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The Complex Interplay of Atmosphere and Sea Ice in the Arctic*

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Abstract: There are various complex interactions between atmosphere and sea ice in the Arctic. The changing atmospheric circulation is one of the main drivers for Arctic sea ice changes. Decadal changes in the large-scale circulation, like different North Atlantic Oscillation (NAO) phases, cause changes in the large-scale Arctic sea-ice drift and thus changes in sea-ice concentration and thickness. A general atmospheric warming/cooling contributes to a mean decrease/increase in sea-ice concentration and thickness. The atmosphere also exerts a distinctive control on the sea-ice cover on the yearly time scale. Changes in sea ice impact the atmosphere via changed heat, momentum, and humidity fluxes. In consequence, both the regional Arctic and the global atmospheric circulations alter. This includes feedbacks to large-scale teleconnection patterns like the NAO.

Zusammenfassung: Es gibt eine Vielzahl von komplexen Wechselwirkungen zwischen der Atmosphäre und dem Meereis in der Arktis. Die sich verändernde atmosphärische Zirkulation ist einer der Haupteinflussfaktoren für arktische Meereisveränderungen. Änderungen in der großskaligen Zirkulation auf der dekadischen Zeitskala, wie verschiedene Phasen der Nordatlantischen Oszillation (NAO), bedingen Änderungen in der großskaligen Meereisdrift und damit Änderungen in der arktischen Meereiskonzentration und -dicke. Eine langfristige Erwärmung/Abkühlung der Atmosphäre bewirkt eine mittlere Verringerung/Zunahme der Meereiskonzentration und -dicke. Die Atmosphäre hat auch einen prägnanten Einfluss auf das Meereis auf der kürzeren, jährlichen Zeitskala. Änderungen im Meereis beeinflussen die Atmosphäre durch geänderte Wärme-, Impuls- und Feuchteflüsse. Als Folge dieser Prozesse ändert sich sowohl die regionale arktische als auch die globale atmosphärische Zirkulation. Dies beinhaltet Rückkopplungen auf die großskaligen Telekonnektionsmuster wie die NAO.

INTRODUCTION

Pronounced natural variability in the Arctic climate complicates the detection and attribution of climate changes. Climate model projections estimate that the warming of the near-surface air temperature in the Arctic at the end of the 21st century is twice as much as globally (IPCC 2007). However, the temperature changes in the Arctic are neither spatially nor temporally uniform (Rinke & Dethloff 2008). Feedback processes where sea ice is involved in, like the ice-albedo feedback, play an important role in the Arctic climate system and are mainly responsible for the amplification of temperature changes. Furthermore, sea ice controls the exchange of heat, humidity, and momentum between the atmosphere and the ocean. Consequently, sea ice exerts a strong influence on the atmosphere. A realistic description of the sea ice and its interaction with the atmosphere in climate models is important for reliable simulations of the present and future Arctic climate.

Sets of century and multi-decadal long observational data of near-surface air temperature and sea-ice extent in the Arctic indicate variations on the decadal and multi-decadal time scales (Johannessen et al. 2004). Two pronounced warm periods, one from the mid-1920s to the 1940s and a second starting in the 1980s, were associated with substantial sea-ice reduction. Correspondingly, an expanded sea-ice cover was observed in the cold period of the 1960s. Thus, the variability of the Arctic air temperature is closely connected with the variability of the sea-ice cover.

The Arctic sea-ice changes in the last 30 years were pronounced (IPCC 2007). The most drastic ice reduction is observed in the summertime. The summer sea-ice extent has been reduced by 11 % per decade since the end of the 1970s (Comiso et al. 2008). The reduction can be explained by thermal and dynamical factors (Köberle & Gerdes 2003), both naturally and anthropogenically caused (Serreze et al. 2007). Important thermal factors are the freeze and melt processes, mainly determined by changing atmospheric and oceanic temperatures and the ice-albedo feedback. The dynamical factors include the changes of the atmospheric and oceanic circulations. Separating the respective contribution of all these factors is a key towards a better understanding of the sea-ice variability and reliable estimates of future sea-ice changes.

The article provides a short insight into some of the complex links between the atmosphere and sea ice in the Arctic, particularly from a modelling perspective.

INFLUENCE OF THE ATMOSPHERE ON SEA-ICE

The changing atmospheric circulation is a main cause for sea-ice changes. Thereby, the phenomenon of the North Atlantic Oscillation (NAO) plays a particular role. The NAO describes the variations of the surface air-pressure difference between the Icelandic Low and the Azores High (Thompson & Wallace 1998). The positive/negative phase of the NAO is characterized by an intensified/weakened pressure difference over the North Atlantic associated with strong/weak westerly winds over the North Atlantic. The NAO shows a strong decadal variability. From the 1980s to the mid-1990s, the atmosphere showed predominantly a positive NAO phase. This shift towards the positive NAO phase implicated changes in the surface ocean currents and large-scale sea-ice drift (Fig.

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1). The Beaufort gyre has been shifted and weakened, and the transpolar ice drift appeared in a more cyclonic path (MARTIN & GERDES 2007). This was associated with a stronger sea-ice export, particularly from the Siberian Arctic and Beaufort Sea, out of the Arctic to the North Atlantic. This sequence of dynamical processes resulted in an increased export of thick multi-year sea ice, and contributed to a transition towards thinner, younger sea ice, which is more vulnerable. This has been discussed as one key factor, besides the general warming of the atmosphere and ocean, for an accelerated sea-ice reduction (OVERLAND & WANG 2010).

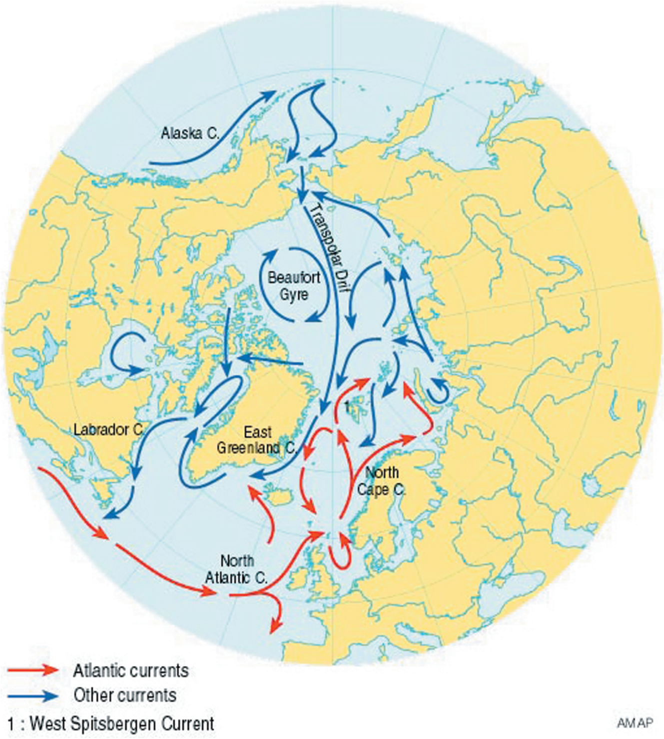

Fig. 1: Surface ocean currents in the Arctic (from AMAP 1998, Fig. 2.20).

Abb. 1: Oberflächennahe Ozeanströmungen in der Arktis (aus AMAP 1998, Abb. 2.20)

The impact of the atmosphere on sea ice is also distinctive on shorter time scales. The year-to-year variability of sea-ice extent is mainly driven by the atmospheric circulation. This can exemplarily be illustrated by comparing two years of extremely large and small summer sea-ice extent within the last 15 years, namely 1996 and 2007. Figure 2 presents the atmospheric conditions in summer of both years based on NCEP/ NCAR reanalysis data (KALNAY et al. 1996). The atmospheric circulation in summer 1996 was characterized by a deep low-pressure system over the central Arctic, associated with ~3 ˚C lower temperatures than normal. Therewith, the Arctic was characterized by a strong cyclonic regime in the sea-ice circulation and small ice export (HAAS & EICKEN 2001). All this contributed to a large summer sea-ice extent of 7.9 Mio. km^2 (~1 Mio. km^2 more than the climatological mean). In contrast, in summer 2007, the minimal (until now) sea-ice extent of 4.3 Mio. km^2 has been observed. The main driver for this ice loss was the unusual atmospheric circulation pattern characterized by a persistent high over the central Arctic Ocean and pronounced low pressure over Siberia. The resulting wind pumped warm air (and water) into the Arctic. This advection and the local atmosphere – ocean fluxes contributed to a ~6 ˚C warmer Arctic which enhanced the ice melting. The cloudless sky under the high pressure conditions supported the strong melt, and the smaller albedo of the thin sea ice (PEROVICH 1996) set the ice-albedo feedback into operation with the result of further ice reduction.

RESPONSE OF THE ATMOSPHERE TO SEA-ICE CHANGES

Changes in the sea-ice cover have direct local thermal and associated dynamical effects on the atmosphere (RINKE et al. 2006, GERDES 2006), particularly in winter when the water and air temperatures differ largely. If open water areas (polynias, leads) form in the cold seasons then the heat loss of the ocean changes dramatically and causes corresponding changes in the near-surface temperature and atmospheric circulation (LÜPKES et al. 2008). Changes in Arctic sea ice show also a large-scale response in the atmosphere due to modified storm tracks and changed planetary waves. To understand how sea-ice changes affect the atmosphere regionally and globally, and to elaborate the associated feedback mechanisms, sensitivity experiments with climate models are helpful.

Response to changes of sea-ice extent and thickness in an atmospheric global model

GERDES (2006) investigated in a model experiment how the observed overall sea-ice changes (sea-ice concentration and thickness) affect the atmosphere in winter. The atmospheric global model GFDL AM2 was run over 40 years, where different composite seasonal cycles of sea-ice conditions were prescribed together with a climatological seasonal cycle for sea-surface temperature. More concretely, the atmospheric model was driven by sea-ice conditions of the 1960s and the 1990s, which represent extreme cases of sea-ice volume during the last 50 years of the 20^{th} century. The 1960s were characterized by lower temperatures and accumulation of sea ice in the Arctic, while the 1990s were warmer and showed reduced sea-ice volume, compared to the climatological mean conditions. Both periods differed also in their NAO phase. In the 1960s and 1990s, mainly the negative and positive NAO phase, respectively, was observed.

The atmospheric response to the overall sea-ice changes indicates a circulation pattern characterized by a dipole of low pressure over the central Arctic and high pressure over sub-polar and sub-tropical regions, particularly over the North Pacific and North Atlantic (Fig. 3). This pattern has similarity with the NAO pattern in its positive phase, although one could rather recognize the positive phase of the Arctic Oscillation (AO) because of the hemispheric character of the pattern. This result indicates a positive atmosphere – sea-ice feedback: a positive NAO phase (like in the 1990s) contributes to a strengthened sea-ice export and associated sea-ice volume anomalies, which on their part account for air pressure anomalies which favour the positive NAO phase.

Further model experiments, which investigated the separate impact of changes in sea ice concentration and thickness on the atmospheric circulation showed that both sea-level pres-

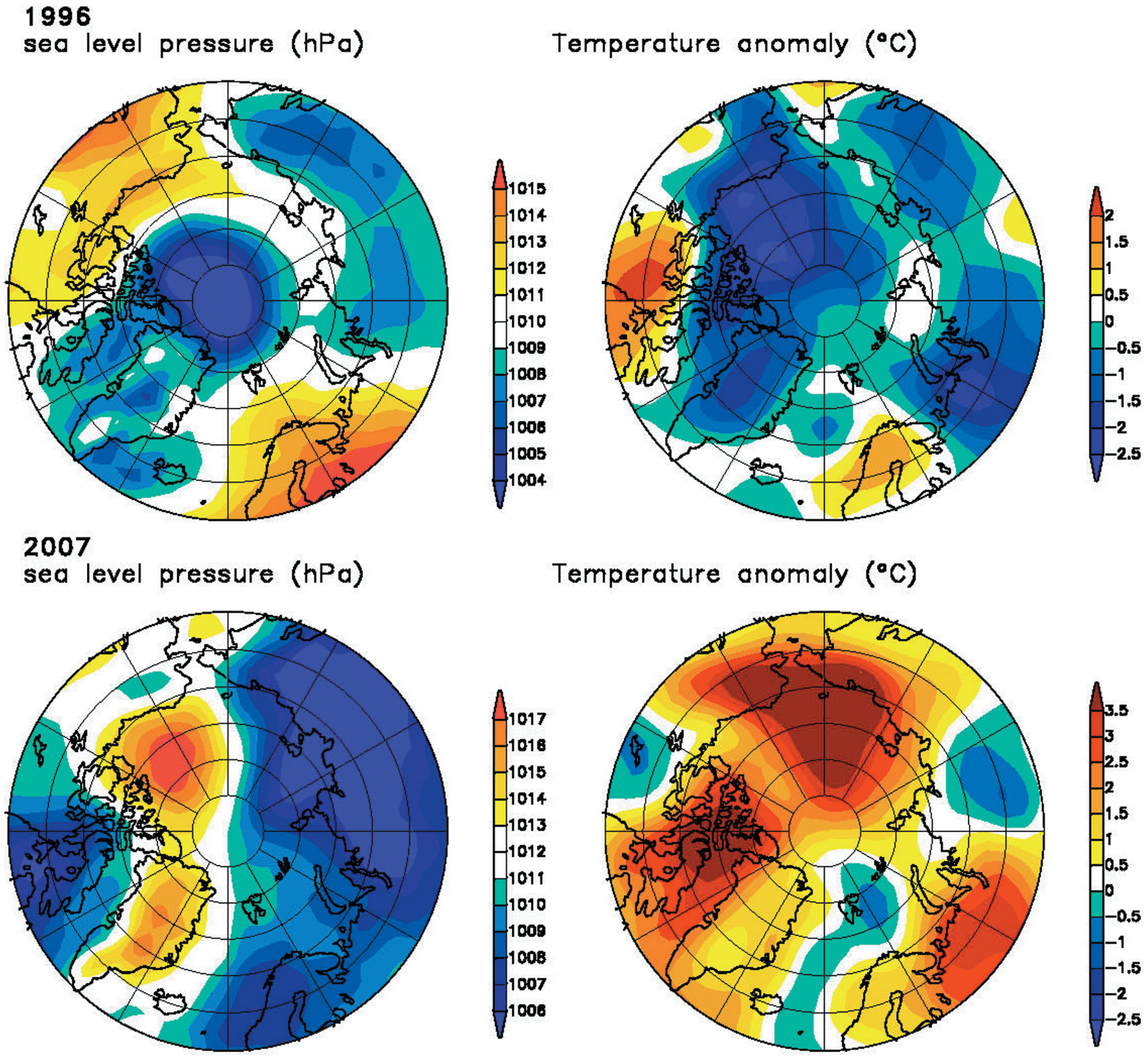

Fig. 2: Atmospheric conditions in summer (July-August) 1996 and 2007. Sea level pressure (hPa) and 925-hPa temperature anomaly (reference period 1948-2008). (˚C), based on NCEP/NCAR reanalysis.

Abb. 2: Atmosphärische Bedingungen im Sommer (Juli-August) von 1996 und 2007. Bodenluftdruck (hPa) und 925-hPa Temperaturanomalie (Referenzperiode 1948-2008) (˚C), basierend auf den NCEP/NCAR Reanalysen.

sure changes have a similar magnitude, but constitute a different phase of NAO (GERDES 2006). The atmospheric response to sea-ice concentration changes shows a negative NAO signal, indicating a negative atmosphere – sea-ice feedback: A positive NAO phase is associated with sea-ice concentration anomalies (ice increase into the Labrador Sea, ice retreat in the Greenland and Barents seas) which on their part effect an atmospheric response that reflects a negative NAO signal. An exclusive reduction of sea-ice thickness causes pressure changes, which reflect the positive NAO phase, and thus a positive atmosphere – sea-ice feedback. The conclusion is that the results of the experiment with both ice concentration and thickness changes, namely the low-pressure anomaly over the Arctic and the high-pressure anomaly over the northern North Pacific, must be attributed to the differences in ice thickness.

Response to changes of sea-ice albedo in an atmosphere – ocean global model

DETHLOFF et al. (2006) demonstrated that the ice–albedo feedback has not only a limited regional effect on the Arctic atmosphere, but also a global impact. They presented an experiment with a coupled atmosphere – ocean global model, where the snow and sea-ice parameterizations were improved according to KØLTZOV (2007). Køltzow suggested a new sea-ice albedo parameterization that includes the effects of melt ponds, snow on the sea ice and the surface temperature. He showed that regional climate simulations using the new albedo scheme are superior to the previously implemented scheme in reproducing the observed temperature climatology. This new sea ice and snow albedo parameterization was incorporated by DETHLOFF

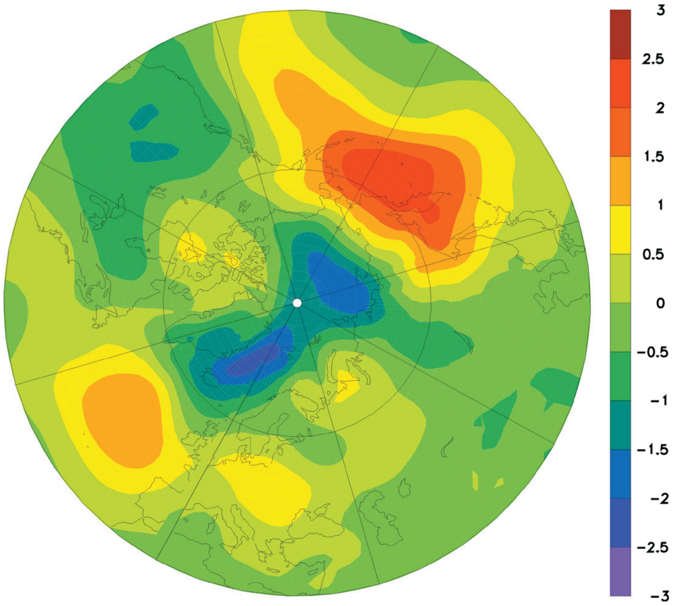

Fig. 3: Simulated winter (January-March) sea level pressure differences (hPa) between the GFDL AM2 experiments forced with sea-ice conditions from the 1990s (1994-1996) and the 1960s (1964-1966).

Abb. 3: Simulierte Luftdruckdifferenzen am Boden (hPa) im Winter (Januar-März) zwischen den GFDL AM2 Experimenten, die mit Meereisbedingungen der 1990er Jahre (1994-1996) und der 1960er Jahren (1964-1966) angetrieben wurden.

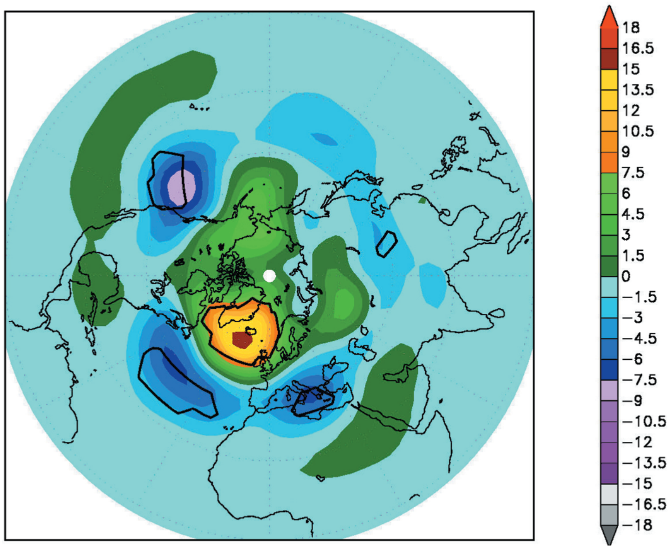

Fig. 4: Simulated winter (December-February) 500-hPa geopotential height differences (m) between the ECHO-G experiments with different sea-ice albedo parameterizations ("new minus old parameterization"), averaged over the first 250 years of the 500 year-long run. Thick black contours describe the 95 % significance level.

Abb. 4: Simulierte 500-hPa Geopotentialdifferenzen (m) im Winter (Dezember-Februar) zwischen den ECHO-G Experimenten, die verschiedene Parametrisierungen der Meereisalbedo benutzen („neue minus alte Parametrisierung"); gemittelt über die ersten 250 Jahre der insgesamt 500-Jahre-langen Simulation. Die dicken Konturlinien zeigen die 95 % Signifikanz.

et al. (2006) into the coupled atmosphere – ocean global model ECHO-G model, and present-day unforced simulations over 500 years were carried out.

The changes in the snow and sea-ice albedo generate changes in the global atmospheric circulation. This is expressed in a 500-hPa geopotential increase over the Arctic and a decrease in a mid-latitude belt (Fig. 4). The albedo changes lead to changes in the large-scale teleconnection patterns, i.e. the atmospheric response in the 500-hPa geopotential projects on the negative NAO phase. This is present in both 250-year-long sub-periods, although there are some shifts of the pressure patterns over the Pacific and Atlantic oceans. These shifts are a result of the non-stationarity of the NAO/AO pattern and could be connected with changes in the oceanic circulation.

The large-scale atmospheric changes are connected with changes in planetary wave patterns. More precisely, the planetary wave energy fluxes in the middle troposphere are affected, inducing perturbations in the planetary wave trains between the tropics and the mid-/high-latitudes. This feedback is stronger in the Pacific than in the Atlantic sector. The changes in the large-scale planetary wave trains are accompanied by changes in the storm tracks on shorter time scales, which in turn influence the Arctic climate system.

MODEL UNCERTAINTIES

The results indicate strong uncertainties concerning possible atmosphere – ice – ocean interactions. All model simulations agree that Arctic sea-ice changes affect not only the Arctic but also the global atmospheric circulation. Changes in sea-ice feedback onto large-scale teleconnection patterns (like NAO, AO). The modelled atmospheric pressure response to changes in sea-ice concentration/thickness represent a negative/positive NAO pattern, while the response to changes in sea-ice albedo projects on a negative NAO phase in an atmosphere – ocean model.

The current Arctic climate models do not include all important processes and feedbacks or describe them in a simplified way. Dorn et al. (2009) discussed how a better description of sea-ice processes (ice growth, snow and ice albedo, snow cover) contributes to improved simulations of the summer sea-ice cover.

A better understanding of the system and its relevant processes is needed to improve climate models. One important prerequisite are extensive measurement campaigns and long-term observations in the Arctic in order to have validation data for comparison with the simulated variables, their interrelationships, variability and trends. Further sensitivity experiments with climate models, like those discussed here, will contribute to better understand the forcing and feedback mechanisms between atmosphere and sea ice.

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