Danmarks
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# DMI Report 22-29
# Teleconnections and Bias Reduction

**Final scientific report of the 2021 National Centre for Climate Research Work Package 4.2, Teleconnections and bias reduction**

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# Kolofon

**Serietitel**
DMI Report 22-29

**Titel**
Teleconnections and bias reduction

**Undertitel**
Final scientific report of the 2021 National Centre for Climate Research Work Package 4.2, Teleconnections and bias reduction

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**Ansvarlig institution**
Danmarks Meteorologiske Institut

**Sprog**
English

**Emneord**
Sea ice leads, heat fluxes, Arctic Ocean, EC-Earth, AGCM

**Url**
http://www.dmi.dk/publikationer/

**ISSN**
2445-9127

**ISBN**
978-87-7478-731-0

**Versionsdato**
15. januar 2022

**Link til hjemmeside**
www.dmi.dk

# Contents

# 1. Scientific summary

## Short description

In general, coupled global climate models show large biases in temperature over the Arctic in winter, resulting in excessive sea ice extent and volume. This includes nearly all CMIP5 and CMIP6 historical simulations. Therefore, it is also challenging to obtain an accurate projection of future Arctic climate change. Here our aim is to reduce this bias by targeted developments. Higher resolution model studies suggest that one possible reason for the cold winter bias in global CMIP type climate models is the lack of representation of heat fluxes through sea ice leads in the Arctic Ocean due to their coarse resolutions (~100 km). In this work package, we have implemented a new scheme to parameterize the effects of sea ice leads on the heat fluxes between ocean and atmosphere. We identify the key atmospheric processes responding to the effect of sea ice leads in atmosphere-only general circulation models (AGCM) on seasonal-to-decadal time scales and investigate the possibility of reducing model bias in surface fields and better representing Arctic warming in the coupled climate models.

## Overall results

1. With the new scheme accounting for the effects of sea ice leads introduced, we see a large seasonal cycle of heat flux from leads depending strongly on the seasonality of the background stability of the lower Arctic atmosphere.
    - In winter, when the lower boundary layer of the Arctic atmosphere is often strongly and stably stratified, the introduction of leads strongly amplifies the surface sensible heat flux coming from the ocean.
    - In summer, there is the opposite effect and despite the generally weak stability in the lower atmosphere there is a reduction in the flux coming from leads, compared to that which would come from an equal area of open water. In this way the scheme has the potential to correct the model seasonal biases, characterized as too-fast freezing in winter and too-fast melting in summer.
2. Ensemble experiments of three AGCMs (NorESM, IPSL-CM5, EC-Earth3) with CMIP6 historical forcing (1979-2014) are used to examine the atmospheric responses to the amplification effect of heat flux through leads:
    - seasonal differences: strongest positive changes in air surface temperature in winter in contrast to little/no effect in summer
    - remote response: in years when there are larger Arctic sea ice cover, the winter effects span from the Arctic to the mid-latitudes
3. Heat flux through leads can reduce the Arctic sea ice volume by more than 10% with the coupled EC-Earth3 and thereby contribute to reduce the strong model biases.

## Next steps

A manuscript based on the multi-model ensemble experiments of AGCMs is in preparation. A joint coupled simulation is planned for the NorESM2 and EC-Earth3 in 2022 to assess change in sensitivity of Arctic climate during a period of rapid Arctic change due to the introduction of the leads in the ocean-atmosphere-ice coupling.

# 2. Scientific reporting

## Introduction

**Motivation**

Almost all coupled global climate models used in CMIP5 and CMIP6 are biased in the Arctic towards being too cold in the winter (Davy and Outten, 2020). Biases in the mean climate during the historical period can introduce biases in the sensitivity of the climate to changes in forcing, e.g. due to the increased concentration of greenhouse gases in the atmosphere (Davy and Esau, 2014). It is therefore very important to reduce the bias in these models in order to create accurate projections of future Arctic climate change. When the observations are out-of-sample from the range of model results, it is not possible to account for these biases using post-processing tools such as emergent constraints, but there should instead be corrections to the model physics.

**Hypothesis**

Part of the reason for this cold bias is the lack of representation of fluxes through sea ice leads in global climate models. High resolution modeling studies (e.g. turbulence resolving Large Eddy Simulations run at resolutions of a few meters) have been able to simulate fluxes of several hundred watts per square meter from leads in winter (Michaelis et al., 2020), which implies that even the presence of a few leads can significantly alter the surface energy budget and hence the air temperature close to the surface. We propose that by accounting for the effect of leads within coupled climate models, we can reduce this winter cold bias in the lower Arctic boundary layer.

## Methods

**Implementing amplification factor in multi-climate models**

The Nansen Environmental and Remote Sensing Center(NERSC) developed a novel scheme for representing the effects of leads in ice on the heat fluxes between ocean and atmosphere. This was based on a combination of results from turbulence resolving simulations of the heat fluxes over leads of different widths and with different background atmospheric stability, and the distribution of lead width sizes derived from satellite observations.

NERSC conducted model development for the Norwegian Earth System Model (NorESM) and provided a guide for other climate models, e.g. the climate model IPSL-CM5, as a deliverable in the H2020 project Blue-Action work package 3 (Davy and Gao, 2019). In the present work package (NCKF21-WP4.2), we have implemented the same development on the EC-Earth3 model at DMI.

The first development was to implement a new scheme to parameterize the surface sensible heat flux (SSHF) coming from leads in the ice. The second was to improve the description of stability functions, which describe the near-surface gradients in atmospheric properties like temperature, humidity, and wind.

The purpose of making these changes to the multi-climate models is to assess the role of leads in determining the surface energy budget in the Arctic and to determine how much we can improve the systematic biases in the near-surface air temperature and the representation of near-surface gradients under strongly-stable stratification.

## Results

**A new parameterization to the EC-Earth 3 at DMI**

The empirical algorithms are derived based on the climatology of background atmospheric stability (θ) of the EC-Earth3 AGCM experiment with prescribed sea surface temperature (SST) and sea ice centration (SIC) over 1979-2014 obtained from the U.K. Met Office Hadley Centre Sea Ice and SST Version 2.2.0.0 data set (Kennedy et al. 2017) at a height of around 300m. With the thermal stability at a height of around 300m in Eq. (1), the depth of convective boundary layer (λ in m) over the Arctic is scaled to [1600 2500] m according to Eq. (2) and  the range comes from that used for the LES simulations (Esau, 2007). Then the factor A (to be applied for SSHF) is determined by Eq. (3) with a range of 0.8-1.2. The constants in the empirical algorithms (2-3) are tuned for the EC-Earth 3 and A strongly depends on the background stability in the atmospheric model.

$$\theta = \frac{\mathrm{dTheta}}{\mathrm{dz}} \quad (1)$$

$$\lambda_{CBL} = 230\theta + 2100 \quad (2)$$

$$A = 6.012 \times 10^{-8} {\lambda_{CBL}}^{2} - 4.036 \times 10^{-4} + 1.56 \quad (3)$$

The scaling factor A modifies modeled SSHF in EC-Earth3 only fully when the area with SIC exceeds 90%, assuming the effect of lead plays the biggest role over the full ice-covered area. A simple linear scaling function is applied on A to ensure it approaches 1 as SIC approaches 70 % (see Figure 5, Davy and Gao, 2019).

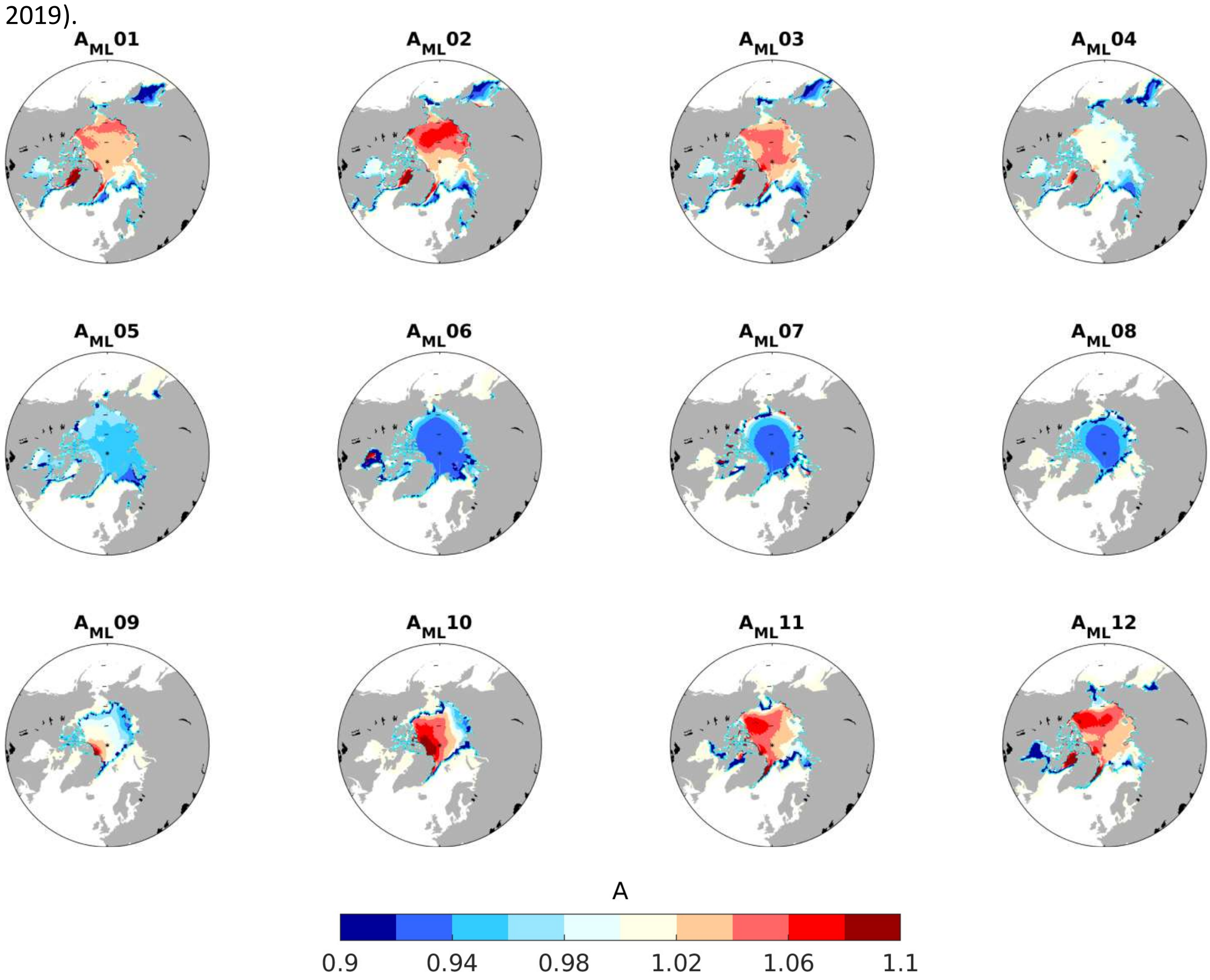


**Figure 1.** Amplification factors in monthly climatology based on the EC-Earth3 AGCM experiment for the period 1979-2014. Note A is a constant of 1 if SIC<70%.

By using the monthly climatology of the atmospheric thermal stability (Eq.1-3) and sea ice concentration (>70%), a clear seasonal cycle of the amplification effect to SSHF over leads is shown in Figure 1. In the winter months when the atmosphere is often strongly stably stratified, the leads strongly amplify SSHF (A>1) in the Central Arctic. In summer there is the opposite effect and the generally weaker atmospheric stability reduces the flux coming from leads with A <1.

**Framework for a paper on AGCM results**
A manuscript based on the multi-model ensemble experiments of AGCMs is in preparation led by Richard Davy from NERSC with contributions from coauthors from LOCEAN/IPSL and DMI. This includes a 20-member ensemble of AGCM simulations for the period 1979-2014 performed with DMI's EC-Earth3 contributing to the joint analysis. Here, the outline of the paper is provided for the report.

Methods: formulation of leads in an ice scheme (Davy and Gao, 2019)

- LES simulations of heat fluxes from leads
- Satellite-derived estimates of lead distributions (based on Marc and Weiss, 2012)
- Integrate the two together to get an amplification factor for the surface sensible heat flux at given atmospheric stability.
- Assumption: when SIC is 90% or greater we assume that all the open water is attributable to leads. Scaled linearly down to none being attributable to leads when SIC is less than or equal to 70%.

Results:

- Models used: atmosphere-only versions of NorESM, IPSL-CM5, EC-Earth3
- Experiments: historical forcing, 1979-2014, 20 member ensembles
- Effects on near-surface fluxes, surface air temperature.
- Seasonal differences: strongest effect in winter, little/no effect in summer

Conclusions/Discussion:

- Seasonally varying response gives the potential for addressing seasonal bias.
- Uncertain long term climate effect of this scheme: a combination of changing atmospheric stability, changing distribution of leads (which is currently unknown)

**Progress in the AOGCM experiments**
The new scheme for the amplification factor to SSHF through leads has been implemented in the coupled EC-Earth3 model. Two sets of 30-year simulations were performed starting from two different initial conditions from one CMIP6 historical simulation with repeated forcing from two respective years, to represent cold (strong stable) versus warm (weak stable) backgrounds atmosphere. For both cases, twin experiments were performed only differing in the activation of lead parameterization, namely the LEAD versus CTRL experiments.

Under the cold background atmosphere, we first defined the model bias in SIC annual maximum (in March) by calculating the difference between the model and reanalysis data (MOD-REF). In Figure 2a there is a large extent of positive bias (in red) with too much sea ice in the Atlantic-Arctic sector in the CTRL experiment. By contrast, there is a remarkable negative difference in model bias between the LEAD (LEAD-REF) and CTRL (CTRL-REF) experiments in Figure 2b indicates effective bias reduction (LEAD-CTRL, in blue) by taking account of the amplified heat flux through leads. Under the warm background atmosphere, the magnitude of changes introduced by the lead scheme is relatively small (not shown). It suggests the scheme can be sensitive to the changes in both atmospheric stability and SIC distribution.

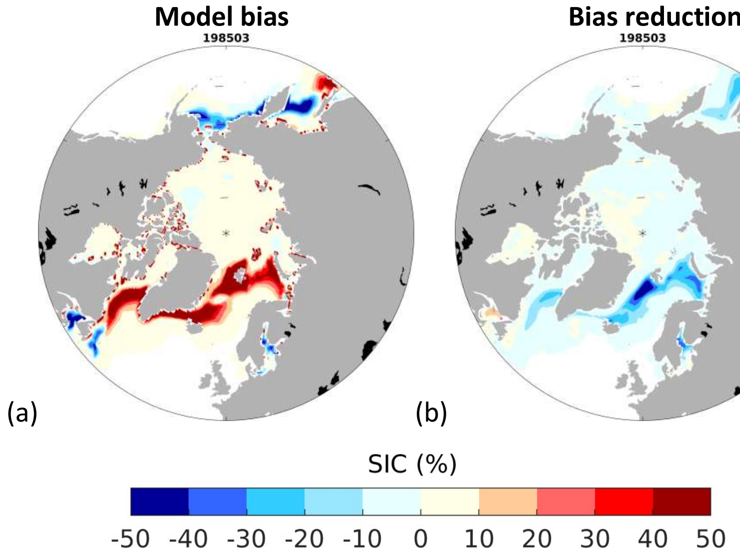


**Figure 2.** 30-year mean difference in annual maximum SIC ( %) under the cold background: (a) model bias (CTRL-REF) and (b) bias reduction (LEAD-CTRL), respectively.

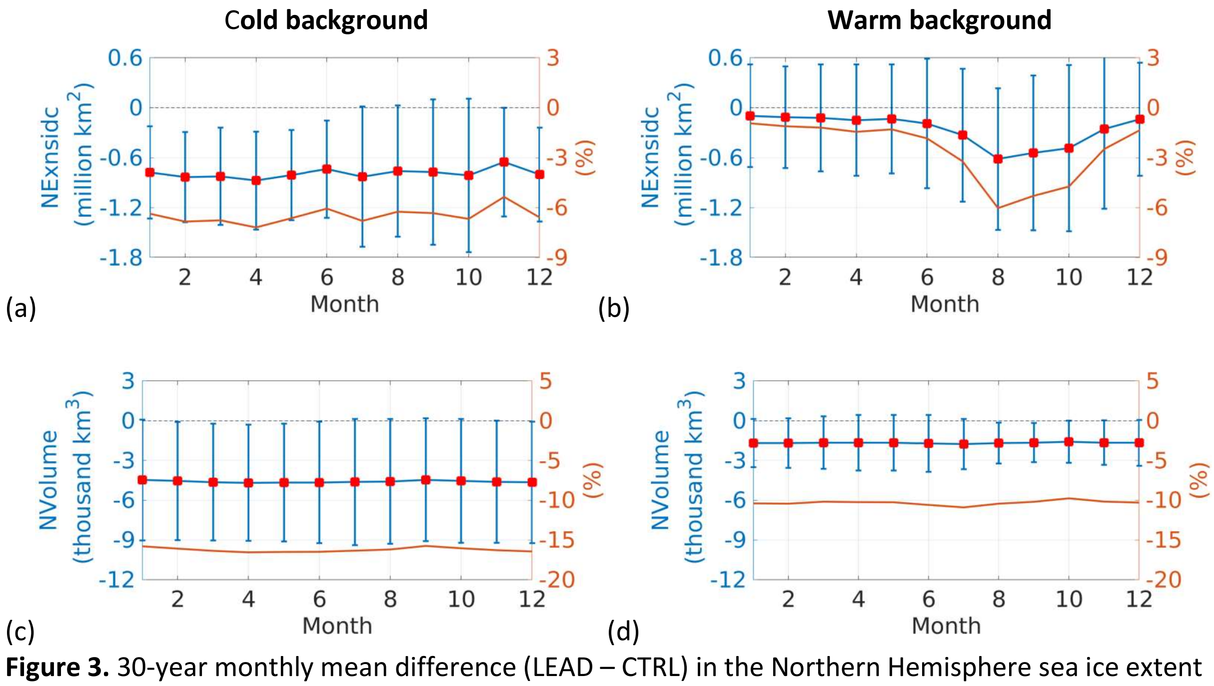


**Figure 3.** 30-year monthly mean difference (LEAD – CTRL) in the Northern Hemisphere sea ice extent (NEexnsidc) and volume (NVolume) under the strongly stable (left) and weakly stable (right) atmosphere background. The errorbar shows the mean (dot) and the standard deviation (year-to-year varability) of the month over the 30 years. The right Y-axis and the red line show the relative changes, i.e. (lead-ctrl)/mean(ctrl) *100%.

Figure 3a and b show the year-to-year variation of sea ice extent in summer (until annual minimum) is much larger than that in winter when responding to the effect of sea ice lead in both atmospheric background states. In contrast to sea ice extent, Figure 3 c and d show that the sea ice volume over the Arctic has minor changes across seasons with an average annual reduction of 16% and 10%, respectively, from the CTRL experiments. Our results suggest the possibility of reducing seasonal bias in the sea ice extent and near surface temperature over the Arctic and reducing the year-round bias in the Arctic sea ice volume.

## Conclusion and future work

The impact of the sea ice lead parameterization on the Arctic can vary seasonally, depending on the sea ice concentration and the background stability in the atmosphere. It has the potential to address known seasonal biases, but it also reveals uncertainties about the effect of leads on long-term climate change. The latter, as a combined effect of dramatic changes in atmospheric stability and spatial distribution of leads, may result in 1) reducing importance of leads under climate change principally due to a reduction in the occurrence of strongly stable stratification in winter, and 2) speeding up the decline of sea ice volume, leading to a more rapid transition from the cold Arctic with thick ice to the warm Arctic that has little perennial sea ice.

Therefore, it is scientifically interesting to assess the change in sensitivity of the Arctic climate (sea ice extent, area, volume, and surface air temperature) during a period of rapid Arctic change (1970-2014) due to the introduction of the leads scheme. Coordinated AOGCM ensemble experiments with two climate models (e.g. NorESM2 and EC-Earth3) are designed to investigate the effect of leads on the trend in sea ice metrics (extent, area, volume) and the trend in surface air temperature over the Arctic with the CMIP6 historical forcing over the period (1980-2014) and to disentangle its added value in reducing model bias.

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