Polarforschung 85 (2), 85–88, 2015 (erschienen 2016)

Evaluation of a Regional Coupled Ocean – Atmosphere – Sea-Ice Model System over Greenland and the Arctic

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Abstract: Rapid changes in key climatic indicators such as sea ice, seasonal snow cover, and glacier and ice sheet surface mass balance show that the Arctic is a region in transition. Understanding the feedbacks and processes requires a wide range of data, observations and model studies. Here we introduce a high-resolution coupled regional model system that describes ocean, atmosphere, ice sheet and sea ice processes in the Arctic Ocean and North Atlantic, with special focus on the area around Greenland. The system has been developed using the regional climate model HIRHAM5 and a fully coupled version of the ocean model HYCOM and the sea ice model CICE. We use the models in offline and coupled mode for a two-year experiment to examine the relative importance of ocean and atmospheric forcing and internal dynamics, as a first step towards investigating the recent rapid decline of Arctic sea ice and low surface mass balance of the Greenland Ice Sheet. The model setup can successfully reproduce the seasonal variability in sea-ice extent and highlights the bounds of internal variability in the system, while Greenland Ice Sheet surface mass processes are well represented.

Zusammenfassung: Schnelle Änderungen klimatischer Kenngrößen, wie Meereis, saisonale Schneebedeckung sowie die Massenbilanz von Gletschern und Inlandeis zeigen, dass die Arktis eine Region im Wandel ist. Um die Rückkopplungen und Prozesse besser zu verstehen, benötigt es einer Vielzahl an Daten, Beobachtungen und Modellstudien. Im Folgenden wird ein hoch aufgelöstes, gekoppeltes, regionales Modellsystem beschrieben, dass die Prozesse in Ozean, Atmosphäre, Inlandeis und Meereis im Arktischen Ozean und im Nordatlantik vereint, mit besonderem Fokus auf die Region um Grönland. Das Modellsystem wurde mit dem regionalen Klimamodell HIRHAM5 und einer vollständig gekoppelten Version des Ozeanmodells HYCOM und des Meereismodells CICE entwickelt. Die Modelle werden im offline und gekoppelten Modus für einen Zeitraum von zwei Jahren betrieben, um die relative Bedeutung der ozean- und atmosphärengetriebenen Antriebsprozesse und der internen Dynamik als einen ersten Schritt in Richtung der Erforschung der jüngsten, schnellen Abnahmen des arktischen Meereises und niedrigen Massenbilanzen des grönländischen Eisschildes zu untersuchen. Die Modellkonfiguration kann die saisonale Variabilität der Meereisausdehnung erfolgreich simulieren und macht die Grenzen der internen Variabilität des Systems deutlich, während die Massenbilanz des Inlandeises auf Grönland gut dargestellt wird.

INTRODUCTION

The Arctic is undergoing rapid climate change due to several feedback mechanisms that amplify global change at high latitudes. The albedo feedback for sea ice and seasonally snow-free land is relatively well understood, and can explain much of the amplification. Other feedbacks are less well mapped, especially when it comes to the interplay between the Greenland Ice Sheet, ocean dynamics and sea ice (e.g., Hall 2004, Crook et al. 2011). To model these feedbacks, and especially the forcing of the Greenland Ice Sheet, high resolution is preferred, raising the need for regional models (e.g., Langen et al. 2015, Lucas-Picher et al. 2012). In this paper, we apply a regional coupled ocean – sea ice – atmosphere model to the entire Arctic domain, to make a first evaluation of how well the climate of Greenland is represented.

MODEL SETUP AND EXPERIMENTS

The model system consists of a stand-alone atmosphere model, a fully coupled ocean and sea-ice model, and a script level two-way coupling procedure. The model domain covers the entire Arctic domain and the Atlantic sub-polar gyre (Fig. 1), whereas the atmospheric domain is about 100 km larger in each direction to avoid forcing the ocean surface with atmospheric data from the boundary zone.

The atmospheric regional climate model

The HIRHAM5 regional climate model (Christensen et al. 2006) is derived from the physical schemes of the ECHAM5 global climate model (Roeckner et al. 2003) and the dynamical scheme of the HIRLAM numerical weatherprediction model (Eerola 2006). In these experiments we use a domain covering the Arctic at 0.25° (~27 km) resolution on a rotated polar grid with a dynamical time step of 300 seconds and 31 vertical levels (Fig. 1). The regional model is forced at the boundaries with the ERA-Interim reanalysis dataset, but allowed to evolve entirely freely inside the domain in a set-up similar to that of Lucas-Picher et al. (2012). Sea ice and snow thicknesses on the lower boundaries are fixed at 2 m and 2 cm, respectively, in all areas with sea ice.

The ocean and sea-ice models

For modelling the ocean and sea ice, we use a fully coupled and slightly modified version of the HYbrid Coordinate Ocean Model (HYCOM) v2.2.55 (e.g., Chassignet et al. 2007) and the Community Ice COde (CICE) v4.0 (e.g., Hunke 2001). The horizontal resolution is roughly 20 km (Fig. 1) and the model has three fixed surface layers in the top ten metres and additional 34 flexible vertical layers. All ocean experiments were made with climatological temperature and salinity (Steele et al. 2001, Conkright et al. 2002) on the open lateral boundaries in the Atlantic Ocean and the Bering Strait, and with a 30-day relaxation of surface salinity. No other assimilation was used in this study. Further details on the ocean and

doi:10.2312/polfor.2016.004

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This extended abstract was presented as an oral contribution at the Inter-national Conference "Our Climate – Our Future: Regional Perspectives on a Global Challenge", 6–9 October 2014 in Berlin, Germany.
Manuscript received 02 June 2015; accepted in revised form 16 October 2015.

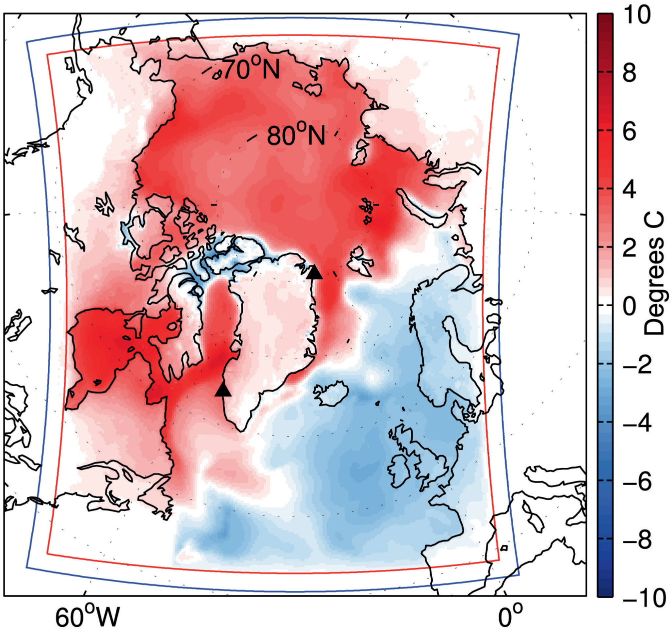

Fig. 1: The model domain of the atmospheric model (blue line) and the ocean and sea-ice models (red line), the 2006–2007 annual mean 2-m air temperature difference between coupled and atmosphere reference runs (colours), and positions of validation stations on Greenland (black triangles: south = Nuuk, north = Henrik Krøyer Holme).

Abb. 1: Modellgebiet des Atmosphärenmodells (blaue Linie) und des Ozean- und Meereismodells (rote Linie), die mittlere 2 m Lufttemperaturdifferenz zwischen Modelsimulation des gekoppelten Modells und Atmosphärenreferenz-Läufen für das Simulationsjahr 2006–2007 (farbig) und die Lage der Validationsstationen in Grönland (schwarze Dreiecke: im Süden = Nuuk, im Norden = Henrik Krøyer Holme).

sea-ice model system and setup can be found in MADSEN et al. (2016).

Coupling method

We apply the 24 hour script-level coupling method of TIAN et al. (2013) which gives us a high level of flexibility to investigate the interplay of the model components without being required to make alterations to the stand-alone models. In this setup of the coupled run, the atmospheric model is first run for 24 hours (0–24h) with 3-hourly output. The ocean and sea-ice models are then run for the same 24 hours (0–24h), forced with the 3-hourly output atmospheric data. Finally, sea-surface temperature and sea-ice concentration at 24h are fed back to the atmospheric model to be used for the next day's run. Though, the models cover the same area, their horizontal resolutions are different, and bi-linear interpolation has been used between them. No flux corrections have been applied.

Experiments

Since both, the atmospheric and the oceanic model setups were new, different experiments have been made to analyse the properties of the models and provide control simulations. We studied the two-year period 2006–2007 and used the Era Interim reanalysis (DEE et al. 2011) as a reference, as suggested by LINDSAY et al. (2014).

The experiments include:

1) Ocean reference run: The ocean – sea-ice model was forced by Era Interim. Initialized by more than nine years spin up (Sep 1996–Dec 2005).
2) Atmosphere reference run: The atmospheric model was forced with the same ocean and sea-ice conditions as used for Era Interim. One year spin up (2005).
3) Uncoupled run: The ocean – sea-ice model was forced by the atmosphere reference run. One year spin up (2005), initialized from the ocean reference run.
4) Coupled run: The atmosphere and ocean – sea-ice models were run coupled. One year spin up (2005), ocean and sea ice initialized from the ocean reference run.

RESULTS

The two years of simulation from the different experiments allow us to examine the importance of the coupling to improve model performance in the Arctic domain. We focus on three key variables sea-ice concentration, air temperature and Greenland Ice Sheet surface mass balance.

Sea ice extent and concentration

All model experiments show that the model system is capable of reproducing the seasonal cycle and magnitude of sea-ice concentration in the Arctic. In the ocean reference run, the timing of the minima, maxima, freeze-up and break-up seasons closely replicates observations (EASTWOOD et al. 2011), while the amplitude of the seasonal cycle of total sea-ice extent is about 10 % too large (Fig. 2). The use of HIRHAM5 as driver for the ocean – ice model (uncoupled run) shows an improvement in the minimum extent, with a value very close to the observed one in 2006 and 0.2 million km^2 too high in 2007. In the coupled simulation, the maximum ice extent and the timing of the break up is close to the observed, whereas a delay in the freeze up of about one month is seen. The minimum sea-ice extent is very similar for the two years and very close to the observed value for 2007, while the model underestimates the extent in 2006.

Atmospheric 2-meter temperatures

Validating a climate model in data-poor regions such as the Arctic is always challenging (LINDSAY et al. 2014). We therefore compare the experiments to ERA-Interim reanalysis data, though note that it also has important biases compared with observations (DEE et al. 2011).

The air temperature time series shown in Figure 3a show that in general the model can reproduce the seasonal cycle in the high Arctic, but there is a delay in cooling in the coupled run, corresponding to the delayed freeze-up. This is seen as a temperature bias of more than 5 °C from end August 2006 to January 2007, and again from mid-October to November 2007. The bias is seen in most sea ice affected areas (Fig. 1). An exception is the Canadian Archipelago, where the increased resolution in the sea-ice product of the coupled model gives significant improvements.

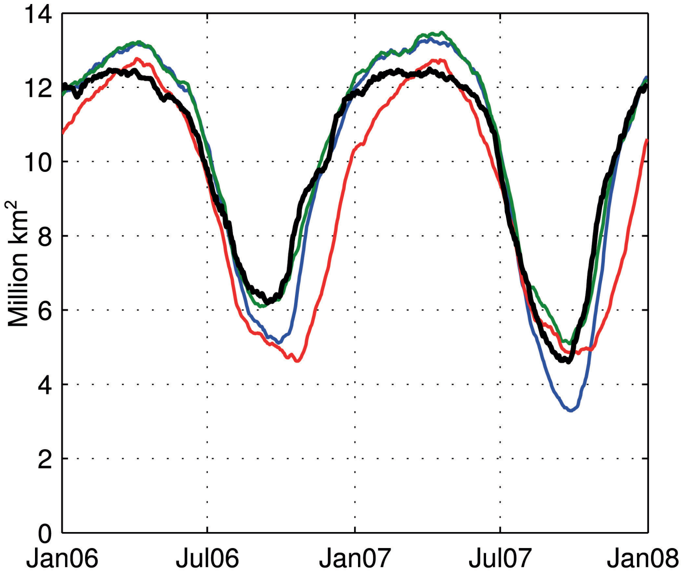

Fig. 2: Daily total Arctic sea ice extent (at least 15 % ice cover, million km^2) in the ocean – sea ice reference simulation (blue line), the uncoupled simulation (green line), the coupled simulation (red line) and as observed by satellite (Eastwood et al. 2011) (black line). The model system shows full ice cover in the Arctic in winter, but summer sea ice concentrations are too low with values 30–50 % lower than observed values in the central Arctic Ocean.

Abb. 2: Tägliche arktische Meereisausdehnung (mindestens 15 % Eisbedeckung, in Mio. km^2) der Ozean – Meereis Referenzsimulation (blaue Linie), der ungekoppelten Simulation (grüne Linie), der gekoppelten Simulation (rote Linie) und der Beobachtung durch Satelliten (Eastwood et al. 2011) (schwarze Linie). Das Modell zeigt vollständige Eisbedeckung der Arktis im Winter. Im Sommer sind die Meereiskonzentrationen mit 30–50 % unterhalb der beobachteten Werte für den zentralen Arktischen Ozean zu niedrig.

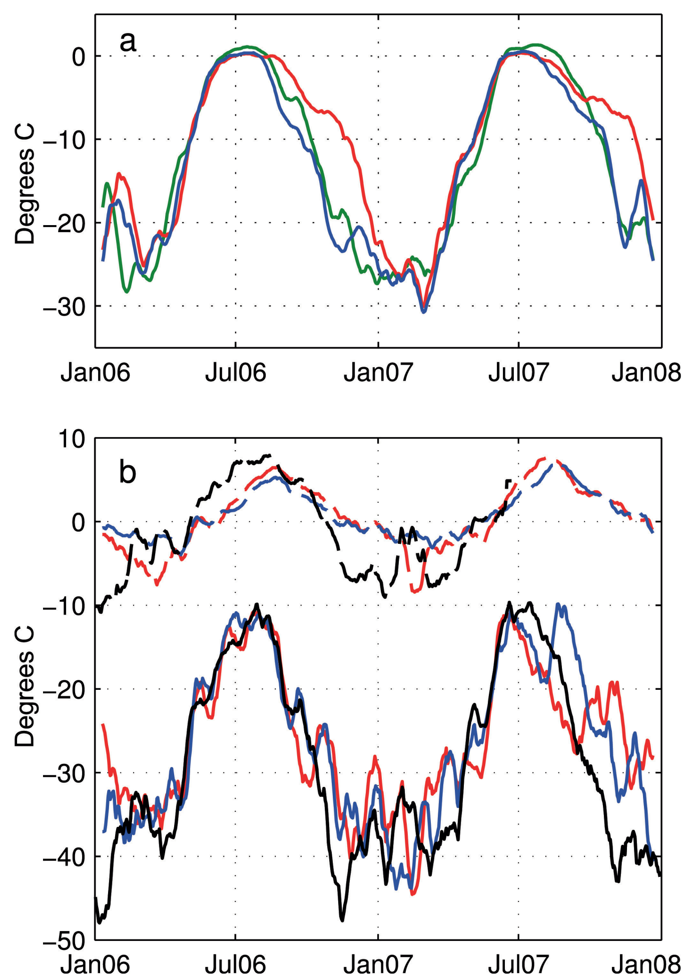

Fig. 3: 21 day running mean 2-meter air temperature a) averaged north of 80°N, b) point data from Greenland (location, see Fig. 1): Nuuk (dashed) and Henrik Krøyer Holme (solid, no observations in July–December 2007); for the reference simulation (blue), the coupled simulation (red), Era Interim reanalysis (green, only a) and observations from validation stations (Cappelen 2014) (black, only b).

Abb. 3: 21-tägige mittlere 2 m Lufttemperatur für a) nördlich 80°N gemittelt, b) Punktdaten von Grönland (Stationen siehe Abb. 1): Nuuk (gestrichelt) und Henrik Krøyer Holme (durchgezogen, keine Beobachtung von Juli bis Dezember 2007); für die Referenzsimulation (blau), die gekoppelte Simulation (rot), ERA Interim Reanalyse (grün, nur a) und Beobachtungen an Validationstationen (Cappelen 2014) (schwarz, nur b).

Comparison with observations on Greenland (Cappelen 2014) also reveals the interplay with the ocean and sea ice (Fig. 3b). Temperatures are highly steered by differences in sea-ice extent, particularly at locations such as Henrik Krøyer Holme. This observation point is on a flat island surrounded by ocean. Temperatures observed here mostly reflect the prevailing sea ice and SST conditions. Nuuk, on a narrow, rocky spit of land with fjords on both sides, is rather poorly resolved in the model, giving a warm bias in January 2007 and cool bias in summer in both HIRHAM5 runs. However, compared to the coarser ERA-Interim, the bias is much reduced.

Surface mass balance of the Greenland Ice Sheet

Surface mass balance (SMB) is the sum of snowfall and melt induced runoff from land ice. The SMB scheme in these runs is rather simple and does not include a parameterisation for retention and refreezing of liquid water (Langen et al. 2015). It is therefore steered by both, precipitation, temperature and radiative forcing in the surface energy budget and indicates the future direction of land ice mass change. Both reference and coupled simulations show a representative distribution of SMB as compared with other models (e.g., Fettweis et al. 2011, Hanna et al. 2014) over the Greenland Ice Sheet, with high values in the South-East and North-West, where most of the precipitation falls, and lower values in South, North-East and West, where there is more melt and run-off during the ablation season (Fig. 4). The coupled model has more precipitation falling further to the south on the east coast than the reference, likely reflecting different ocean forcing. The higher SMB overall in the coupled simulation likely reflects the warmer air temperatures in autumn and early winter, bringing more snowfall in the early part of the accumulation season.

SUMMARY AND DISCUSSION

A coupled model is applied to the Arctic and North Atlantic domain. In the Arctic region, it is common practice to tune the sea-ice model to fit observations, due to uncertainties in models and lack of observations. We have investigated the effects of switching between ERA-Interim and HIRHAM5 atmospheric forcing, and of coupling the ocean – sea-ice – system with the atmosphere, without the need for tuning.

The low 2007 sea-ice minimum is captured in the reference models, but not in the uncoupled model, which likely reflects the greater freedom for the weather to evolve freely

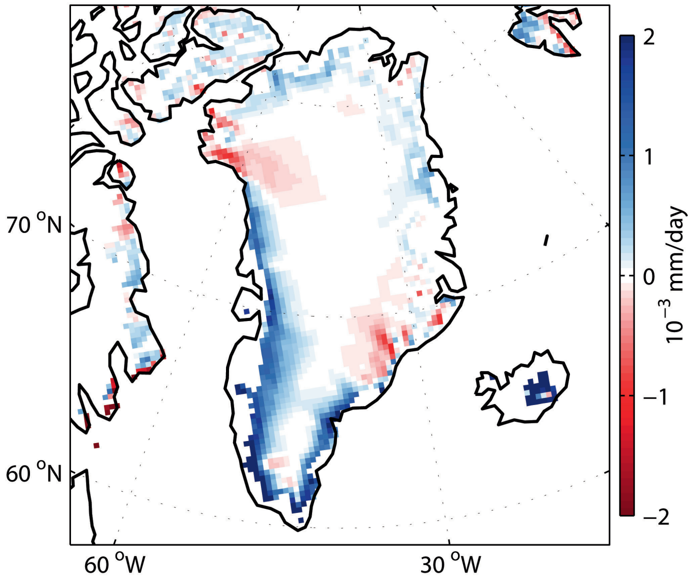

Fig. 4: Mean difference in surface mass balance (colours, 10–3 mm water equivalent per day), coupled minus reference run.

Abb. 4: Mittlere Differenz der Oberflächenmassenbilanz des Inlandeises (farbig, 10–3 mm Wasseräquivalent pro Tag) für den gekoppelten Lauf minus Referenzlauf.

in the large domain as with ice sheet SMB (Koenigk et al. 2015, Dorn et al. 2012). This indicates that regional coupled models, like our setup, have an important role in evaluating the importance of stochastic weather processes, and should preferably be used in ensemble-mode to span the range of internal variability.

Another important result is the role of ocean heat fluxes in modulating sea-ice formation. The low summer sea-ice concentration in the Arctic initiates a heating of the surface ocean in the coupled simulation. This heat needs to be released before freeze-up occurs, resulting in a delay of the atmospheric surface cooling and sea-ice freeze-up of about one month with knock-on effects on precipitation and SMB. In the uncoupled simulation, the feedback does not occur, since SST and sea-ice concentration are prescribed in the atmospheric model. This is a focus for future work on the coupled model system.

The limited simulation- and spin-up times of this study means that results should be used with care. Still, we have proof of concept of a coupled atmosphere – ocean – sea-ice model system for the Arctic, which may be used to further study climate processes in the Arctic and assist in attributing environmental changes in the future.

ACKNOWLEDGMENTS

This study has been financially supported by the Danish Agency for Science, Technology and Innovation and is a part of the Greenland Climate Research Centre. Helpful comments by Annette Rinke and one anonymous reviewer are gratefully acknowledged.

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