Improved key process in representing Arctic warming

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Lead authors
Nansen Environmental and Remote Sensing Centre (NERSC): Richard Davy, Yongqi Gao
Centre National de la Recherche Scientifique (CNRS): Guillaume Gastineau
Danish Meteorological Institute (DMI): Tian Tian
Institute of Atmospheric Physics of the Chinese Academy of Sciences (IAP-NZC): Ying Zhang

Reviewer
Danish Meteorological Institute (DMI): Chiara Bearzotti

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Cover picture: Leads in sea ice, courtesy of Wendy Pyper

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Summary for publication

In the work presented in this deliverable the Blue-Action teams 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 due to the presence of leads in the sea ice cover and turbulence under strongly stable thermal stratification.

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 characterizes 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. Together, this gives us a scheme to describe how the presence of leads affects the surface sensible heat flux, and this depends upon the concentration of sea ice and the background atmospheric stability. We implemented this scheme in four climate models (NorESM, EC-Earth3, IPSL/ LMDZ6A and CAS-ESM/ IAP4) and tested the scale of the effect using multiple single-model ensemble simulations of historical climate.

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 greatly 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. The net effect is to increase near-surface temperatures over sea ice in winter, with little or no change in the summer. Therefore this scheme may be used to address the long-standing winter cold bias over ice in many contemporary global climate models, as shown in CMIP6.

Work carried out

Development of the climate models in the consortium

NERSC conducted model development for the Norwegian Earth System model (NorESM) and created a guide (https://zenodo.org/record/4728073) for other partners who implemented the same leads scheme within their own climate models: DMI implemented the scheme within EC-Earth3, CNRS implemented it in LMDZ6A, the atmospheric component of the IPSL Climate Model, IAP-NZC implemented the scheme within IAP4, the atmospheric component of the Chinese Academy of Science's Earth System Model.

The first piece of model 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 scheme

We created a novel scheme for representing the effects of leads in ice on the surface sensible heat flux to the 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.

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.

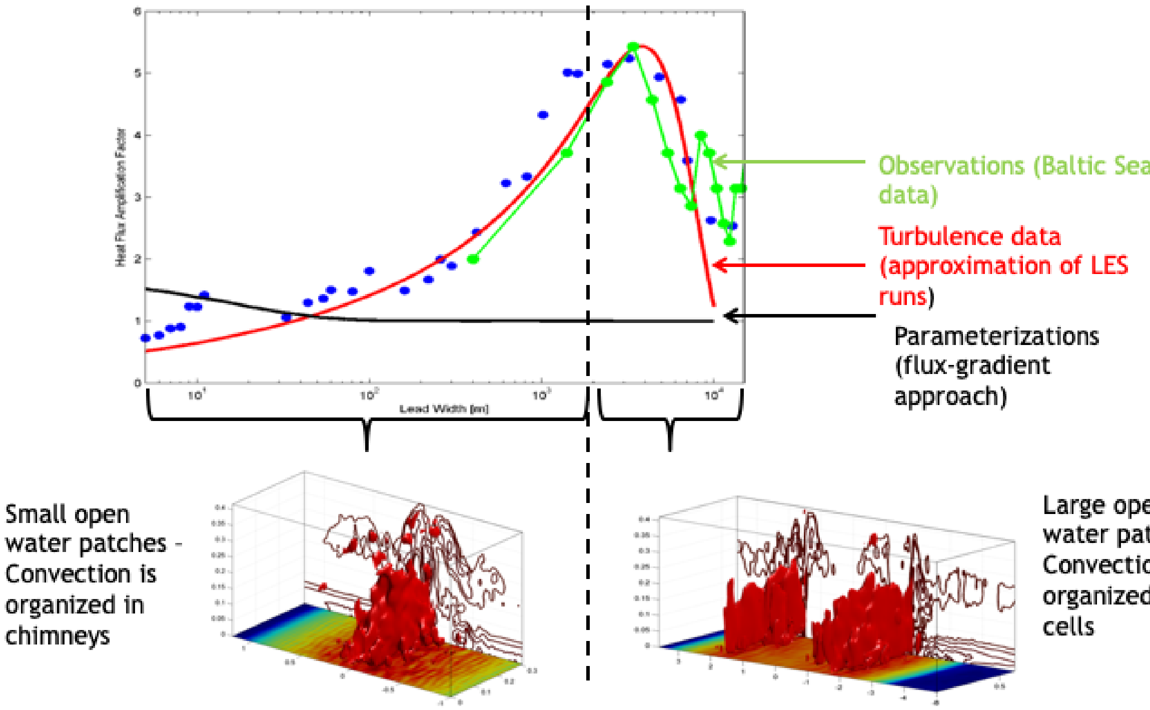

Figure 1: The top plot shows the heat flux amplification factor (how much larger the heat flux coming from leads is compared to the heat flux form open water under the same air-sea temperature difference) as a function of the width of the leads. The blue dots indicate results from individual model simulations, 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 an equal area of open water under the same atmosphere-ocean temperature difference; $x\,[m]$ is the width of the lead; and λ_{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.

We 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. Based on the analysis of Marcq and Weiss (2012) we take the distribution of lead widths to follow 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.

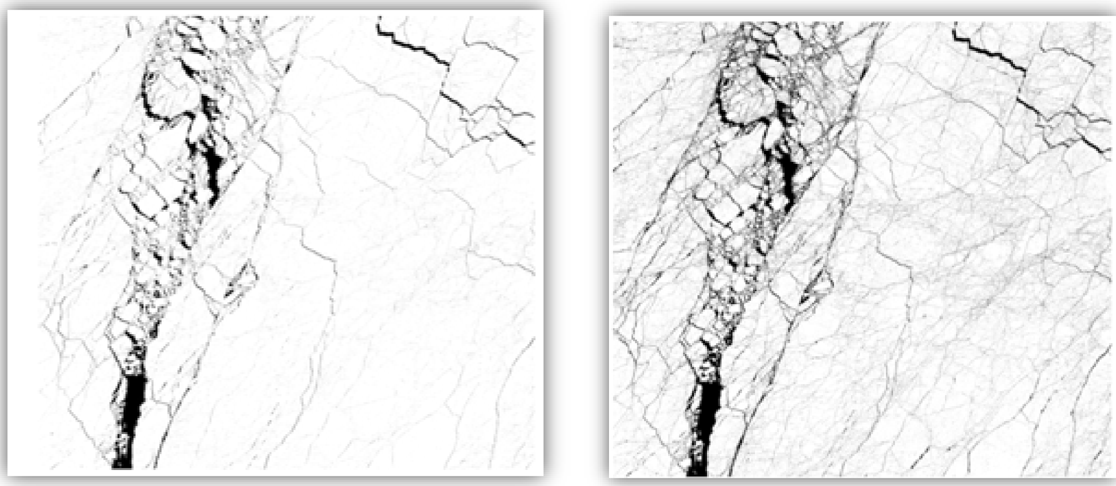

Figure 2: An example of SPOT images processed using two different, but reasonable, choices of the threshold for luminance to separate the presence of leads from ice (Marcq and Weiss, 2012).

The power law fit to these satellite images under the two different luminosity thresholds 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.

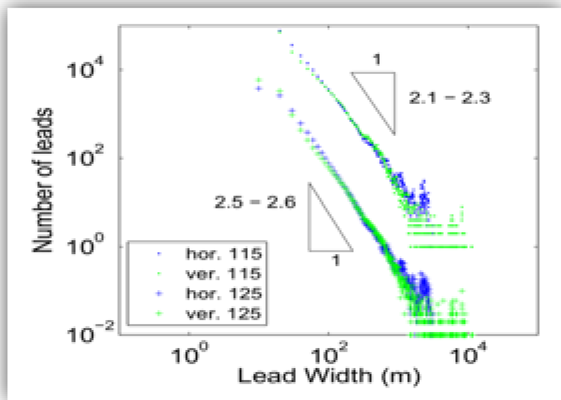

Figure 3: The number of leads as a function of lead width derived using the two different luminance thresholds shown in Figure 2, and using either a horizontal (hor.) or vertical (ver.) scan to identify the leads. The estimated coefficient for the power law distribution is indicated using the triangles. 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 an equal area of 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 dependent 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. Since in winter the atmosphere is typically strongly stably-stratified over ice, we can expect this scheme to result in an increase in the sensible heat flux from open water, and hence increase the surface air temperature.

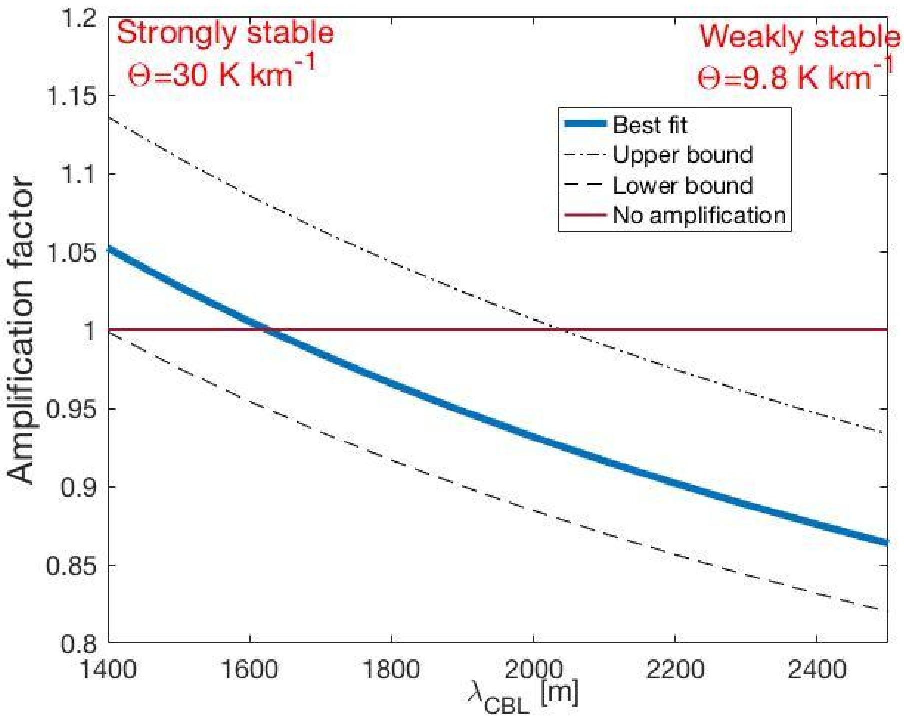

Figure 4: The amplification of sensible heat flux from all leads

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).

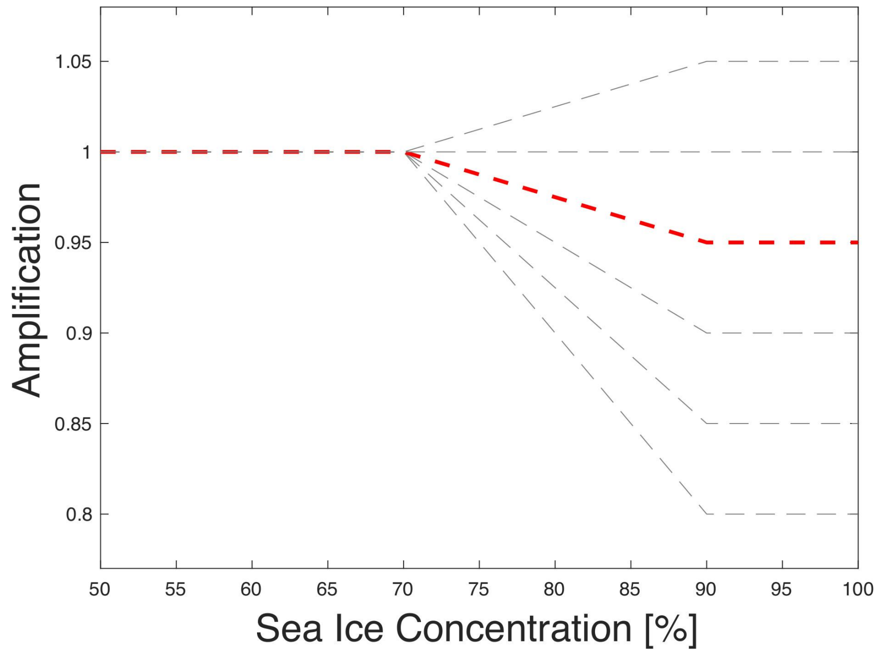

Figure 5: This figure shows how the amplification factor at a given time step was scaled according to the sea ice concentration in each gridcell. Each grey line indicates how the applied amplification factor was modified according to the gridcell sea ice concentration, with an example highlighted in 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%).

We 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. If a climate model allows the sea ice concentration to reach 100% in a given gridcell this limit can be reached 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 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. Even when the open water fraction is limited to around 2%, the modification of sensible heat fluxes due to the leads scheme can substantially change the gridcell energy budget and thus the surface air temperature, as we show below.

Effect of leads in ice within climate models

NERSC assisted with the implementation of the leads in ice scheme into the following climate models:

- NorESM2 (Seland et al., 2020);
- LMDZ6A (Hourdin et al., 2020), the atmospheric component of the IPSL-CM6A-LR model, thanks to the contribution of the CNRS team;
- EC-Earth3 climate model of the EC-Earth consortium (Döscher et al., 2021), thanks to the contribution of the DMI team;
- IAP4, the atmospheric component of the Chinese Academy of Science's Earth System Model (Zhou et al., 2020), thanks to the contribution of the IAP-NZC team.

For the Norwegian and French climate models an ensemble of simulations of historical climate were performed using the baseline simulations "A1" as the control group (see D3.1). Both the Norwegian and French models used a 20-member ensemble for the simulations including the leads scheme, while they had a 20- and 10- member ensemble respectively for the control runs. These ensemble sizes were sufficient to find a statistically-significant effect of the leads scheme on the surface sensible heat flux and air temperature. A set of ensemble simulations using the same experimental protocol are also planned by the IAP-NZC team for the IAP model, and by the DMI team for the EC-Earth3 model. Once these simulations are completed the results from the multi-model ensemble will be prepared for publication by a collaboration between the CNRS, DMI, NERSC and IAP-NZC teams.

This Leads scheme is designed to alter the surface sensible heat flux based on the presence of leads in sea ice, so the sensible heat flux over sea ice is where one can expect to see the first-order effects. Figure 6 shows the climatological mean difference in the surface sensible heat flux between the ensemble mean of the simulations which include the effect of leads and the control simulations. This is shown for the annual mean and for the months of March and September which correspond to the maximum and minimum of the sea ice extent respectively and therefore can be used to characterize the winter and summer responses. In the annual mean we can see that the net effect of accounting for leads is a modest increase in the sensible heat flux over sea ice (on the order of 1-2 W m-2), but also over land across the northern hemisphere. However, this modest change in the annual mean masks a strong seasonality to the response, as we predicted based on the sensitivity to the background atmospheric stability. In March when the atmosphere is generally strongly stably stratified over sea ice we see a relatively strong increase in the sensible heat flux of around 4 W m-2, and we see a large reduction in the sensible heat flux in the marginal ice zones in the Atlantic and Pacific sectors. This pattern is exactly what we would predict based upon the sensitivity of the scheme to the background atmospheric stability: in the marginal ice zone the atmosphere is more well-mixed in the winter due to the strong air-sea fluxes and so the leads scheme acts to reduce the net flux in this region. Whereas over ice where the atmosphere is strongly stably-stratified, this leads scheme tends to strongly amplify the fluxes coming from the open water. Since the regions of open water in the central Arctic are relatively small (<5%), the net effect on the fluxes is not large, but it nevertheless has a large effect on the winter temperatures over sea ice. We see no significant net effect on the fluxes over land in March. In contrast, in September the atmosphere is much closer to neutrally stratified everywhere in the Arctic, so the leads scheme has very little effect on the sensible heat fluxes.

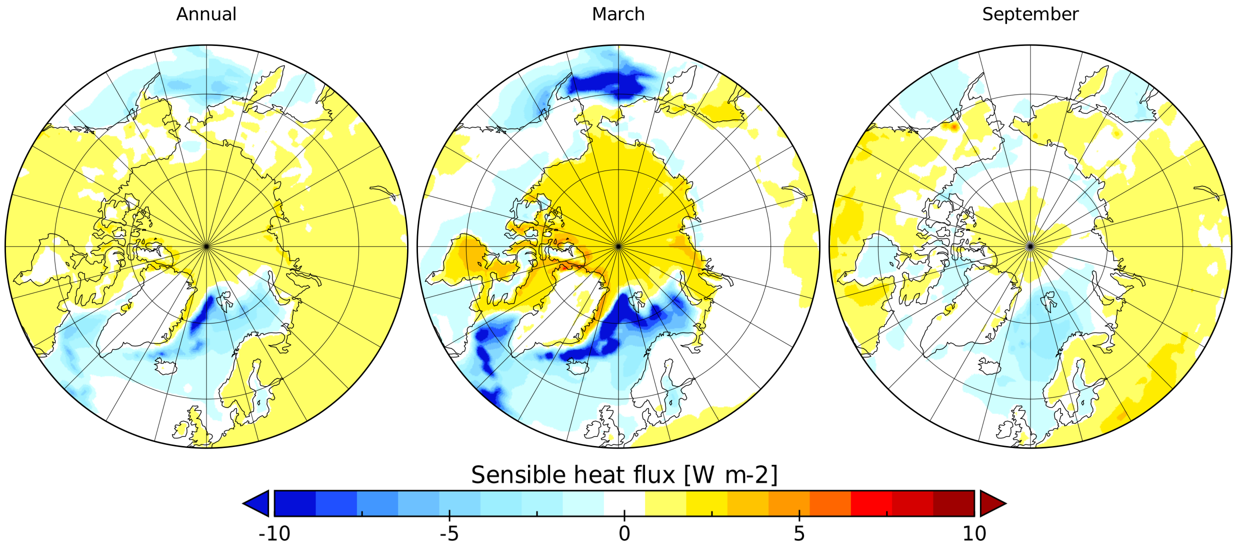

Figure 6: The difference in the climatological mean surface sensible heat flux for the period 1980-2014 from the simulations with the leads scheme compared to the control run. The difference in the climatologies is shown for the annual mean (left), and the months of March (middle) and September (right).

The general increase in sensible heat flux over sea ice results in a warming of the near surface air temperatures. This is summarised in Figure 7 which shows the difference in climatological mean surface air temperature between the ensemble mean of simulations with leads and the control simulations. This is shown for the annual mean and for the months of March and September. We can see that the largest temperature changes occur over the interior of the ice pack with no change in temperature over the open ocean despite the difference in surface fluxes seen over the ocean in Figure 6. This is because over the ocean these changes in heat flux are small compared to the climatological-mean heat fluxes. Whereas over sea ice even small changes in the sensible heat flux can strongly affect the surface air temperature due to the presence of shallow, stably stratified boundary layers (Davy, 2018). These shallow boundary layers trap any additional heat added at the surface in a thin layer of air close to the ground, and because this heat is distributed through a thin layer of air, it warms relatively rapidly (Davy and Esau, 2016).

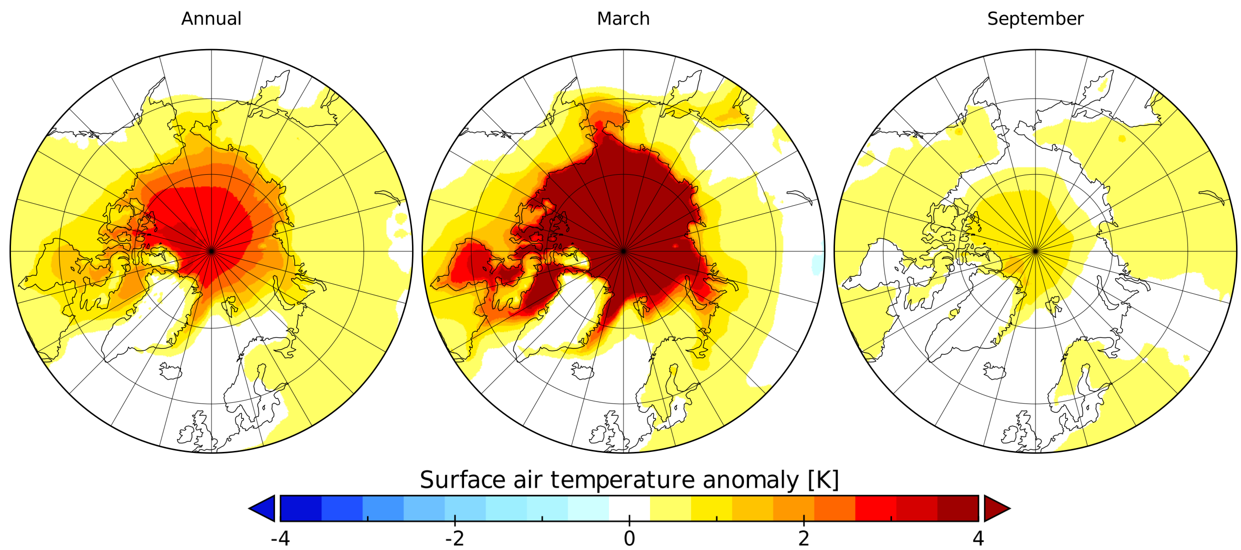

Figure 7: The difference in the climatological mean surface air temperature for the period 1980-2014 from the simulations with the leads scheme compared to the control run. The difference in the climatologies is shown for the annual mean (left), and the months of March (middle) and September (right).

We can see how the extra heat added to the atmosphere from the enhanced surface fluxes gets vertically distributed from the vertical profile of air temperature anomalies in Figure 8. In the annual average we can see that the principal effect is a warming which is strongest closest to the surface within the Arctic and decreases rapidly with height. This is consistent with our expectation that surface heat anomalies are trapped close to the surface by the presence of a strong stably stratified atmospheric boundary layer (Davy and Esau, 2016). This is confirmed when we contrast the profiles of temperature anomalies in March and September. In March the sea ice extent is at its maximum, and the atmosphere is strongly stably stratified. We can see that the surface warm anomalies are very strong across the whole Arctic at this time, but that warming is mostly contained close to the surface, below 950 hPa. There is some indication that the stratosphere (range 100 hPa to 1 hPa) is slightly warmed in March by the inclusion of the leads scheme. In contrast, in September when the sea ice reaches its minimum and the atmosphere is more neutrally-stratified we can see there is very little surface warming due to the presence of leads. The same seasonality can be seen over the sea ice in the southern ocean, with similar magnitudes of surface warming due to the presence of leads as is seen in the Arctic.

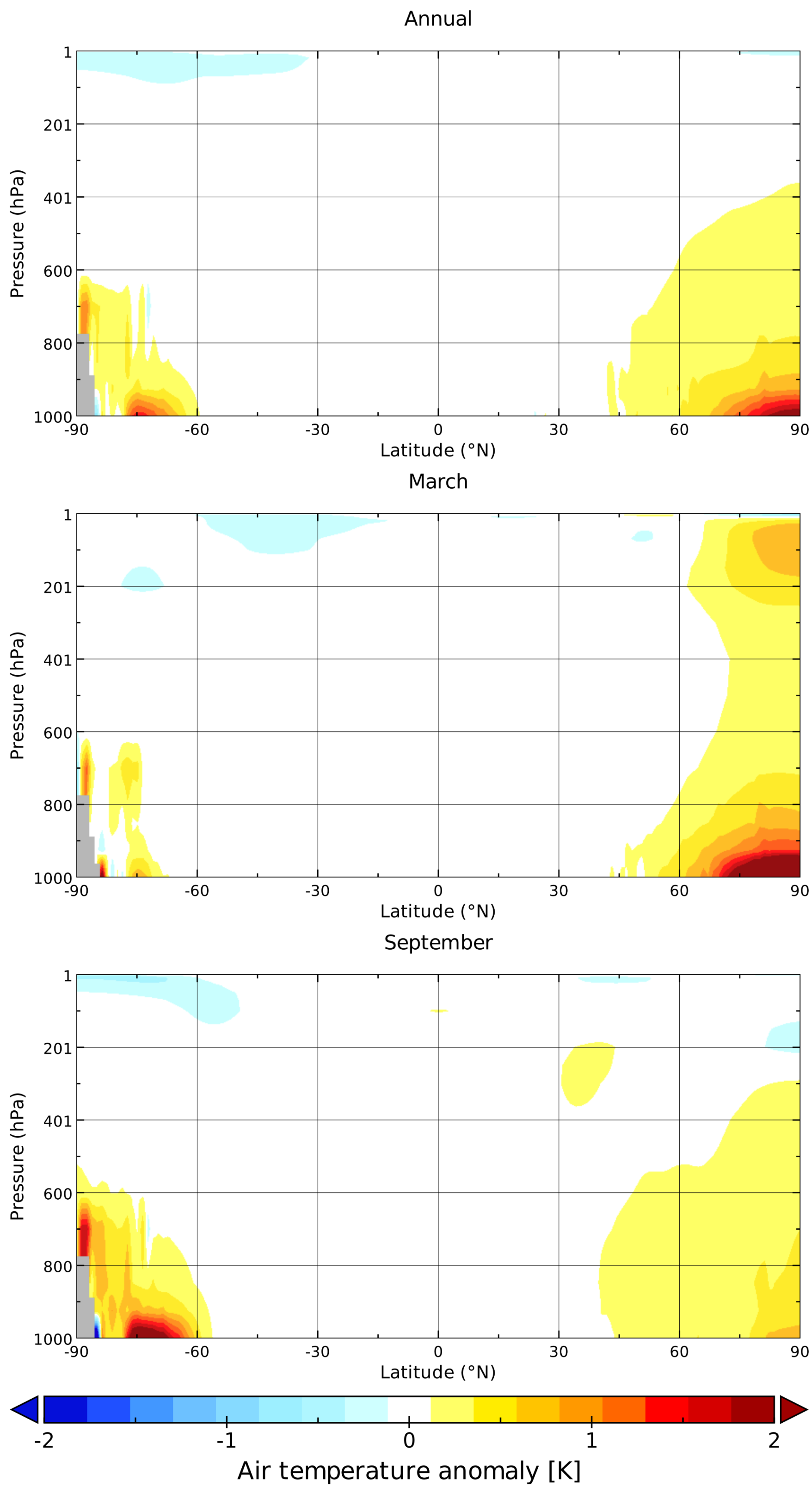

Figure 8: The difference in the climatological mean air temperature for the period 1980-2014 from the simulations with the leads scheme compared to the control run. The difference in the climatologies is shown for the annual mean (top), and the months of March (middle) and September (bottom).

Strongly stable stratification

NERSC updated the parametrization scheme in NorESM 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 9). 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 9: 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 can have a large effect on the diagnosed near-surface air temperature (2m above the surface) and partly corrects the systematic bias in contemporary climate models to under-estimate the mean surface air temperature in winter (Davy and Outten, 2020). 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 10, 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.

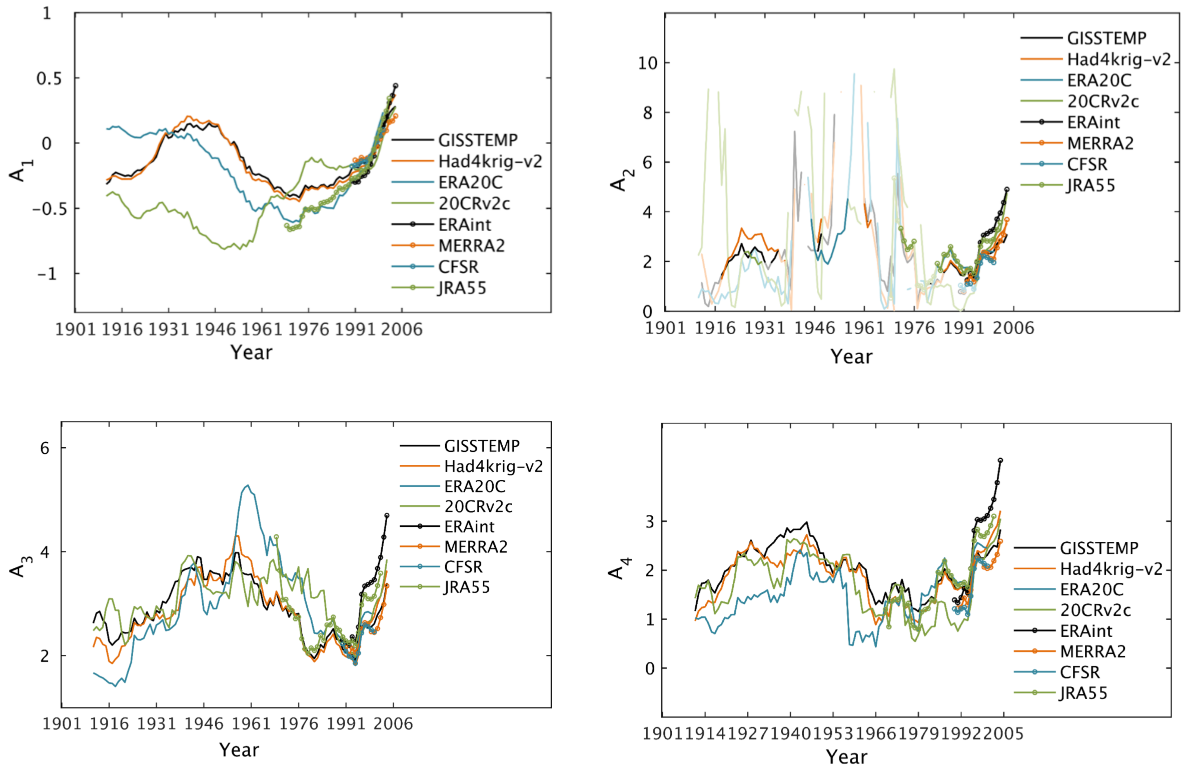

Figure 10: Four metrics for Arctic amplification based on comparing surface air temperature anomalies in the Arctic (defined as >66 N) and the rest of the Northern hemisphere. Clockwise from top-left these are A1: the difference in anomalies, A2: the difference in trends, A3: the difference in variability, 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 11. 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.

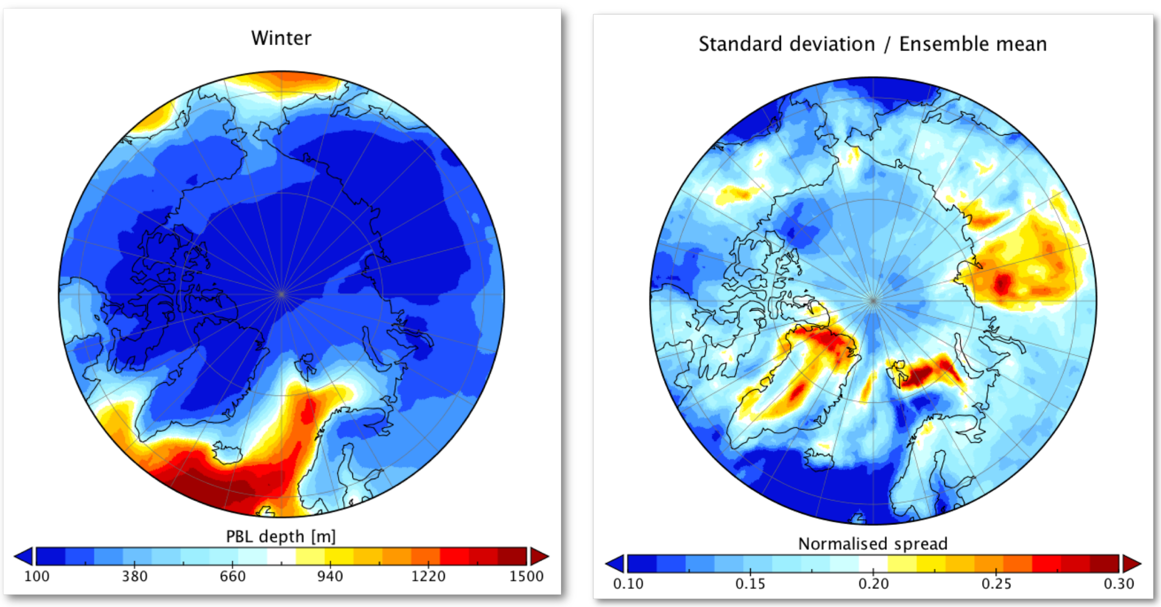

Figure 11: The climatology of the winter (December-January-February) atmospheric boundary layer depth (left) and the normalised inter-model spread in this climatology (right) from an ensemble of 16 global climate models. Data taken from the 1979-2004 historical simulations of CMIP5.

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 turbulent structures over leads greatly 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. This is important because atmospheric boundary layer depth determines the sensitivity of surface air temperature to changes in radiative and thermal forcing.

- 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

The model development by the CNRS, IAP-NZC, DMI, and NERSC partners represents the first time that the effects of turbulent dynamics over leads in ice have been included in climate models. We have also produced the first estimate of the effect these dynamics have on the surface climate in the Arctic using an ensemble from the CNRS and NERSC teams.

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 global climate models.

Development of evaluation criteria

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

We 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 the atmospheric boundary layer. NERSC conducted the first inter-model comparison of the depth of the atmospheric boundary layer in global climate models which included an analysis of the causes of model spread.

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 this within four climate models: the Norwegian Earth System Model, the

EC-Earth3 climate model, the Chinese IAP model, and the French LMDZ6A model. We also 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 any Earth System Model used by others around the world: https://zenodo.org/record/4728073

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 Leads scheme implemented here represents the first of its kind in using turbulence resolving simulations to calculate the contribution of fluxes from leads within a global climate model. We have shown how accounting for the presence of leads can greatly alter the surface climate in the Arctic with changes to the surface air temperature of up to 4K in winter.

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 coupled climate models which can be used to alter the surface climatology in the Arctic – especially within the sea ice model component. 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 the different model architectures used by the CNRS, NERSC, DMI and NZC teams. Previously overlooked aspects of a model can become important. For example, the maximum sea ice concentration that can be reached in a gridcell was 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 the following objectives of the project:

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

The work by CNRS, DMI, NZC, and NERSC presented in this deliverable supports the achievement of objective 4: we have introduced new model physics into four climate models used by our consortium 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.

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Dissemination and exploitation of Blue-Action results

Peer reviewed articles

We have published two papers detailing:

- the climatology of the atmospheric boundary layer in climate models and causes of model spread (doi: 10.1175/JCLI-D-17-0498.1)
- a review of the different metrics for Arctic amplification and their consistency within eight of the most commonly used observational and reanalysis products (DOI: 10.1002/joc.5675)

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.
We also plan a publication together with the authors of this deliverable, this is going to be further developed in the upcoming months.

Uptake by the targeted audiences

This deliverable is made available to the general public (PU). The deliverable is made available to the world via CORDIS and OpenAIRE.

- A practical guide as to how to implement the model development developed by NERSC was prepared and presented at the annual meeting of Blue-Action in Edinburgh, 15-17 October 2019. This was used as the basis for implementing the leads scheme within the three other climate models. The document is available on Zenodo in open access: https://zenodo.org/record/4728073
- The work done in this deliverable will be presented at the final meeting of Blue-Action in September 2021.