circulation anomaly, consistent with an enhancement of the positive NAO phase. The response was not restricted to the near surface but also clearly significant at 500 hPa. Because of the large internal variability of the high northern latitude atmosphere, the response to the sea ice forcing was not apparent in each year of the ensemble, even sub-ensembles of 10 years each did not necessarily show the full ensemble mean response. The atmospheric reaction was strongly shaped by the sea ice thickness anomaly. Another experiment where only sea ice concentration anomalies were prescribed yielded a completely different response, consistent with the earlier experiments of Alexander et al. (2004).

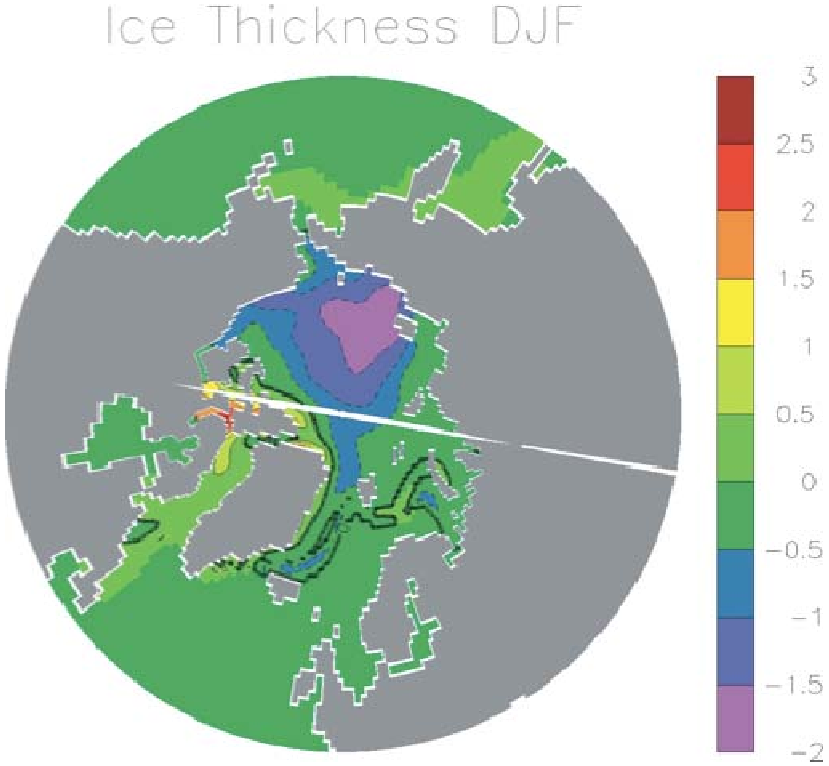


*Figure 1. Sea ice thickness anomaly used in the AGCM simulations of Gerdes (2006).*

Zhang et al. (2008) describe a shift of the SLP centers of action in recent years. While the Arctic Oscillation constitutes the dominant pattern until the end of the 20th century, a new pattern with centers over Siberia and northern Canada dominates the early years of this century. The shift involves an eastward migration of the former Icelandic low, a process that has been described previously (e.g. Zhang et al., 2004) and has been associated with reduced sea ice cover over the Russian shelf seas and larger ocean-atmosphere heat fluxes there. Thus, it is conceivable that the pattern identified by Zhang et al. (Arctic Rapid Change Pattern, ARP) is a response to declining winter sea ice cover in the eastern Arctic. This is especially interesting because the ARP is associated with large atmospheric, and presumably also oceanic, heat transports from lower latitudes into the Arctic. A strong ARP would lead to strong reductions in Arctic sea ice which could reinforce the ARP according to the above mechanism. This positive feedback could play a role in the recent decline of sea ice in the Arctic. This feedback is probably not well captured by climate models because of deficiencies in atmospheric boundary layer representation and a general lack of atmospheric variability in high northern latitudes.

Rinke et al. (2006) compare simulations with the regional AGCM HIRHAM for different sea ice boundary conditions. In experiment A, sea ice concentration and SST are taken from the ERA15 reanalysis while sea ice thickness is assumed to be constant. In experiment B, sea ice conditions and SST are taken from a hindcast simulation with an ocean-sea ice model forced with ERA15. The main difference between the two bottom boundary conditions is the variable sea ice thickness in the ocean-sea ice model result. The near-surface air temperature response shows a strong, seasonally dependent sensitivity to sea ice changes. The response is small in summer but significant in winter. The direct thermodynamic response in winter is limited to below about 800hPa. The specification of the winter marginal sea ice zone is important for the simulation of regional circulation patterns and atmospheric temperature profiles. During summer the direct thermodynamic effect of sea ice changes is small, while the dynamic response is still important. The authors recommend that atmospheric simulations specify the SST/sea ice fraction and the spatial distribution of sea ice thickness realistically, especially in winter.

So far, most of the studies were concerned with the impact of winter sea ice anomalies. Since atmospheric variability in summer does not include such pronounced patterns as the AO or the ARP, there was little incentive to investigate possible feedback mechanisms involving summer conditions. However, the recent large sea ice extent anomalies and strong summer SST changes demand more attention. A recent study has been undertaken by Balmaseda et al. and is described in this volume.

As pointed out above, sea ice thickness anomalies can have an impact on the large scale atmospheric circulation that is comparable to that of observed (winter) sea ice extent anomalies. There are indications that sea ice volume has declined since the mid-1960s (Rothrock et al., 1999) and there are regional studies that show sea ice volume decline north of Fram Strait (Wadhams et al., 2000; Haas et al., 2008). Unfortunately, these sea ice thickness measurements only cover a small part of the Arctic Ocean and impact assessments based on these observations is not yet feasible.

In the context of the strong sea ice extent decline in 2007 it remains to be seen how much sea ice volume was left. The winds over a long period of summer 2007 pushed sea ice from the eastern to the western Arctic. Thus, model simulations show an accumulation of sea ice in the Canadian Basin. Is most of the sea ice volume still present in the Arctic Ocean and could thus be distributed over most of the Arctic Ocean should a favorable wind pattern persist for a long period in the summer? This was apparently the case in 1996 when a persistent low pressure anomaly over central parts of the Arctic Ocean replenished the sea ice cover that was previously reduced by a large sea ice export event in the winter 1994/95 (Vinje, 2001). The failure of simulations to recover the large ice extent with 1996 forcing starting from early 2008 initial conditions, the reduction in multi-year ice cover, and the relatively unrestricted movement of sea ice in parts of the western Arctic are indications that sea ice volume has recently been reduced and is no longer available to quickly regain large sea ice covers in the Arctic.

## 4. Surface properties of sea ice and their impact on vertical heat and momentum fluxes

Arctic cold air outbreaks are characterized by the strong organized roll convection over the open ocean and by large fluxes of sensible heat. As cold polar air reaches the open ocean, it is heated from below and a convective boundary layer forms. The boundary layer is very shallow immediately behind the ice edge, and the depth increases with increasing distance from the ice edge due to the input of heat from below.

Cold air outbreaks affect large areas of Europe and the North Atlantic. Compared to conditions immediately before a cold air outbreak, Wacker et al. (2005) showed that ocean-atmosphere heat fluxes over most parts of the Nordic Seas increased by typically $100 Wm^{-2}$ five days into a cold air outbreak. The properties of the advected air depend on the upstream conditions and thus on the properties of sea ice in the Arctic Ocean.

Surface heat and momentum fluxes over sea ice depend on the thickness and concentration of sea ice, its surface roughness, the albedo which in turn depends on the presence of snow and sediment, and the presence of melt ponds, and the orientation of leads relative to the prevailing wind direction. Melt ponds, snow cover, and ice thickness also affect the heat capacity of the ice. The roughness is a function of the age and the history of the ice. Leads and surface roughness reflect the forcing by wind and oceanic stresses. Only a few of these processes have been parameterized in sea ice models and have been tested in comprehensive coupled models of the Arctic. An example of the sensitivity of a regional climate model to parameterizations for lateral freezing and temperature dependence of the sea ice albedo is given in Dorn et al. (2007). They conclude that coupled models need improved descriptions for Arctic clouds, snow, and sea-ice albedo, and lateral freezing and melting of sea ice, including the treatment of snow to reduce existing model biases.

Rinke and Saha (2005, private communication) show pronounced differences in surface air temperature and sea level pressure between two versions of the regional climate model HIRHAM. The versions differ in the parameterization of atmospheric drag based on sea ice surface roughness in the marginal sea ice zone. A new parameterization takes into account the ridges at the edges of ice flows that are shaped by freezing and frequent collisions of floes in the marginal ice zone. SAT differences are mostly present in the marginal ice zone itself. SLP, however, shows clear differences that are on a much larger spatial scale than the SAT differences.

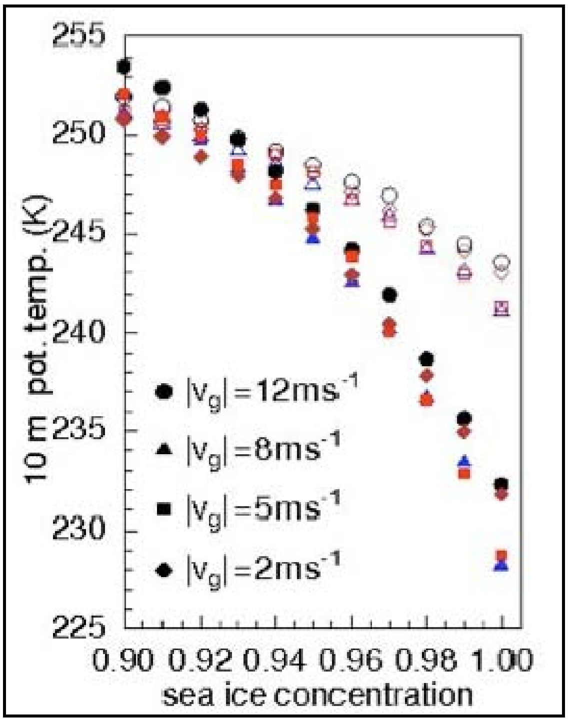


*Figure 2. Boundary layer temperature as a function of sea ice concentration and wind speed. Open symbols show result after 12 hours and solid symbols show temperatures after 2 days (modified from Lüpkes et al., 2008a).*

A good representation of the processes that govern the surface energy budget is essential for climate and weather prediction models. Perhaps the most important sea ice related factor in this context is the presence of leads, small, elongated areas of open ocean or very thin ice that exist even in winter. Upward sensible and latent heat fluxes are much enhanced over leads. A good satellite picture of sea ice with leads can be found in Lüpkes et al. (2008a). Because of the large temperature differences between freezing at the lead surface and the surface of the surrounding ice, strong turbulent convection is generated over the leads. Flow of stably or neutrally stratified air from ice cover over a lead results in enhanced convection over the lead and a modification of the atmospheric boundary layer downstream of the lead. A number of publications regarding the role of leads in the Arctic boundary layer have been published by the AWI group around Christof Lüpkes. The recent article by Lüpkes et al. (2008a) provides an overview over published results and a new parameterization of the convection over leads. Lüpkes et al. (2008b) discuss the effect of leads on the atmospheric boundary temperatures and stratification. The results demonstrate that small changes in sea ice concentration have a strong effect on the near-surface temperature. At concentrations above 90% a change by 1% causes a temperature change of 1 to 3.5K. In the example given by Lüpkes et al. (2008a) of a 1 km wide lead and wind perpendicular to the lead direction the surface heat flux from a single lead amounted to 180Wm$^{-2}$. The effect on the atmospheric boundary layer temperature was a few tenth of a degree and the lead contributed to stabilizing of the boundary layer.

Based on observations in Fram Strait and high-resolution modeling, Dierer et al. (2005) describe the influence of the sea ice edge on the formation and pathway of polar lows. Cyclogenesis is strongly affected by the temperature contrast between ocean and sea ice cover areas. The pathway of cyclones tends to follow the sea ice edge. Surface properties of sea ice, especially surface roughness and thus the form drag are important for the momentum exchange between cyclones and sea ice, affecting both the development of the cyclones and sea ice drift and concentration.

## 5. Summary

Sea ice affects atmospheric conditions over a large range of spatial and temporal scales. Persistent sea ice extent and sea ice thickness anomalies can modify the large scale atmospheric flows that are associated with the Arctic Oscillation. Sea ice conditions can change the paths of cyclones and perhaps lead to a shift of the dominant pattern of high northern latitude sea level pressure anomalies. Cold air outbreaks affect atmospheric conditions over large latitude ranges and depend themselves on the upstream sea ice conditions. Locally, sea ice conditions like thickness, concentration, snow cover, roughness, and albedo affect the atmospheric boundary layer in various ways. Thus, sea ice properties beyond sea ice concentration need to be taken into account for a proper forecast over days to months and seasons. The most important quantities seem to be sea ice thickness and the presence, orientation, and frequency of leads because these immediately affect the larger scale atmospheric flow and temperature.

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