Improved key process in representing Arctic warming

Leads in sea ice (Photo credit: Wendy Pyper)

Blue-Action: Arctic Impact on Weather and Climate is a Research and Innovation action (RIA) funded by the Horizon 2020 Work programme topics addressed: BG-10-2016 Impact of Arctic changes on the weather and climate of the Northern Hemisphere. Start date: 1 December 2016. End date: 1 March 2021.

The Blue-Action project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No 727852.

About this document

Deliverable: D3.5 Improved key process in representing Arctic warming
Work package in charge: WP3 Linkages of Arctic climate to lower latitudes
Actual delivery date for this deliverable: Project-month 34 (30 September 2019)
Dissemination level: The general public (PU)

Lead authors
Nansen Environmental and Remote Sensing Centre (NERSC): Richard Davy, Yongqi Gao

Reviewer
Danish Meteorological Institute (DMI): Chiara Bearzotti

We support Blue Growth!
Visit us on: www.blue-action.eu

Follow us on Twitter: @BG10Blueaction

Access our open access documents in Zenodo:
https://www.zenodo.org/communities/blue-actionh2020

Table of contents

Summary for publication

This Blue-Action task was focused on improving the representation of some of the most important physical processes which contribute to Arctic warming within the climate models used by the consortium. The two processes we addressed were the effect on the atmospheric state of the fracturing of the sea ice cover and turbulence under strongly stable thermal stratification. The creation and development of

The work done: We first analysed the results of previously performed large eddy simulations which resolved the turbulence over leads to determine the effect leads have on sensible heat flux from open water. Because of the effect of three-dimensional structures in the turbulent mixing above leads, the heat flux coming from leads can be amplified compared to the fluxes one would get from open water under the same air-sea temperature difference. The amplification effect strongly depends on the width of the lead, with the largest effect occurring for leads of widths around 1.4 km. We assessed the functional sensitivity of this amplification effect to key parameters used in the turbulence-resolving model, including the length scale for the convective boundary layer, which reflects the background stability in the atmosphere.

We combined this relation between the amplification effect of heat fluxes as a function of lead width with observed distributions of lead widths. These were taken from the peer-reviewed literature where

The key findings: The presence of leads in sea ice dramatically alters the surface energy balance in the Arctic. There is a large seasonal cycle to the effect of the presence of leads, because the flux from the leads depends strongly on the background stability in the atmosphere. In the winter when the atmosphere is often strongly stably stratified, the leads strongly amplify the surface sensible heat flux coming from open water. In the summer there is the opposite effect and the generally weaker atmospheric stability reduces the flux coming from leads.

Work carried out

Development of the Norwegian Earth System model

NERSC conducted model development for the Norwegian Earth System model and created a guide for other partners who use climate models to implement the same development within their own climate models. The first development was to implement a wholly new scheme to parameterize the sensible heat flux coming from leads in 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 model were to assess how important leads can be in determining the surface energy balance in the Arctic, and determining if we can improve the systematic biases in the near-surface air temperature by improving the representation of near-surface gradients under strongly-stable stratification.

Leads in ice

NERSC created and implemented a novel scheme for representing the effects of leads in ice on the atmospheric heat fluxes. 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.

The large eddy simulation (LES) results described the functional relationship between lead width and the sensible heat flux from leads (Esau, 2007). This was quantified as an amplification effect i.e. how much extra sensible heat flux comes from leads compared to an equal amount of open water under the same air-sea temperature difference. These LES results fit well to observed fluxes from leads (Figure 1) and represent a stark contrast to previous assumptions about the fluxes from leads which was that the narrowest leads have the largest flux-per-unit-area (Marcq and Weiss, 2012). This emphasizes the importance of accounting for three-dimensional effects of turbulence within a parameterization scheme which describes such a complex small-scale process.

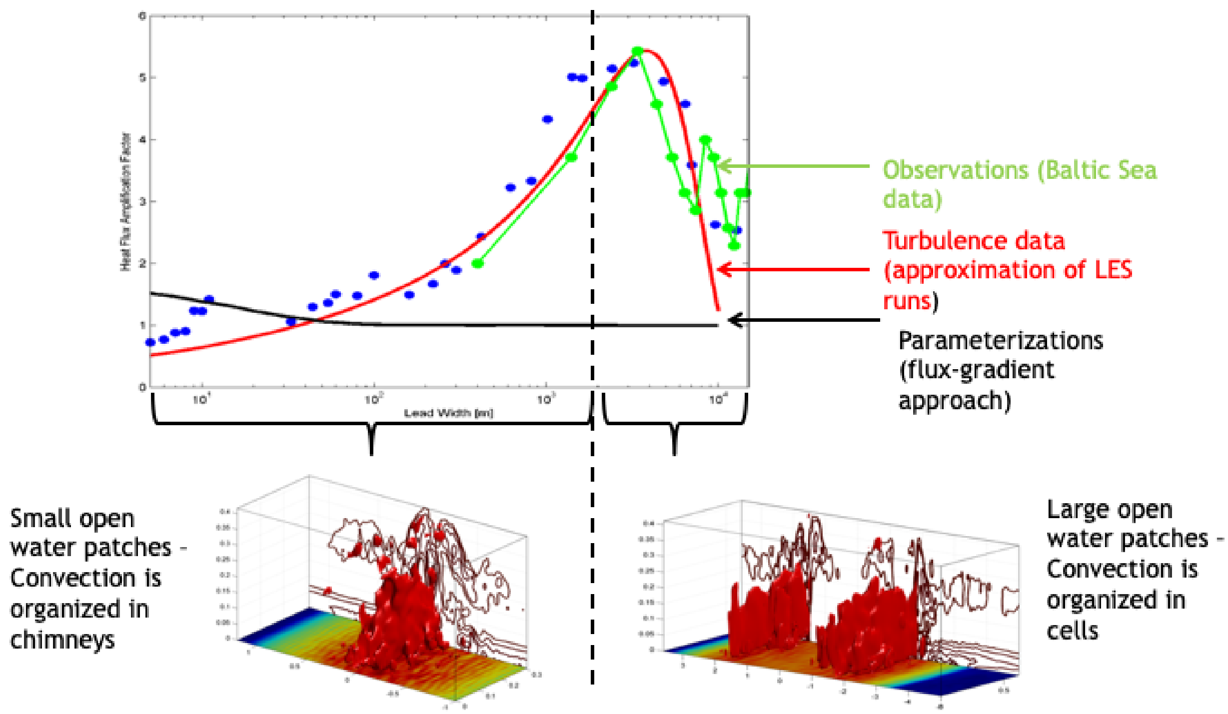

Figure 1. The top plot shows the heat flux amplification factor (how much larger the heat flux coming from leads is compared to the heat flux form open water under the same air-sea temperature difference) as a function of the width of the leads. The blue dots indicate results from individual model simulations, the thick red line is the best fit to these data, the black line indicates the relationship that has been derived using arguments from 2-dimensional schematic descriptions, and the green dots indicate the results from aircraft observations made over the Baltic sea. The lower two plots are snapshots of the vertical velocity from the turbulence resolving simulations showing the column structure formed over narrow leads (left) in contrast with the cell structure formed over wide leads (right).

The best fit to the large eddy simulation results was an amplification effect which depended upon the background atmospheric thermal stability, characterised by the length scale of the convective boundary layer, and the width of the lead. The relationship takes the form:

$$A(x) = 5\left(\frac{x}{\lambda_{CBL}}\right)^{1/3} \exp\left(\frac{-\left(x/\lambda_{CBL} - 1\right)^2}{4.84}\right)$$

where A is the amplification factor i.e. how much bigger the sensible heat flux-per-unit-area is from the lead than from open water; $x\,[m]$ is the width of the lead; and $_{CBL}$ *[m]* is the length scale of the convective boundary layer. This length scale depends upon the background stability of the atmosphere and is smaller for a more stably-stratified atmosphere.

NERSC conducted a review of the available estimates of the distribution of lead widths from the literature to determine a best-estimate and the uncertainty in the estimate derived from observations. Estimates from satellite observations indicate that lead width is distributed according to a power law with a negative exponent such that narrow leads are the most common (Marcq and Weiss, 2012;). Figure 2 shows an example of the SPOT satellite images used to estimate the distribution of lead widths after they have been filtered to a luminance threshold to separate the presence of ice from that of open water in leads. There is some subjectivity in the choice of threshold because there is no clear separation in luminance between
The distribution of lead widths follows a power law distribution of the form:

$$P(x) = \frac{a-1}{L_0}\left(\frac{x}{L_0}\right)^{-a}$$

where *P* is the probability of finding a lead of width $x\,[m]$, $L_0\,[m]$ is the limiting length scale of the distribution which is prescribed by the resolution of the satellite images (here it is 10m), and a is the coefficient describing the steepness of the distribution which is obtained from analysis of these observations.

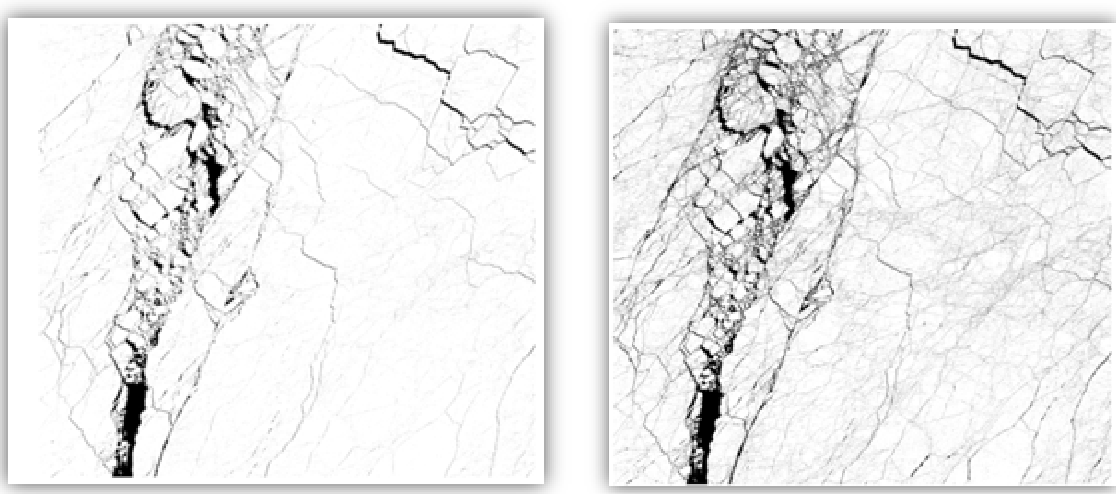

Figure 2. An example of SPOT images processed using two different, but reasonable, choices of the threshold for luminance to separate the presence of leads from ice (Marcq and Weiss, 2012).

The power law fit to these satellite images under the two different luminosity thresholds depicted in Figure 2, and using two different approaches, vertical scan and horizontal scan, is shown in Figure 3. The difference in the coefficient of the power law distribution from the vertical and horizontal scans is relatively small. For example, under the low luminance threshold the best-fit to the results obtained from the horizontal scan is a factor of 2.1, whereas the best-fit to the results from the vertical scan is 2.3. This is a relatively small uncertainty compared to the uncertainty coming from the choice of luminance threshold. For the low luminance threshold the best-estimate of the coefficient for the distribution is 2.2, whereas it is 2.55 for the high-luminance threshold. Since there is no objective reason to assume one threshold over the other, we took the mean of these estimates, but we also included the uncertainty in this distribution to assess confidence in the total, large-scale effect of leads on the surface energy balance.

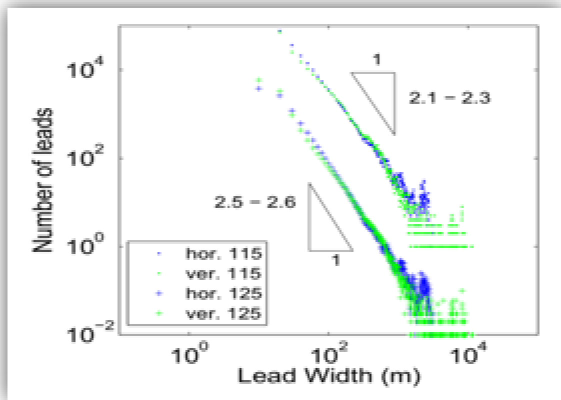

Figure 3. The number of leads as a function of lead width derived using the two different luminance thresholds shown in Figure 2, and using either a horizontal (hor.) or vertical (ver.) scan to identify the leads. The estimated coefficient for the power law distribution is indicated using the triangles. For the low luminance threshold we get a coefficient of 2.1 to 2.3, and for the high threshold we get a coefficient of 2.5 to 2.6.

We then calculated the total amplification factor of sensible heat flux that would come from a gridcell with a mix of ice cover and open water, assuming that open water was the result of leads following the same power-law distribution as derived from observations detailed above. This was done by integrating the product of the probability distribution and the amplification factor derived from the LES results:

$$\hat{A} = \int_{L_0}^{\infty} A(x)P(x)dx$$

where $\hat{A}$ is the total amplification of sensible heat flux from the open water within the gridcell compared to that from an equal area of open water, $A(x)$ is the amplification of heat flux over a lead of width $x\,[m]$, and $P(x)$ is the probability of having a lead of width x. This equation cannot be solved analytically, so we used a numerical solver to find the total amplification factor for a range of values of the length scale for the convective boundary layer. The results are summarised in Figure 4. This also shows the uncertainty associated with the power-law fit of the lead distribution, with the results for the mean and lower and upper bounds to the shape of the distribution, as detailed in Figure 3.

These results show the strong dependence of the effect of the leads on the background stability of the atmosphere. In a strongly stable atmosphere, such as is typical in winter, the turbulent processes over leads act to amplify the sensible heat flux, compared to what would be expected from open water. Whereas when the atmosphere is weakly stratified, the dynamics over leads act to damp the sensible heat flux, compared to that from open water. While the stratification of the atmosphere is strongly dependant on the synoptic activity in addition to seasonality, we might expect from this functional relationship that there will be very different effects of leads in summer compared to in winter.

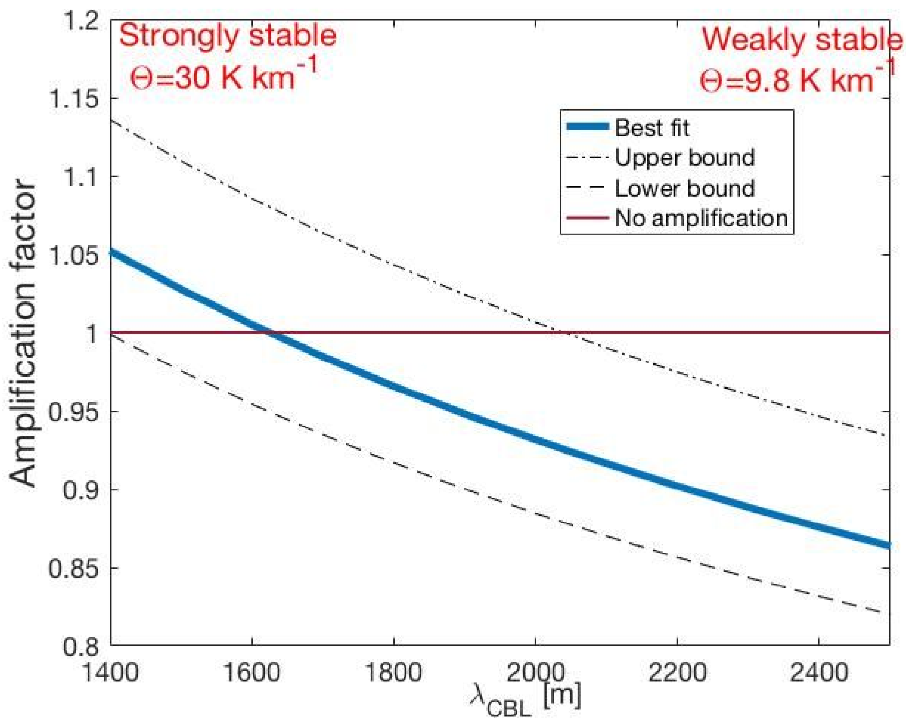

Figure 4. The amplification of sensible heat flux from all leads

To include this amplification effect from leads in a climate model we need to make an assumption about when the open water in a gricell can be attributed to the presence of leads. Here we assumed that the amount of open water flux that can be ascribed to leads depends upon the sea ice fraction in a given gridcell. We assumed that for sea ice concentrations less than 70% that none of the open water is associated with leads, and that when the sea ice concentration in a gridcell is greater than 90%, all of the open water can be attributed to leads. We then applied a simple linear extrapolation between these two points to scale the applied amplification factor for sensible heat flux (Figure 5).

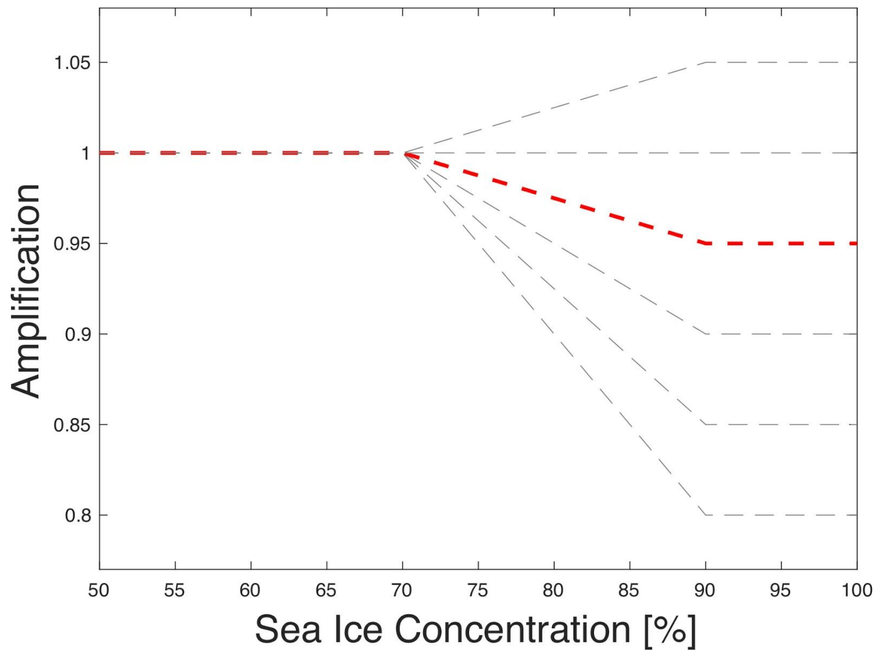

Figure 5. This figure shows how the amplification factor at a given time step was scaled according to the sea ice concentration in each gridcell. Each grey line indicates how the applied amplification factor was modified according to the gridcell sea ice concentration, with an example highlighted in red where the maximum amplification effect of 0.95 is reached when we assume all the open water is associated with leads (i.e. for sea ice concentrations greater than 90%).

NERSC conducted several tests of this new scheme to ensure reasonable constraints were applied to the surface fluxes. We capped the amplification effect at +/- 15%, so that regardless of the atmospheric stability, the effect would not extend outside of the range of values explored using the turbulence resolving simulations. This was done to prevent non-physical extrapolations of the functional dependency.

A second important issue in global climate models is how they limit the sea ice concentration in a gridcell. In the Norwegian Earth System model the sea ice concentration is allowed to reach 100% in a given gridcell, which is the case across much of the central Arctic. Therefore it is only in the marginal ice zone where the effects of leads become important. It is possible to specify alternative maximums in the sea ice concentration (e.g. 98%) to allow that even in dense ice-pack there is often some amount of open water due to the dynamic deformation of sea ice. This can be done in the Norwegian Earth System Model and is already done in many climate models. This could substantially alter the effect of introducing this leads scheme as the modification of the sensible heat fluxes would occur not just in the marginal ice zone, but also in the central Arctic. However, the open water fraction is normally limited to around 2%, so even if there is a strong modification of these fluxes due to the leads scheme, it may not substantially change the gridcell energy budget. There was not the opportunity to explore this issue within the set of simulations performed here, but is left as an open question for further research.

Strongly stable stratification

NERSC updated the parametrization scheme which describes turbulent mixing in the surface layer (the lowermost part of the atmospheric boundary layer) based upon observed fluxes over sea ice in cases of strongly stable thermal stratification (Grachev et al, 2007). This involved introducing new stability functions which describe how the wind speed and temperature of the atmosphere change with height, depending upon the stability of the atmosphere. These are based on the well-established Monin-Obukhov similarity theory (Monin and Obukhov, 1954). These stability functions are not part of the atmospheric model but are included separately in the sea ice model (CICE) and the land-surface model (CLM) as the solution to these are solved iteratively in combination with the surface properties.

Monin Obukhov similarity theory postulates that the vertical gradient in the wind speed and potential temperature are functions of height, surface turbulent scaling-parameters, and dimensionless functions of the atmospheric stability (Figure 6). It is these universal scaling functions that we changed in the climate model. The original functions were derived from observations made at flux-towers in the Netherlands and while they capture the functional behaviour well at moderate atmospheric stabilities, they do not cover the range of stability found in the extreme winter-time conditions over sea ice. The functional forms we introduced here converge to the original formulation in weakly stably-stratified conditions, and only diverge under strongly-stable stratification.

$$\frac{\kappa z}{u_*}\frac{\mathrm{d}U}{\mathrm{d}z} = \varphi_m(\zeta), \qquad \varphi_{m\ \mathrm{SHEBA}} = 1 + \frac{a_m\zeta(1+\zeta)^{1/3}}{1+b_m\zeta} \equiv 1 + \frac{6.5\zeta(1+\zeta)^{1/3}}{1.3+\zeta},$$

$$\frac{\kappa z}{\theta_*}\frac{\mathrm{d}\theta}{\mathrm{d}z} = \varphi_h(\zeta), \qquad \varphi_{h\ \mathrm{SHEBA}} = 1 + \frac{a_h\zeta + b_h\zeta^2}{1+c_h\zeta+\zeta^2} \equiv 1 + \frac{5\zeta+5\zeta^2}{1+3\zeta+\zeta^2},$$

Figure 6. The equations used in Monin Obukhov similarity theory to describe the vertical gradient in the wind speed, U, and potential temperature, θ, as a function of height, z, turbulent scaling properties that are constants in the surface layer, u_* and θ_*, and universal, dimensionless scaling functions, φ_m and φ_h. These scaling functions depend upon a normalised length scale which characterises atmospheric stability, ξ.

Altering these stability functions had a large effect on the diagnosed near-surface air temperature (2m above the surface) and partly corrects the systematic bias in NorESM to under-estimate the mean surface air temperature in winter. Since this is a common bias in many global climate models, even in the new generation of CMIP6 models, the introduction of these revised stability relations could bring an improved characterisation of the variability and sensitivity of near surface atmospheric properties in the Arctic winter.

Evaluation criteria

NERSC created new evaluation criteria for assessing model performance in the Arctic and created a new diagnostics package for assessing model representation of the atmospheric boundary layer for both the

Norwegian Earth System Model and any CMIP model results (i.e. CMORized model output). We expected that the representation of stable boundary layers and the climatology of the atmospheric boundary layer would strongly affect the sensitivity of the surface climate in the Arctic to changes in radiative or thermal forcing. In previous work we had linked both the magnitude of internal variability and the response-to-forcing of the surface air temperature to the climatology of the atmospheric boundary layer. We therefore created two sets of evaluation metrics to determine how our model development had changed both the climatology in the model and the response of the surface air temperature to changes in forcing.

Arctic amplification

The first evaluation criteria we looked at is the metrics we use for quantifying Arctic amplification. Because of the shallow, stably-stratified boundary layers in the Arctic, any additional thermal forcing introduced at the surface gets trapped in a thin layer of air close to the surface. Since the heat is distributed through such a thin layer of air (compared to at lower latitudes) the near-surface air temperature in the Arctic warms more in response to the same change in forcing (Esau et al., 2012). This is the primary cause of Arctic amplification (Davy and Esau, 2016; Pithan and Mauritsen, 2016). However, this process acts across timescales, affecting both short term and highly-varying forcings associated with natural variability; and the long term change in forcing due to anthropogenically-driven climate change. This raised the question about the different ways we measure Arctic amplification and what they tell us about change in the Arctic and our ability to model changes in the Arctic across timescales.

NERSC first conducted a literature review to determine the metrics used to describe Arctic amplification. Several metrics have been introduced, all using the surface air temperature and comparing the Arctic to the rest of the northern hemisphere: the most commonly used being the difference in anomalies; a second is to take the difference in trends; one can take the difference in the variability; and finally to find the regression coefficient between anomalies in the two regions. Each method has its own advantages and disadvantages. There is also different temporal behaviour in each metric, and some are more consistent in the different observational records than others. A full summary of the properties of each of these metrics and their consistency in different observational and reanalysis datasets was published in our paper in the International Journal of Climatology (Davy et al., 2018). The purpose of this study was to determine the uncertainty from observational and reanalysis records of historical Arctic amplification to provide a robust baseline against which to compare the model results.

An example of the application of these four metrics using a 21-year moving window is shown below in Figure 7, adapted from Davy et al. (2018). One can see that, while there is generally good agreement between all products, there are some large differences even in the period of good satellite observations (since 1979) and between the two gridded-observation products, GISSTEMP and Had4Krig-v2. This emphasizes the importance of accounting for observational uncertainty, and using multiple observational and reanalysis products when assessing climate model skill in the Arctic.

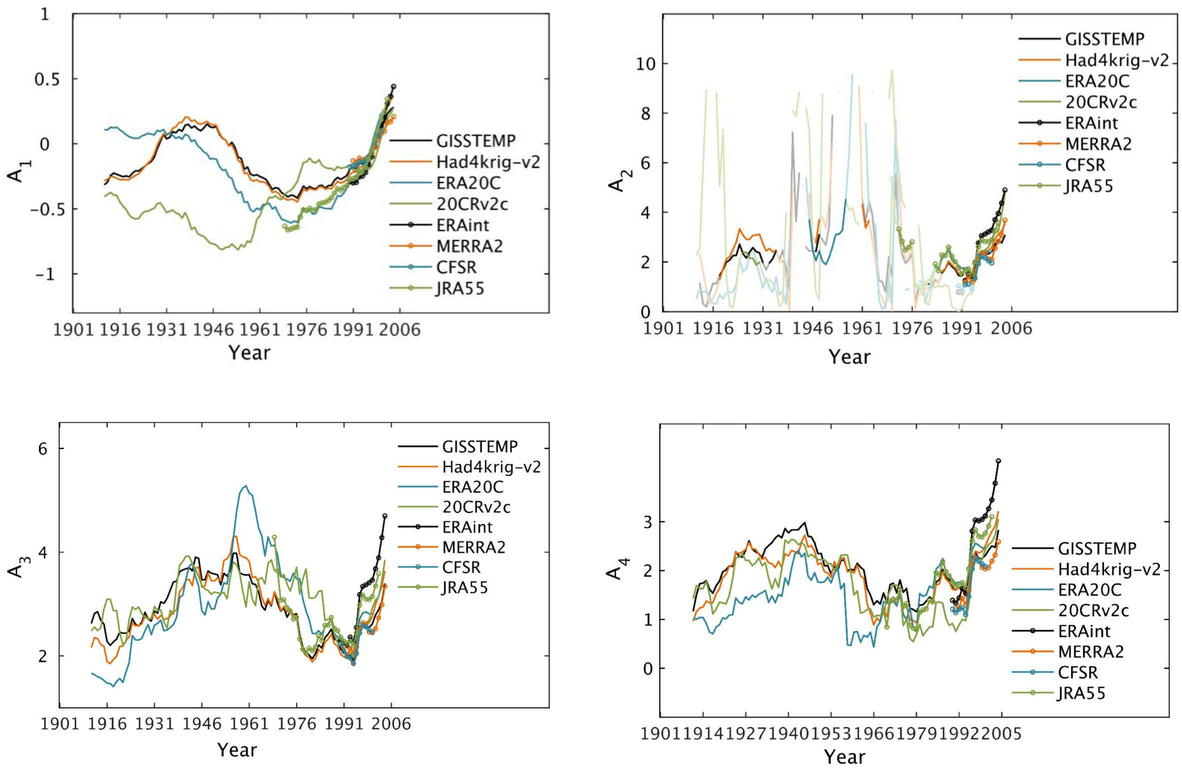

Figure 7. Four metrics for Arctic amplification based on comparing surface air temperature anomalies in the Arctic (defined as >66 N) and the rest of the Northern hemisphere. Clockwise from top-left these are A1: the difference in anomalies, A2: the difference in trends, A3: the difference in variability, A4: the coefficient of the regression of the anomalies. These metrics were calculated for two gridded-observation products, GISSTEMP and Had4Krig-v2, and six reanalysis products.

Planetary boundary layer depth

The depth of the atmospheric boundary layer acts to buffer changes in the surface climate in response to changes in thermal and radiative forcing. It is therefore an important parameter in determining the sensitivity of the surface climate, both in terms of natural variability and response to forcing changes such as enhanced CO2 concentration. The climatology of the atmospheric boundary layer depth can explain a large part of the spatial and temporal differences in surface air temperature variability and trends, and is the leading cause of Arctic amplification. Despite this, it is not considered an essential climate variable and although there have been model-observation intercomparisons for some specific climate models, there has been no systematic evaluation of the atmospheric boundary layer depth across all CMIP models. NERSC conducted the first such systematic analysis by taking advantage of the CMIP5 archives.

We first reviewed all methods for defining the depth of the atmospheric boundary layer, and chose the method which best suited the available data: the bulk-Richardson method. We then created an evaluation software which would take standardized climate model output and apply this method to find the atmospheric boundary layer depth. The method and results were summarised for a peer reviewed publication and published in the Journal of Climate (Davy, 2018).

Of particular interest to us was the climatology of the atmospheric boundary layer in the Arctic in these models and the inter-model spread. An example of this is given below in Figure 8. This is the winter (December-January-February) climatology and normalised inter-model spread in an ensemble-mean of 16 CMIP5 climate models. The standard deviation of the ensemble is relatively large (>15%) across much of the Arctic regions. This we attribute to large differences in the minimum atmospheric boundary layer depth that occurs under strongly stable stratification across much of the Arctic (Davy, 2018). In a stably stratified atmosphere turbulence in the atmospheric boundary layer is principally driven by wind shear. We demonstrated that over the sea ice in winter it is the differences in near-surface wind speed between the models that explains almost all the differences in atmospheric boundary layer depth (Davy, 2018). In contrast, in the summertime (June-July-August) it is the differences in the surface sensible heat flux that explain almost all the inter-model differences in the atmospheric boundary layer depth over ice.

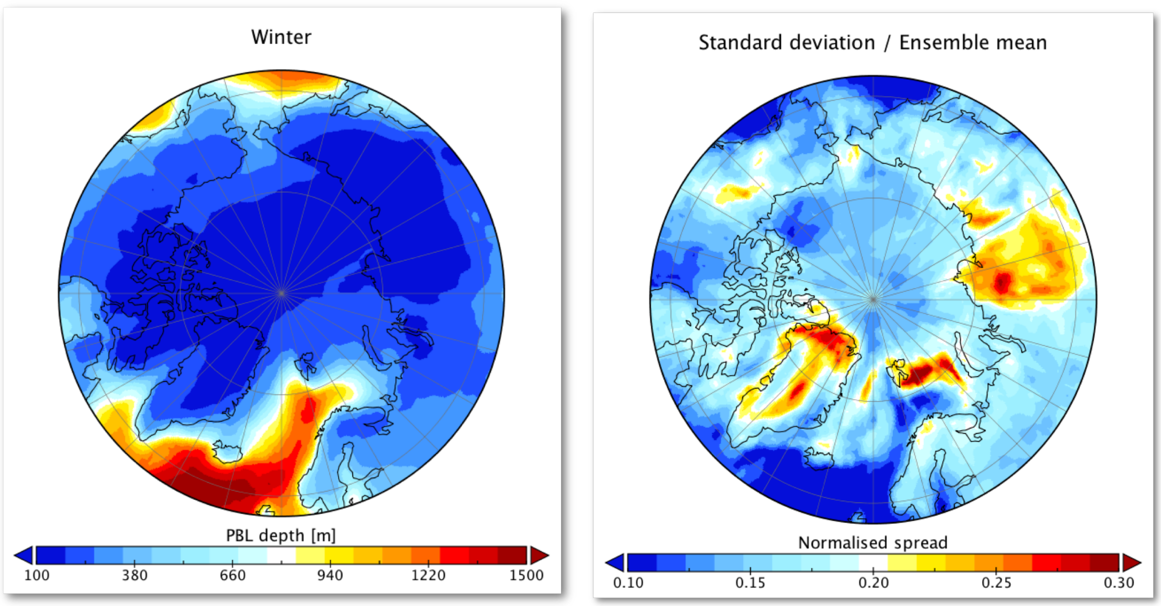

Figure 8. The climatology of the winter (December-January-February) atmospheric boundary layer depth (left) and the normalised inter-model spread in this climatology (right) from an ensemble of 16 global climate models. Data taken from the 1979-2004 historical simulations of CMIP5.

Main results achieved

The key findings: The presence of leads in sea ice dramatically alters the surface energy balance in the Arctic. There is a large seasonal cycle to the effect of the presence of leads, because the flux from the leads depends strongly on the background stability in the atmosphere. In the winter when the atmosphere is often strongly stably stratified, the leads strongly amplify the surface sensible heat flux coming from open water.

There is a large spread in contemporary climate models in terms of the climatology of the atmospheric boundary layer over sea ice. In our analysis we have attributed this spread to differences in the near surface wind speed in the winter, and to differences in the surface sensible heat flux in the summer. This gives the community a clear indication of which processes are important in which season when it comes to reducing model spread in atmospheric boundary layer depth.

We assessed the consistency of different metrics of Arctic amplification in observations and reanalysis and found that even in the well-observed recent history there are quite large differences in the degree of Arctic amplification, depending upon the choice of metric and dataset used. This work provides the range of uncertainty from observational and reanalysis products and provides a robust constraint for climate model comparisons.

Progress beyond the state of the art

Novelty of model development

This is the first time that the effects of leads in ice have been included in a climate model and we have produced the first estimate of the effect these features have on the surface climate in the Arctic.
The introduction of a modified scheme to describe the near-surface vertical gradients in atmospheric properties over sea ice based upon observations made in the Arctic winter marks the first time this has been implemented within a global climate model.

Development of evaluation criteria

NERSC conducted the first review of existing metrics of Arctic amplification and their consistency within the observational record; and NERSC created a new metric for global climate models which characterises the sensitivity of the surface climate to changes in forcing using a definition of the depth of atmospheric boundary layer.

Many metrics for evaluating Arctic amplification have been introduced in the literature, and NERSC provided the first comprehensive review of all the available metrics and their consistency within eight of the most commonly used gridded-observation and reanalysis products.

NERSC conducted the first inter-model comparison of the depth of the atmospheric boundary layer in global climate models. This included an analysis of the causes of model spread, and a demonstration of how this model spread explains a large part of the differences between climate models as to the sensitivity of the Arctic surface climate to changes in forcing.

Impact

The work summarised in this report directly contributed to the intended impacts of :

- "**Improved representation of processes specific to the Arctic**" and
- "**Improved representation of stable boundary layers over ice**".

We developed a new parameterization scheme to describe the impact of turbulent heat fluxes from leads and implemented an improved representation of turbulent exchange under strongly stable stratification within the Norwegian Earth System Model. We have prepared a user-guide for implementing these model developments within the other Earth System Models used within the consortium and others around the world.

The dynamics and thermodynamics of leads in sea ice are a phenomenon unique to the polar environments and have previously been hypothesized to be one of the most important unaccounted-for phenomena in determining the Arctic surface energy balance, especially in winter. The scheme implemented here represents the first of its kind in including the contribution of fluxes from leads within a global climate model.

Lessons learned and Links built

Challenges of model development

The climate effect of leads was hard to predict because of the sensitivity to the background stability of the atmosphere, which is in-turn affected by the presence of leads. The way the scheme was designed we could expect to get enhanced heat fluxes under stable stratification but damped heat fluxes under weakly unstable stratification. The net effect therefore depended upon the shape of the probability density function of the background stability, and the strength of the feedback effect from the leads affecting the stratification.

There are many parameters within the NorESM which can be used to alter the surface climatology in the Arctic – especially within the sea ice model. For example, there is a high sensitivity to the definition of the albedo of snow-covered ice even within constraints from observations. These parameters are often used to tune the climate within the Arctic under historical simulations and so the values used in the model correspond to a local optimum. This creates a problem when implementing a new parametrization scheme as we did here: even if the new scheme represents an improvement in capturing the physical processes in the Arctic, it is likely to make the surface energy budget in the Arctic worse when first implemented. In order to realise the benefits of including this new physics it is necessary to re-tune the model using the tunable elements of other physics schemes, such as the snow albedo. This is a laborious process and requires holistic knowledge of the physics packages relevant in the Arctic, how they interact, and the range of tunable parameter space that can be used. For the time being this is done in a rather ad-hoc way by experienced modellers; but the development of the use of data assimilation within a coupled environment brings the potential to have a more objective method of conducting model development.

There was also a substantial challenge in creating new physics schemes that would work well across different model architectures. Previously overlooked aspects of a model can become important. For example, the maximum sea ice concentration that can be reached in a gridcell of great importance in implementing the leads scheme. However, this was an extremely valuable experience in creating robust methods for conducting model development across different platforms and developing approaches to resolve the common difficulties that arise. This experience will greatly ease future co-development efforts.

Contribution to the top level objectives of Blue-Action

This deliverable contributes to the achievement of all the objectives and specific goals indicated in the Description of the Action, part B, Section 1.1: http://blue-action.eu/index.php?id=4019

Objective 4 Improving the description of key processes controlling the impact of the polar amplification of global warming in prediction systems

The work presented in this deliverable supports the achievement of objective 4: we have introduced new model physics into the Norwegian Earth System Model to improve the description of surface coupling processes in the Arctic. This was done in two stages: firstly by introducing a wholly novel scheme for representing the fluxes from leads in ice; and secondly by improving the stability functions used to describe the near-surface gradients in wind, temperature, and humidity. Together these play an important role in influencing the state of the atmospheric boundary layer, which in turn determines the degree of Arctic amplification.

Objective 8 Transferring knowledge to a wide range of interested key stakeholders, including the scientific community, via intensive dissemination activities, organisation of joint workshops with other projects, and scientific publications.

References (Bibliography)

These are the papers or publications you consulted during the research.

- Davy, R., 2018. The Climatology of the Atmospheric Boundary Layer in Contemporary Global Climate Models. *Journal of Climate*, *31*(22), pp.9151-9173.
- Davy, R., Chen, L. and Hanna, E., 2018. Arctic amplification metrics. *International Journal of Climatology*, *38*(12), pp.4384-4394.
- Davy, R. and Esau, I., 2016. Differences in the efficacy of climate forcings explained by variations in atmospheric boundary layer depth. *Nature communications*, 7, p.11690.
- Esau, I.N., 2007. Amplification of turbulent exchange over wide Arctic leads: Large-eddy simulation study. *Journal of Geophysical Research: Atmospheres*, *112*(D8).
- Grachev, A.A., Andreas, E.L., Fairall, C.W., Guest, P.S. and Persson, P.O.G., 2007. SHEBA flux–profile relationships in the stable atmospheric boundary layer. *Boundary-layer meteorology*, *124*(3), pp.315-333.
- Marcq, S. and Weiss, J., 2012. Influence of sea ice lead-width distribution on turbulent heat transfer between the ocean and the atmosphere.
- Monin, A.S. and Obukhov, A.M., 1954. Basic laws of turbulent mixing in the surface layer of the atmosphere. *Contrib. Geophys. Inst. Acad. Sci. USSR*, *151*(163), p.e187.

Dissemination and exploitation of Blue-Action results

Dissemination activities

Type of dissemination activity	Title	Date and Place	Estimated buget	Type of Audience	Estimated number of persons reached
Participation at a workshop	10-yearly workshop on Stable boundary layers	Delft (NL),27th March - 2nd April 2017	See form C of the partner organisation	Scientific community (research)	250
Participation to a conference	Blue-Action annual meeting	Lisbon (PT) 17-29 November 2018	See form C of the partner organisation	Scientific community (research), , Industry, Policy makers	100
Presentation at a conference	Bjerknes annual meeting 2018	Bergen (NO), 24th November 2018	See form C of the partner organisation	Scientific community (research)	300
Web-site	Nansen center website	Bergen (NO) 28th Jan 2019	See form C of the partner organisation	General Public	>200

Peer reviewed articles

Title	Authors	Publication	DOI	Is Blue-Action correctly acknowledged?	How much did you pay for the publication?	Status?	Open Access granted	Comments on embargo time imposed by the publisher	If in Green OA, provide the link where this publication can be found
The climatology of the atmospheric boundary layer	Davy, Richard	Journal of Climate	10.1175/JCLI-D-17-0498.1		See form C of the partner	Published on 17 April 2018	Yes	Available in open access since 17 April 2019	
Arctic amplification metrics	Davy, Richard ; Chen, Linling; Hanna, Edward	International Journal of Climatology	10.1002/joc.5675		See form C of the partner	Published on 13 July 2018	Yes	Available in open access since 13 July 2019	

Uptake by the targeted audiences
As indicated in the Description of the Action, the audience for this deliverable is the general public (PU) is and is made available to the world via CORDIS.

This is how we are going to ensure the uptake of the deliverables by the targeted audiences:
We have published two papers detailing: the climatology of the atmospheric boundary layer in climate models and causes of model spread and; a review of the different metrics for Arctic amplification and their consistency within eight of the most commonly used observational and reanalysis products. Both of these papers were published in peer-reviewed journals with relatively high impact factors for the field, and so are expected to have good uptake within the research community.

A practical guide as to how to implement the model development developed by NERSC will be prepared and presented at the annual meeting of Blue-Action in Edinburgh, 15-17 October 2019.