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APPLICATE

Advanced Prediction in Polar regions and beyond: Modelling, observing system design and LInkages associated with a Changing Arctic climaTE

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Recommendations on the coupling methodology in prediction and climate models

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EXECUTIVE SUMMARY

Different practices are currently being used to couple the different components of global models for weather forecasts (several days to weeks ahead) and climate applications (several decades to centuries). This report provides a summary of the coupling methods currently used for Numerical Weather Prediction (NWP) and climate applications. We have reviewed the different approaches employed in the community and used them as a motivation to design novel experiments aimed at improving the coupling between the atmosphere, ocean and sea ice. The results of these experiments, together with prior results from the literature, have guided the recommendations provided in this report.

To improve coupling methodology in NWP and climate models, we recommend using fluxes that are consistent at the interface between the atmosphere, the ocean and the sea ice. More specifically, we show that accounting for the differences in horizontal resolution between the different components of the Earth System when computing the surface fluxes, or accounting for the different sea ice thickness categories can lead to small but detectable differences in the representation of key variables like Arctic sea ice extent and volume. Even if the differences are small, computing the fluxes in a consistent way is more physical and could lead to a better representation of the atmospheric boundary layer and consequently of near-surface weather. We further show that the representation of key physical processes such as snow over sea ice is essential for a realistic representation of near surface temperature in coupled models and it is particularly important for NWP. Representing processes such as snow over sea ice is key to reduce model biases in the polar regions and hence to improve short term predictions and the representation of the model climate.

We expect that the results presented in this report will help weather and climate model developments in the future.

1. Introduction

Quantities are exchanged between atmosphere, ocean and sea ice models when performing climate simulation or numerical weather predictions (NWP). These include ocean surface variables (temperatures, albedo, currents ...) and fluxes (wind stress, heat, water). Ocean and sea ice models have only recently been added to NWP systems while they have been an integral component of climate models for some time. For instance, at the start of APPLICATE, the ECMWF high-resolution deterministic ten-day forecasts (HRES) were uncoupled, and the sea ice cover was considered to be constant throughout the forecast range. However, coupling the atmosphere with the ocean and sea ice in weather forecasting brings opportunities, but also new challenges compared to climate prediction. It involves much shorter spatio-temporal scales; and model initialisation needs to take coupling into account. The way coupling is currently done in NWP models and climate models includes, thus, inconsistencies that can result from choices made either to simplify the representation of a complex system or to save computational resources. For example, the ECMWF Integrated Forecasting System (IFS) surface module does not model the presence of snow over sea ice, which means that surface temperatures can not adjust as quickly as in reality to changes in the atmospheric forcing. The top of the snow layer would rapidly cool during the passage of a cold air front, while the temperature of the 1.5m sea ice layer would remain relatively constant (and too warm) because the thermal inertia of this thick sea ice layer is much larger than that of the snow. Several tests and experiments have been performed within WP2 of APPLICATE to improve the coupling of sea ice with the ocean and the atmosphere and to evaluate the benefits of a more consistent representation of the surface fluxes that are exchanged.

The goal of WP2 is to improve the weather and climate models in their representation of the Arctic through improved atmosphere, sea ice and snow processes, and improved coupling between the different components. The goal of this deliverable is to make recommendations on coupling methods based either on past experience or on experiments done within APPLICATE. We present results from experiments that were designed specifically to improve the coupling between the atmosphere, the ocean and sea ice and provide recommendations on the coupling choices. In section 2, we first present the coupling choices at the start of APPLICATE and the caveats that have been identified. In section 3, we describe the experiments that were designed to improve the coupling and present the main results. The conclusions and recommendations for a better coupling framework in NWP and climate models are provided in section 4.

2. State of the art of the coupling methodologies used in APPLICATE NWP and climate models

In this section we highlight some inconsistencies in the coupling methods commonly used for NWP and climate applications that motivated the experiments we have conducted within APPLICATE.

2.1 Motivations to improve the coupling between the sea ice and the atmosphere in climate models

The surface fluxes and variables that are exchanged between the atmosphere, ocean and sea ice components of a climate model can be inconsistent in space because usually, the model grids are different both in their nominal resolution and respective position. For instance, in the CNRM-CM6 climate model, recently developed by the CNRM-CERFACS group for CMIP6, low resolution components show large differences in resolution (ratio of ~1/5), particularly in the equatorial band and in the Polar regions (Figure 1).

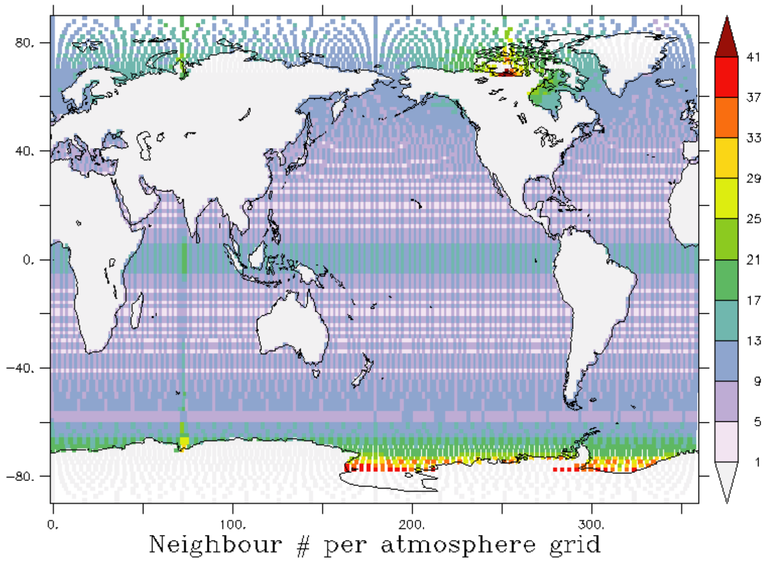

Figure 1: Number of ocean grid point intersected per atmosphere grid point in the CNRM-CM6 climate model, ORCA1 (1 degree) to T127 (140km) grid interpolation, SCRIP [2] "CONSERV" method

In this model, like in many models used for climate applications, atmosphere cells are bigger than ocean cells. These differences lead to errors during flux calculation: one single mean ocean surface value is used, instead of separate values for each ocean grid cell. Errors result from nonlinear dependence of fluxes from atmosphere, ocean and sea ice parameters. One solution to reduce these errors is to compute the fluxes at every atmosphere/ocean grid intersection and to re-build a flux on the oceanic cell. Such experiments, conducted at CERFACS and CNRM, and at the Met Office, will be described in section 3.1.1.

Another source of uncertainty can result from not accounting for the different sea ice thickness categories when computing fluxes during the coupling process. In many climate models, the surface variables (ice temperature, ice cover, albedo) are averaged over the different categories before being sent to the surface model, which introduces uncertainties. We quantify the errors resulting from this approximation by developing a coupled system that computed a multi-category flux. Results are described in section 3.1.2.

2.2 Motivations to improve the coupling between the sea ice and the atmosphere model in NWP models

Since June 2018, the ECMWF HRES forecasts have been produced with a coupled atmosphere-ocean-sea ice system. The IFS has been coupled to an ocean model (NEMO version 3.4.1) which includes a dynamic-thermodynamic sea ice model (LIM2, see Keeley and Mogensen 2018 for more details). This means that all ECMWF forecasts – both deterministic and ensemble medium-range and extended range forecasts – now include an interactive ocean and sea ice component. In the ECMWF operational HRES forecasts, the ocean-sea ice model is coupled to the atmosphere every hour, and the ocean and sea ice model integrations are each performed with a time step of 20 minutes. The sea ice model LIM2 is coupled to the ocean model as part of the NEMO Surface Boundary Condition (SBC) and does not need to be called every ocean timestep. This means the sea ice model can have a different timestep to that of the ocean model itself. Here we explore the impact of changing the timestep of the sea ice model integration to one hour (consistent with the atmosphere coupling frequency and with the timestep used for the atmospheric radiation scheme) and describe the results in section 3.2. The frequency of the call to the sea ice model has a direct impact on computational cost. LIM2 is a relatively expensive component of the ocean-sea ice model as its rheology is solved using an iterative process. Future sea ice modelling upgrades are foreseen to increase further the model complexity, for example by considering multiple thickness categories for representing sub-grid variability of sea ice thickness. For this reason, it is essential to explore potential efficiency gains that do not impact forecast quality but reduce the relative computational cost and preserve the overall speed of computation, which is a strong requirement for operational NWP delivery within critical time slots.

Furthermore, predictions made on timescales from days to months are inherently an initial value problem. The initial conditions must be created with data assimilation systems that are consistent with the models used to forecast the evolution of the different components of the coupled systems (atmosphere, ocean, sea ice). In the absence of a coupled atmosphere-ocean-sea ice data assimilation framework, different data assimilation systems are used to initialize the atmosphere and ocean/sea ice components in the coupled forecasts performed at ECMWF. Atmosphere initial conditions are produced with the four-dimensional variational (4DVAR) data assimilation system included in the IFS (Rabier et al., 2000), while ocean and sea ice-sea initial conditions are taken from the 3DVAR analysis OCEAN5 (Zuo et al. 2018). This imposes constraints on how the coupling of the different components of the coupled forecast system is implemented, and has impacts on predictions, particularly at the ocean/sea ice/atmosphere interface. All ECMWF coupled forecasts only make use of the sea ice cover information provided by the dynamic-thermodynamic LIM2 model. The thermodynamics of the sea ice is recomputed independently at each time-step within each model. For the IFS this is done using the 4-layer ice scheme within the tiled surface module. This is referred to as "ice-to-ice" coupling and means the LIM2 ice model changes the sea ice concentration through advection and growth/melting of ice through thermodynamics and dynamics (ridging rafting), but there is not complete thermodynamic consistency between the IFS and LIM2. This 'ice-to-ice' coupling is necessary due to the needs of incremental 4DVAR data assimilation system of IFS which is not yet coupled with the ocean and sea ice models and for which the surface-atmosphere coupling needs to be running at different spatial resolutions (inner loops of the 4DVAR minimisation). As the surface energy balance needs to be solved within each iteration of the 4DVAR, avoiding as much as possible shocks or spin-up issues, the only possibility is to use the IFS surface module for calculating the sea ice thermodynamics in the surface energy budget.

The thermodynamic schemes of the two models (IFS and LIM2) differ in the processes they represent and in the choice of discretisation. The IFS determines the sea ice temperature profile over 4 vertical layers which have fixed thickness (7,21,72 and 50 cm respectively); it assumes that the ice has no snow cover and is uniformly fixed to 1.5m in depth. The thermodynamic component of LIM2 calculates the sea ice temperature profile over 2 layers whose thickness is defined by the total ice depth at the grid point. The depth of the ice can vary at each grid point both due to ice accretion and melting and ice advection. The LIM2 skin temperature of the ice can be modulated by the presence of snow which is modelled using a single layer of snow (with varying depth).

The evolution of the skin temperature can be affected by the inconsistencies between IFS and LIM2 concerning: (1) the different integration time-steps; (2) the different sea ice thickness, which can impact the heat storage and (3) the treatment of snow, and more precisely the fact that IFS does not allow for snow on the ice and is therefore missing the insulating properties of snow.

The impact of these inconsistencies on skill of the coupled forecasts is seasonally dependent. As the IFS thermodynamics is unable to reduce the ice cover or thickness this leads to excess energy warming the surface rather than melting the ice. This is predominantly a summer problem, which will be discussed in more detail in section 3.2.

3. Description and results of the numerical experimentation performed to improve coupling

3.1 Improving the computation of fluxes between the ocean, sea ice and the atmosphere

3.1.1 Using an exchange grid

This study investigates the solution implemented by Balaji et al. (2006), which consists of computing the fluxes at every atmosphere/ocean grid intersection and reconstructing the aggregated fluxes on the oceanic cells. The model we use is the newly developed CNRM-CM6 model, which is based on the ocean model NEMO3.6 in the ORCA1 configuration (i.e. 100 km resolution on average with a refinement to about 30 km at the equator), coupled to the ARPEGE-ClimatV6 atmosphere model with a resolution of about 150 km (T127). We replace the atmospheric model with an "exchange grid" simulator (Figure 2), the SURFEX model, where the fluxes are calculated. The atmosphere feedback is thus disabled and replaced by atmosphere forcing, calculated during a previous full CNRM-CM6 (ARPEGE-SURFEX-NEMO) coupled simulation. The fields exchanged between atmosphere and ocean, the coupling fields, are the same in CNRM-CM6 and in the SURFEX-NEMO configuration.

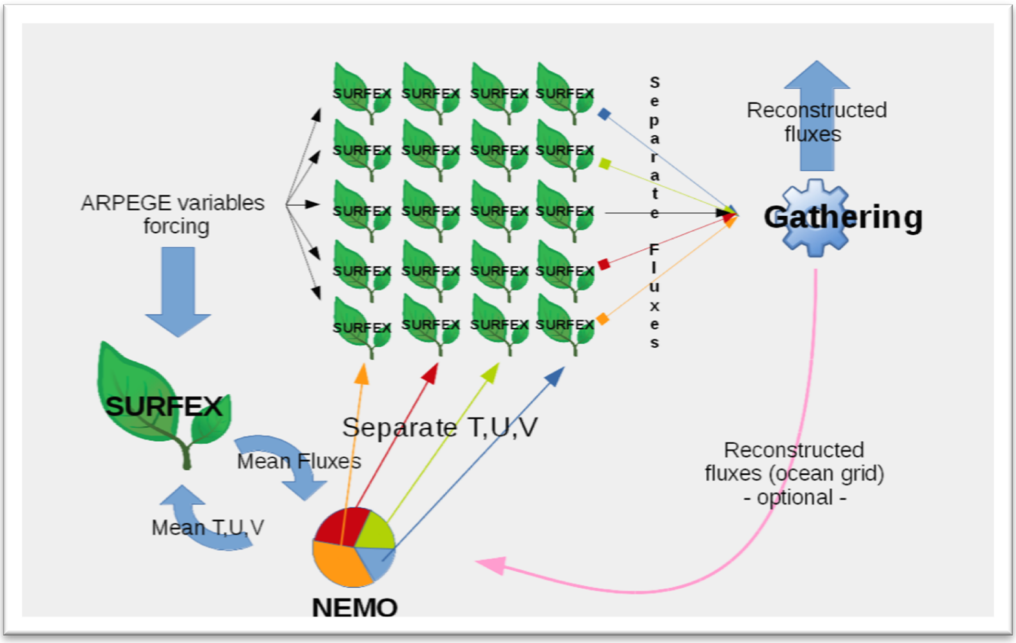

Figure 2: Schematic of the exchange grid simulator implemented to produce mean ocean surface variables (interpolated on the SURFEX grid), mean atmospheric fluxes (interpolated on the NEMO grid) and ocean surface variables at each cell of the exchange (SURFEX-NEMO intersection) grid. A toy model gathers the fluxes calculated by SURFEX clone models (one per intersected cell). The resulting fluxes can be sent back to the NEMO ocean model. Coupled fields from/to SURFEX clones, NEMO and toy models are exchanged/interpolated through the OASIS3-MCT library

In this SURFEX-NEMO simulator, fluxes are calculated at every ocean cell intersected by an atmosphere cell: each calculation on each sub-cell is managed by a separate SURFEX executable ("clone"). Then, the NEMO model is coupled with as many SURFEX clones as the maximum number of ocean cell intersected per atmosphere cell. Fluxes are combined in an additional executable to rebuild one flux per atmosphere cell. This new set of fluxes is finally compared to the fluxes calculated in a standard way, i.e. where no changes are made. Fluxes are also combined to build the fluxes that will be seen by the ocean.

A relatively short simulation of one year (after one year of spin up) is realized to technically validate the exchange grid implementation and estimate the flux differences resulting from the new exchange grid calculation. This 1 year simulation is called EXG simulation and it is contrasted with the standard simulation where no changes are made (STD). As a second step, the atmospheric rebuilt fluxes are used by NEMO in an additional simulation to evaluate the feedback on the ocean and sea ice, the SMO simulation. We evaluate the differences between EXG and STD for solar and non-solar fluxes, i.e. the latent and sensible turbulence heat fluxes. Systematic differences are found over polar regions for non-solar heat fluxes in particular (Figure 3).

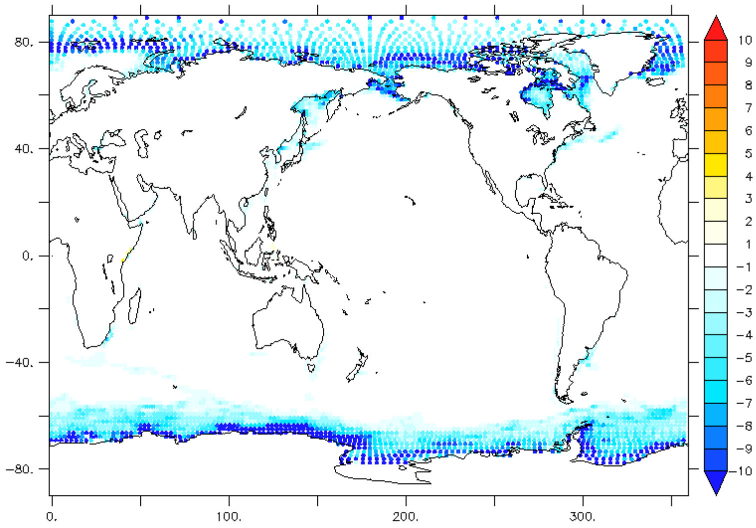

Figure 3: Difference between EXG and STD experiments for the non-solar fluxes in W/m²

The systematic difference observed on non-solar heat flux is clearly an effect of the new exchange grid flux calculation in areas covered by sea ice. It appears that the latent and sensible heat fluxes explain most of the difference shown in Figure 3 (the contribution of longwave fluxes is small). More figures can be found in Maisonnave and Voldoire (2018). The more precise calculation of the fluxes allows indeed a better representation of the strong temperature gradients between the atmosphere and sea ice during the ice production phase. We illustrate this by looking at one particular grid-point over the Greenland Sea for which the difference in non-solar heat flux between the EXG and STD simulations is among the largest (Figure 4, left panel). We show that this difference in non-solar heat fluxes is strongly anticorrelated with the variance of ice temperature over the 4 ocean grid points contributing to the EXG flux calculation, which are permanently covered by ice during the considered period (January) but with different ice ages. It appears clearly that the maximum difference of non-solar fluxes occurs when ice temperatures of some contributing ocean grid points exceed the air temperature (Figure 4, right panel), yielding larger fluxes from the ocean to the atmosphere, hence the negative pattern in Figure 3.

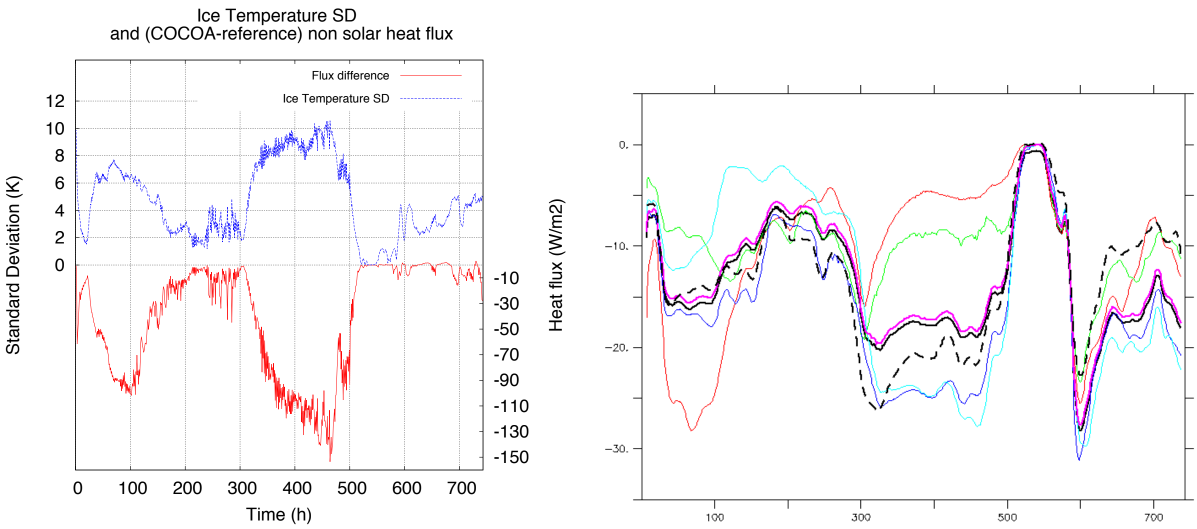

Figure 4: Focus on a grid point located in the Greenland Sea for the month of January (the x-axis corresponds to the time in hours, keeping in mind that the coupling time step in the model is one hour). Left: Difference of non-solar fluxes between the EXG and STD simulation (blue line, W/m2) and variance of ice temperature (red line, K). Right: Ice temperature in the EXG simulation (black solid), in the STD simulation (magenta) and unweighted contributions from the 4 ice-covered ocean grid points (red, green, light and dark blue) contributing to the EXG flux calculation. The black dotted line indicates air temperature.

The differences are largest during sea ice production. This is confirmed when the feedback to the ocean is switched on (SMO experiment). Figure 5 (left) shows that the larger non-solar heat fluxes resulting from the exchange grid calculation lead to a slightly larger volume of sea ice during wintertime (about 2% larger), particularly in the Arctic, because of a higher production of sea ice during the dark season. The major part of this extra ice volume comes from the larger extent of sea ice in the marginal ice zone (Figure 5, right).

Note that the impact of the changes in the flux calculation on the atmosphere has not been evaluated yet and will be the subject of future work.

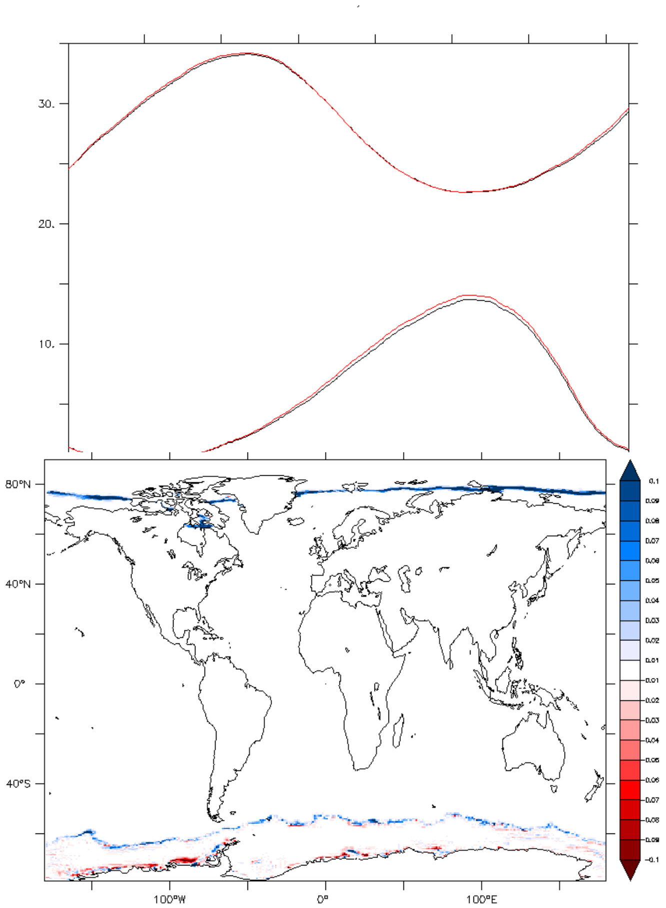

Figure 5: Top panel shows sea ice volume simulated in the STD (black line) and SMO (red line) experiments. Both experiments are run for one year and the x axis indicates the days. Top lines are for the Arctic, bottom lines for the Antarctic. Bottom: Difference in sea ice concentration between the SMO and STD simulation after 9 months (September mean value). In the SMO simulation, the exchange grid fluxes are applied to NEMO.

3.1.2 Accounting for multi-category ice

We evaluate the impact of computing fluxes over sea ice when we account for each of the five thickness categories represented in the GELATO sea ice model. The configuration described in the previous section and shown in Figure 2 is modified such that the surface properties of each ice category (ice cover, temperature, albedo) computed by the GELATO sea ice model are sent to SURFEX, which then calculates a specific flux for each category. The resulting fluxes are then aggregated, taking into account the contribution of each ice category (Figure 6). We run a one-year experiment with this configuration that accounts for the different sea ice categories, and we compare the results with those from the exchange grid experiment (EXG) in order to determine which strategy would be worth implementing first in the next ARPEGE release. In both simulations, the reconstructed fluxes are prescribed to the NEMO model to see the effect on the ocean and sea ice.

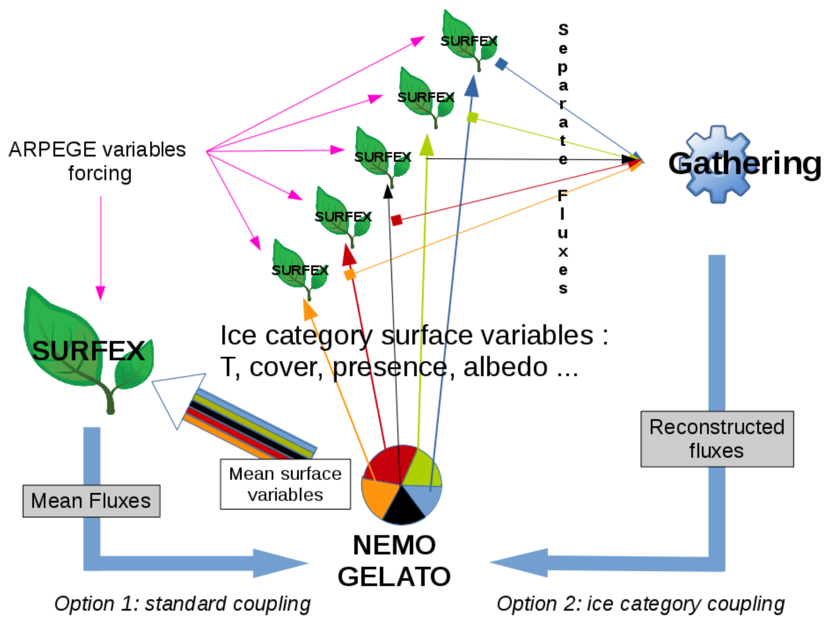

Figure 6: Coupled system implemented to execute n parallel flux calculation for n ice category surface variables

It is not possible to directly compare fluxes with the exchange grid ones (SMO), because the sea ice cover, which changes the fluxes, is modified differently with the fluxes calculated by the exchange grid and with the fluxes calculated by multi-ice categories. Hence, we compare ice cover and volume between the STD experiment (reference simulation), the SMO experiment (flux calculated by exchange grid) and the SMI experiment (flux calculated by multi-ice categories). Melting is accelerated in SMI compared to SMO and STD, which can be an effect of less negative non-solar flux values. Freezing seems as strong in SMI as in SMO compared to STD (see Figure 7). But stronger melting leads to smaller ice cover in SMI, particularly over Arctic marginal areas, where the non-solar flux is smaller (Figure 8). However, local ice cover differences are too small to conclude that the exchange grid flux calculation has effects on Arctic sea ice volume that justify its systematic implementation in climate models. More results on these experiments can be found in Maisonnave and Voldoire (2019).

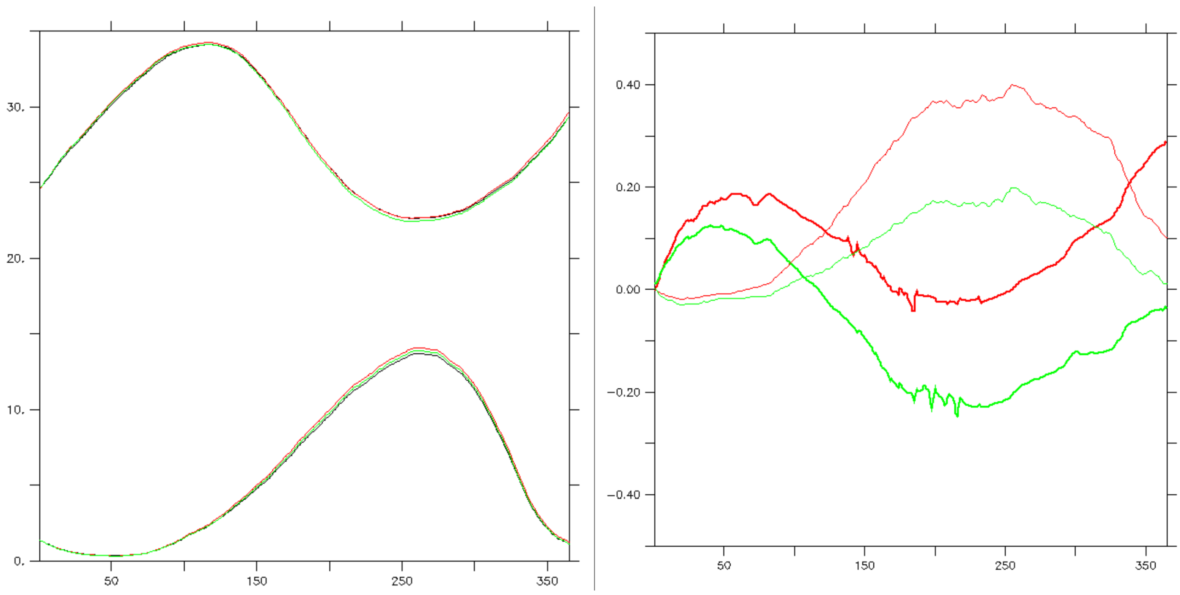

Figure 7: Sea ice volume (1000 km^3) in STD (black), SMO (red) and SMI (green) experiments during the one-year long simulation (time unit: days). Left: Full values. Top lines are for the

Arctic, bottom lines for Antarctic. Right: Anomalies with respect to STD, for Arctic (thick) and Antarctic (thin) regions.

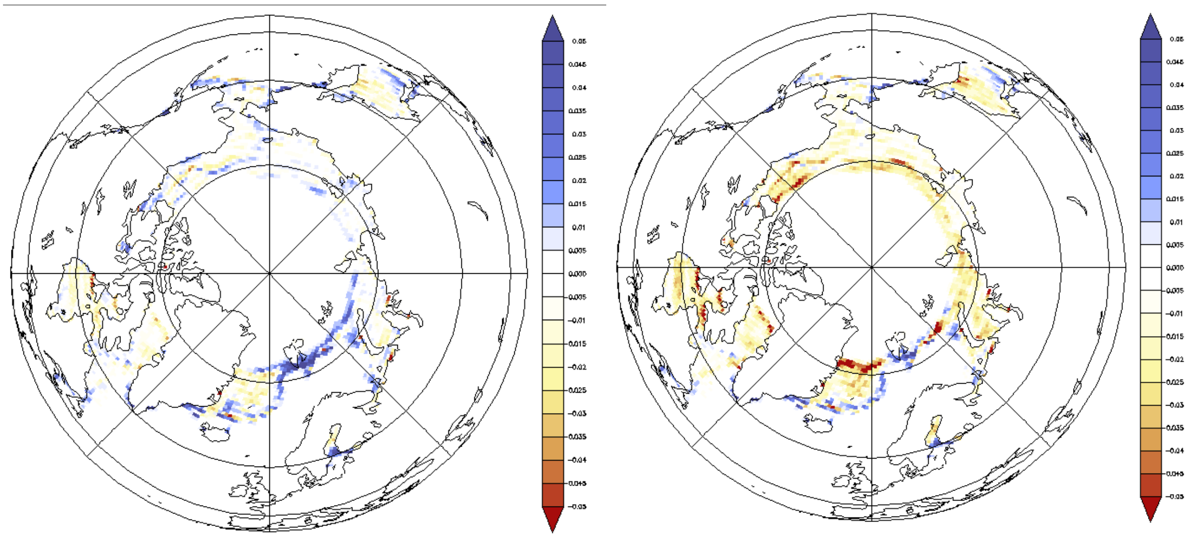

Figure 8: Annual sea ice concentration anomalies (in %) computed using STD as a reference for SMO (left) and SMI (right) experiments.

3.1.3 Further evidence of the importance of using consistent approaches for coupling

The experiments described in sections 3.1.1 and 3.1.2 were designed within APPLICATE to improve the consistency of the fluxes exchanged between the atmosphere, the ocean and sea ice. Other experiments performed by the Met Office prior to APPLICATE confirm the importance of developing complex but consistent methods for coupling. Indeed, to solve the inconsistencies between the fluxes computed over land and those computed over the ocean and sea ice, the Met Office has been using for several years a method whereby all surface fluxes are calculated within the JULES surface exchange scheme (see Best et al., 2004 for more details). This scheme is still used for CMIP6 with HadGEM3-GC3 (Williams et al., 2018). However, this approach did not include ice thermodynamics as this was not possible using the JULES scheme, which calculated the fluxes the whole way through the sea ice to the base. Including the ice thermodynamics required to either 1) develop a more complex coupling methodology or 2) change the coupling to a more standard approach like bulk formulae. In the West et al. (2016) study, option 2) was tested to see how much the near-surface atmosphere would be degraded by using a simpler coupling approach. The results of this experiment are described below.

The experiment consisted on a 1D idealised study using an offline version of the CICE (Bitz and Lipscombe 1999) solver. We imposed an atmospheric temperature with a diurnal cycle, and run two cases: 1) A 'standard' CICE solver with 'standard' coupling methods 2) A modified solver using the JULES/Best coupling method as described in West et al. (2016) and Ridley et al. (2018) and illustrated in Figure 9. In the latter experiment, instead of using the bulk formulae, we computed the surface exchanges entirely within the atmosphere/land component and we tested two frequencies for the coupling: 1 hour and 3 hours.

The results are shown in Figure 10. In the JULES coupling (red lines), the surface fluxes into the ice are much closer to the control runs (black lines). Meanwhile the standard coupling has “steps” that show the impact of maintaining the ice surface at a fixed temperature for several atmospheric time-steps. For the extreme case of 3-hourly coupling the atmosphere time-step of 20s is very short compared to the 3h coupling frequency. The improvements seen with the JULES coupling essentially come from the fact that the ice surface temperature is updated on every time-step, whereas for the 'standard' approach, the surface temperature is only updated on the (longer) coupling time-step. The results shown in Figure 10 indicate a large degradation of the surface energy exchange particularly for low-coupling frequency (3-hourly). These results confirm the importance of implementing a new coupling framework in the Met Office model with consistent fluxes like those computed by the JULES scheme but including ice thermodynamics.

Extending these results to the full 3D model presented several challenges that are discussed in Ridley et al. (2018). In particular we extended the coupling approach to calculate surface exchanges separately for each of the ice thickness categories using the tiling functionality in JULES, and implemented a semi-implicit approach to weight conductive fluxes by ice area rather than grid-cell area. This latter point is done by dividing fluxes by the new ice fraction within JULES before passing through the coupler and then multiplying by ice fraction once they come through the coupler. This is comparable to the experiments done with the CNRM-CERFACS model and described in sections 3.1.1 and 3.1.2 and further support the findings of those experiments.

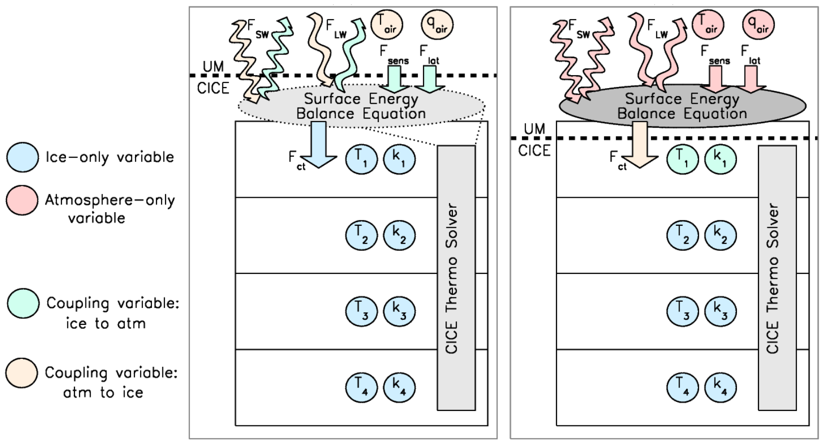

Figure 9: Schematic illustrating the coupling between the atmosphere and sea ice typically implemented in a coupled model using a standard coupling approach in which the surface fluxes are calculated using bulk formulae (left) and when the surface exchanges are computed entirely within the atmosphere/land component (right).

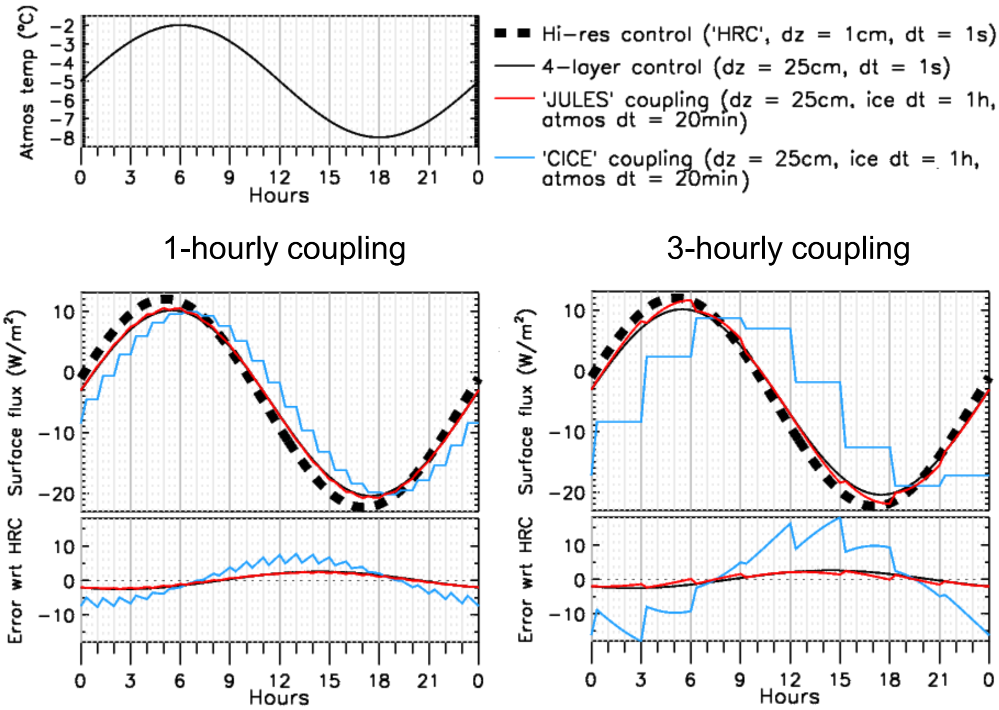

Figure 10: Results from a 1D idealised study using CICE sea ice thermodynamics and JULES surface exchanges as documented in West et al. (2016). Top plot shows an imposed diurnal cycle of near-surface atmospheric temperature. Lower plots show the surface fluxes into the top of the sea ice using 1-hourly (left) and 3-hourly (right) coupling between atmosphere and sea ice. The thick black dashed lines are from a high resolution (1cm in vertical and 1s in temporal) control and are essentially the solution that we would want to match. The thin black line is a low-res version of the same thing using 4 vertical layers. The red line is using Met Office coupling ('JULES coupling') and the blue line is using standard coupling ('CICE coupling') - as depicted in Figure 9.

3.2 Adjusting the frequency of (internal) ocean-sea ice coupling

As described in Sect. 2.2, we evaluated the impact of the choice of the timestep for the sea ice model integration (i.e., one hour instead of 20 minutes) in the ECMWF deterministic forecasts. For this purpose, we ran a year of ten day forecast experiments, initialized once every other day, with an atmospheric resolution of Tco399 (approximately 25km resolution in the mid-latitudes) and ¼° ocean/sea ice resolution. These forecasts are thus performed with the same ocean resolution, but a lower atmospheric resolution than the operational ECMWF HRES ten-day forecasts which are performed at a Tco1279 atmospheric resolution (approximately 9 km in the mid-latitudes).

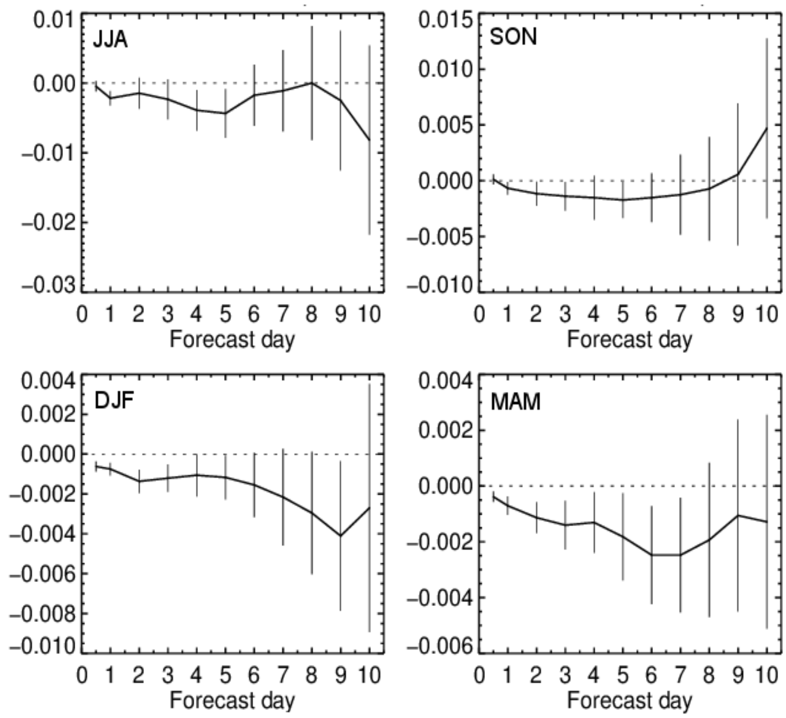

Figure 11: Normalised difference in RMSE of sea ice concentration over the region 60-90N when calling the sea ice model less frequently. Negative means errors are reduced when calling frequency is reduced.

We present forecast skill scores for the 4 seasons for the sea ice itself (see Figure 11) along with surface parameters (Figure 12). In all cases the forecasts are verified against the operational ECMWF analysis. The results are neutral with a slight reduction in RMSE in all seasons for the sea ice concentration. The surface variables in the atmosphere are not degraded significantly by calling the ice model less frequently. This setting, for the current coupling and configuration, allows us to save time/computing resource while not degrading the forecast skill of the atmosphere or sea ice.

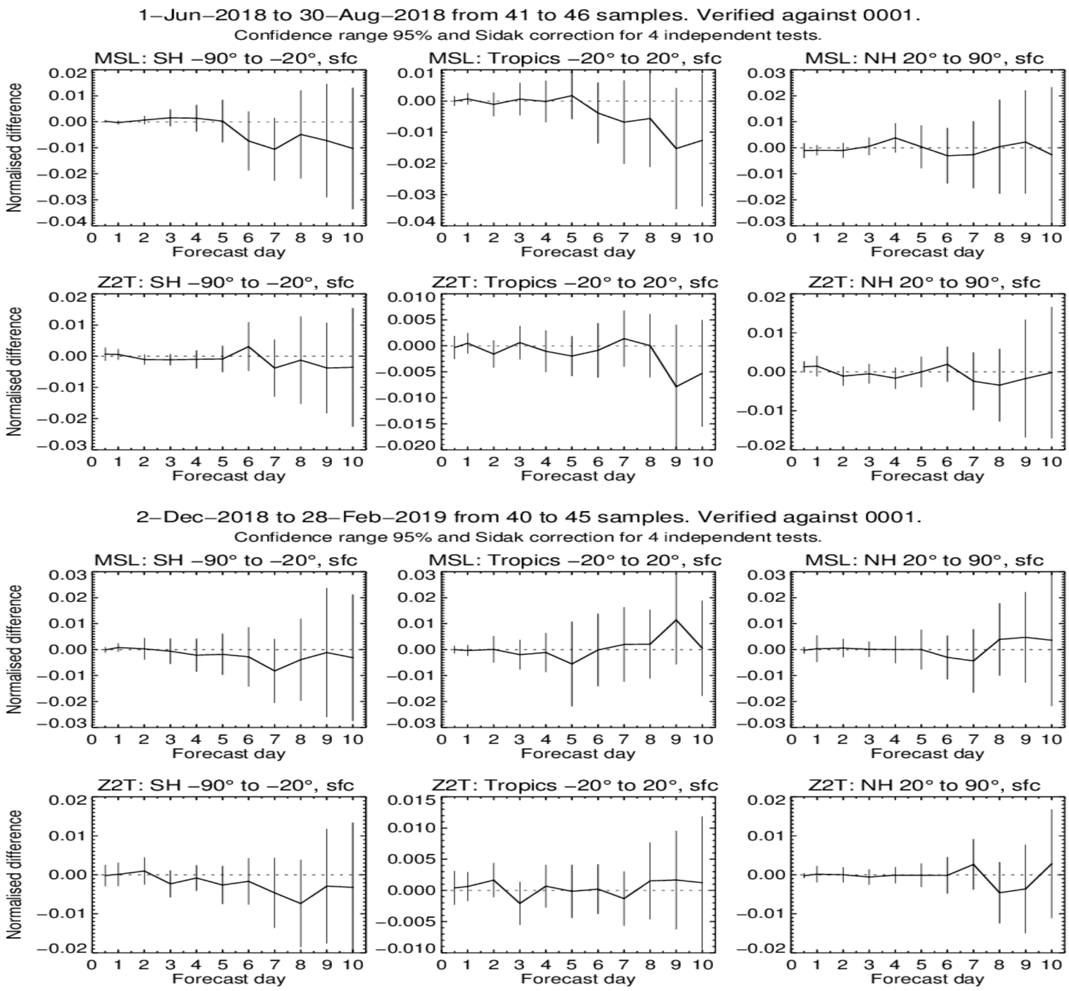

Figure 12: Normalised difference in regional RMSE for boreal summer (JJA) and winter (DJF) for mean sea level pressure (MSL) and 2m temperature (Z2T). Negative differences mean that calling ice model less frequently reduces the RMSE.

3.3 Improving the representation of physical processes involved in the coupling of sea ice with its environment

3.3.1 Representing snow and sea ice in terms of depths and temperatures

We evaluated the impact of including a thermodynamic coupling of the sea ice in ECMWF IFS HRES forecasts, on top of the already existing dynamical (or 'ice-to-ice') coupling described in section 2.3.1. To do this, we coupled the skin temperature calculated by the thermodynamic component of LIM2 to the surface ice tile of the IFS surface module. More precisely, we disabled the thermodynamic calculations on the sea ice tile in the IFS surface module and its skin temperature was fixed to that of LIM2 and updated every hour when the ocean and atmosphere models are coupled[1]. This "tight" coupling scheme ensures that the effects of variable sea ice thickness and the presence of snow on sea ice (which are represented in LIM2) on the evolution of the sea ice/atmosphere interface are accounted for when performing coupled HRES forecasts with IFS. This tight coupling has only been tested in forecast only experiments, which are initialized with initial conditions from the 4DVAR data assimilation system for the atmosphere and from OCEAN5 for the ocean and sea ice. In the absence of a

[1] The choice of sequential coupling in the IFS system, which is unique compared to other climate and NWP systems, means that the sea ice model is driven with fluxes with no lag and LIM2 provides the IFS sea ice surface tile with a surface skin temperature valid at the time of coupling.

coupled data assimilation framework, the impact of accounting for different ways of coupling the different components when creating the initial conditions cannot be tested for now and will be subject of future work.

A winter example of snow-covered sea ice from the SHEBA campaign in early January 1998 is shown in Figure 13. The skin temperature in the current setup for ECMWF coupled forecasts (including an ‘ice-to-ice' only coupling, red) is that of bare ice and is too warm compared to that observed (top of snow layer) when, in reality, the surface can rapidly cool during clear sky events (e.g. 6th and 15th-20th January). Indeed, sea ice has a much higher conductivity than snow, so it can transmit ocean heat to the atmosphere much more readily when there is no overlying snow layer. Hence, with no snow to decouple the ice and atmospheric surface heat exchange, the surface temperature simulated with the IFS thermodynamic model remains too warm because the sea ice is warmed by heat transport from the relatively warm ocean below. In cloudy conditions the picture is more complex with the model skin temperature cooler than the observed skin temperature which could be due to the lack of snow over the sea ice but also to the (in)ability of the model to: (1) produce clouds at the right height and (2) produce clouds which have the correct partitioning between liquid and ice water, which in turn effect the downwelling longwave radiation. This highlights the need for the model to correctly capture the ice surface processes but also the cloud cover and structure to correctly reproduce the surface properties of the region.

The impact of coupling the skin temperature from LIM2 (which has variable sea ice thickness and a single layer snow model) is to produce a more responsive surface temperature, as shown in the magenta curve in Figure 13. The surface cooling is more rapid in clear sky events and the model is able to achieve lower temperatures. Statistics for the day 2 forecasts for this period are shown in **Error! Reference source not found.** and show a reduction in bias and RMSE when using the tight coupling. More cases are required to understand the full impact of these coupling changes but point to this as a potential improvement in the coupled NWP system and is also the subject of studies using the AOSCM in combination with field data.

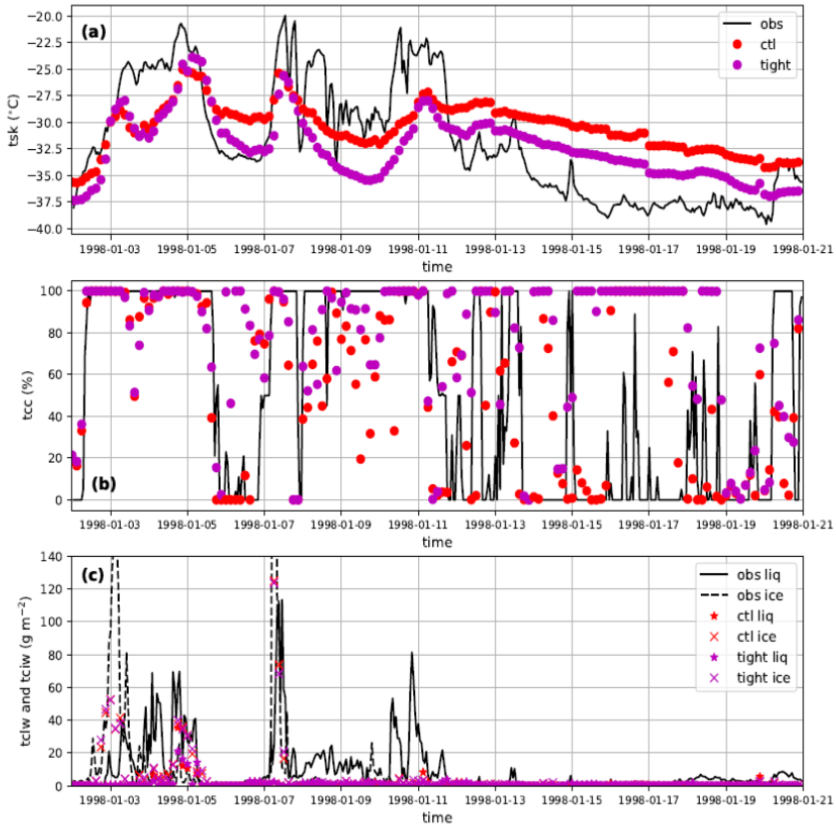

Figure 13: SHEBA observational data (black line, courtesy of O. Persson, NOAA) and model forecasts for the nearest grid point (symbol) with the current coupling (red) and tight coupling (magenta), showing skin temperature (top), total cloud cover (middle) and total column liquid and ice water (bottom). Forecasts are concatenated between t+24h to t+47h to create a continuous time series.

Table 1: Summary statistics for the analysed SHEBA period from 1998-01-01 to 1998-01-21 for model forecasts at a lead time of 2 days.

Tskin	**Bias**	**RMSE**	**Std deviation**
ctl	1.33	4.68	4.49
tight	-0.56	4.20	4.16
T10m	**Bias**	**RMSE**	**Std deviation**
ctl	2.55	4.54	3.69
tight	0.37	3.46	3.40

3.3.2 Improving the representation of melting processes at the interface (skin) layer

With the current ‘ice-to-ice’ coupling used in the ECMWF IFS coupled forecasts, the surface energy balance is calculated in the atmospheric surface module component of the IFS, which considers a fixed 1.5m ice depth and thereby does not take into account any potential phase changes. This means that the skin temperature can go above the freezing point because excess energy is warming the surface rather than melting the ice. The frequency of this problem occurring during June 2018 with the current ice-to-ice coupling used in ECMWF coupled HRES forecasts is shown on the left-hand side of Figure 14. Two methods can be used to alleviate this problem:

1. **Tight:** The tight temperature coupling between the IFS and LIM2 ice models described in the previous section. Melting is in this case represented because the used surface thermodynamic balance is that of LIM2 which simulates melting.
2. **Melt:** Enhancing the coupling strength between the atmosphere and the ice tile of the IFS surface module. This mimics the phase change energy sink by forcing the skin temperature over the ice tile to freezing when it exceeds 0°C and then recalculating the surface energy balance. The excess of energy is then passed to the ice layer underneath.

The impact of implementing method 2 is shown in the right-hand side of Figure 14. The occurrence of the skin temperature being greater than the freezing point is removed. This is not completely energetically consistent as we do not pass this information to the ice melting processes or to reduce the ice cover, but it allows the fast thermodynamics over the ice points to be calculated in the atmospheric model.

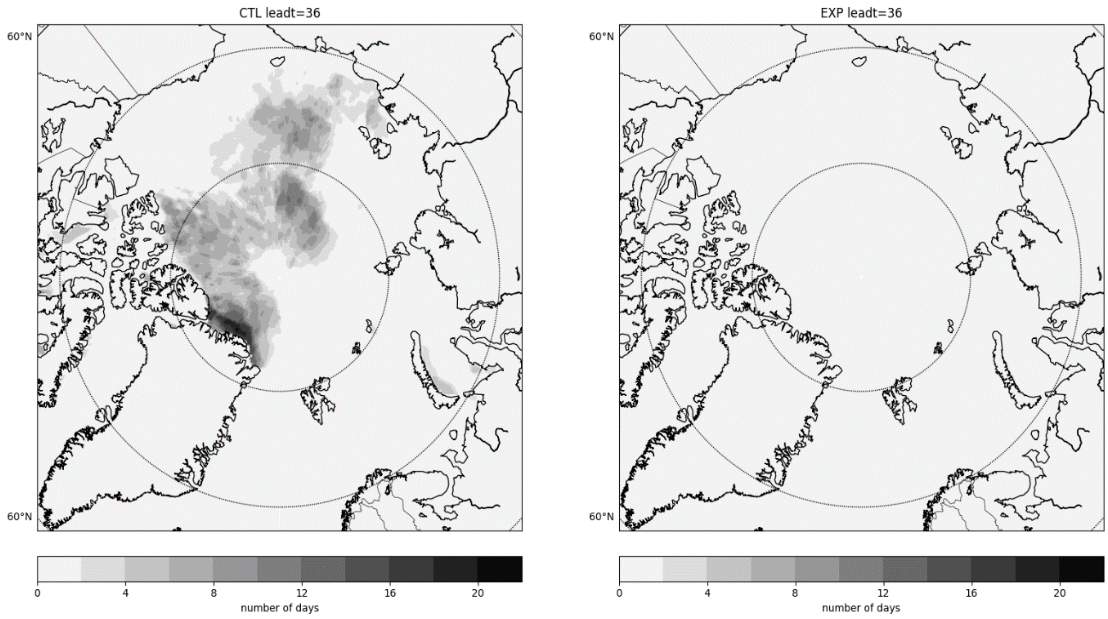

Figure 14: Occurrences (no. days) of the skin temperature of the IFS (Tsk) being greater than 0°C at forecast lead time of 36 hrs for June 2018. Numbers are shown for the current operational setup (CTL) (left) and in the new melting scheme (EXP) (right).

Using a case study for a 2018 summer Arctic drift campaign (around 89°N) carried out by Tjernström et al. (2019), we can compare the sensitivity of the surface temperatures to the two methods of simulating melting processes. Figure 15 shows the comparison of the control IFS 3-day forecasts with observations for the summer campaign and highlights the fact that the predicted temperatures are too warm during the period.

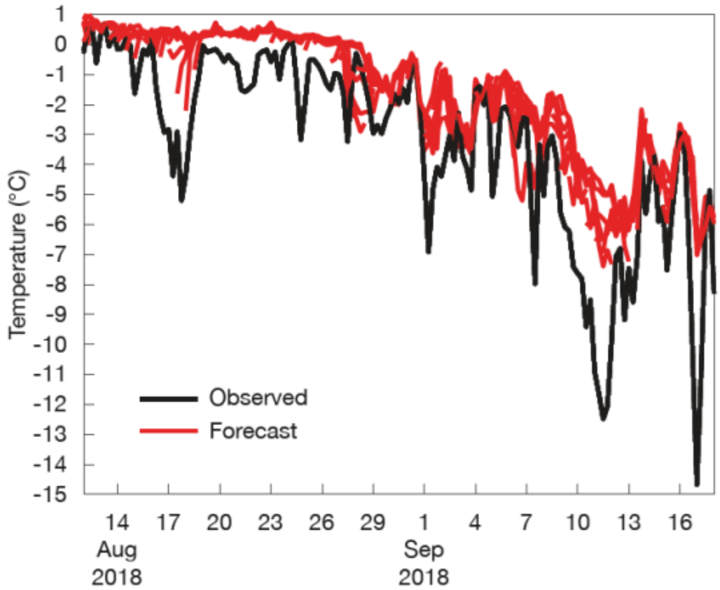

Figure15: Observed and predicted (CTL) 20m temperature at the ship's location. Overlapping 3-day forecasts are initiated every 12 hours while the observations are 5-minute averages around forecast times. Taken from Tjernström et al. (2019).

By changing the 'ice-to-ice' coupling methodology with either of the two methods detailed above, the skin temperature is limited to a maximum value of 0°C (Figure 16). The predicted temperatures are generally slightly colder with the two new coupling methods than with the control 'ice-to-ice' (CTL) coupling methodology. The temperatures are still much higher than those observed, which may be due to the fact that the surface initial conditions in all of the predictions did not contain any snow. At the observation site there was snow present throughout the campaign and new snow also fell during it. In the beginning the snow was melting, large grained, and later froze to a hard surface and on top of that new snow fell (personal communication, Tjernström, 2019). The results for the coupling methodologies are encouraging but further examination over a longer period and a broader spatial scale are needed to fully assess their impact and sensitivity to errors in the initial conditions.

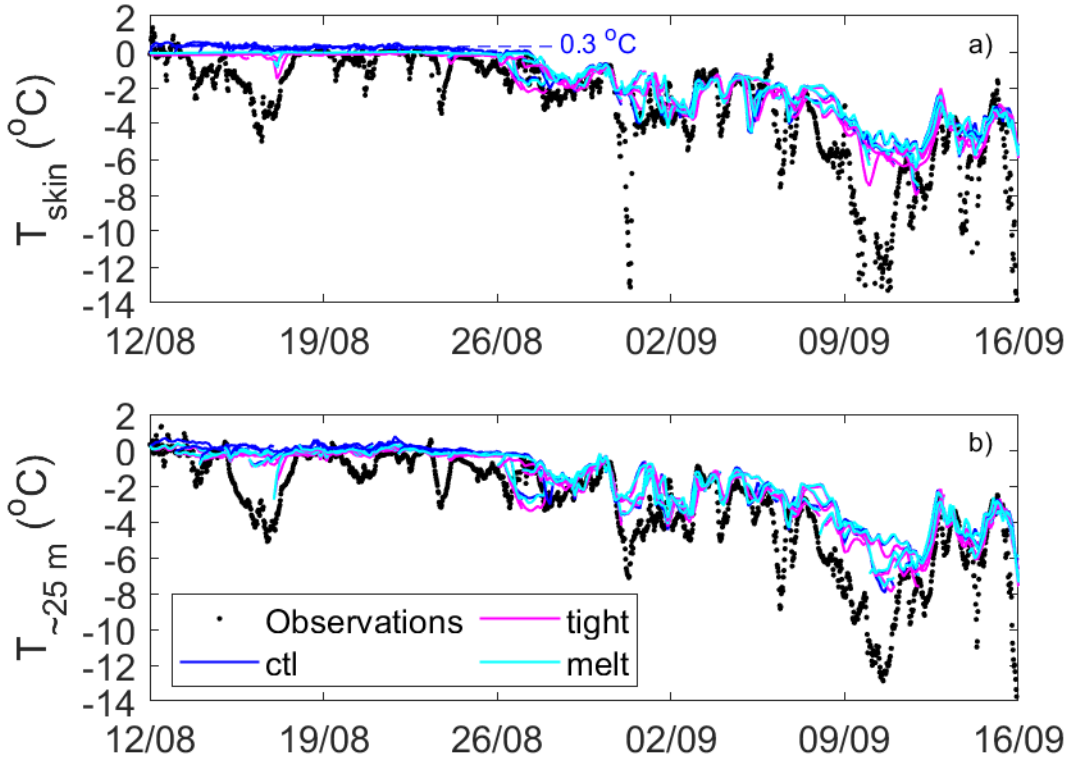

Figure 16: As for Figure 15 but for skin and 25m temperatures for predicted temperatures using control (blue line), tight (magenta line) and melting (cyan line) coupling methodologies.

4. CONCLUSIONS AND RECOMMENDATIONS

In this report, we have gathered the results of several experiments done by the different partners with the goal of improving coupling and eventually model simulations of Arctic weather and climate. We focused on coupling choices at the sea ice-ocean and sea ice-atmosphere interface for both NWP and climate frameworks. The results of these experiments are important because coupling choices, and the initialisation of coupled models, can considerably influence predictive skill (addressed in WP5 of APPLICATE).

Regarding the frequency of sea ice to ocean coupling, we have shown that NWP models using sequential, hourly coupling allows run the sea ice model to be run with a relatively long timestep without degradation of the atmospheric surface or sea ice cover predictions. Further experiments based on other models should be conducted in the future to check whether this statement holds true for models other than those tested in this study.

Regarding the representation of fluxes at the interface, experiments performed prior to APPLICATE have shown that computing the surface exchanges entirely within the atmosphere-land component instead of using simple formulation like bulk formulae leads to a better representation of the fluxes. Also using consistent fluxes between the atmosphere, ocean and sea ice can lead to an improved representation of near-surface atmospheric boundary-layer stability, which is important to consider in the coupling choices (Ridley et al. 2018). Experiments performed within APPLICATE support these findings and further show that:

1. The variability of ice temperature, when interpolated onto the atmosphere mesh, is larger than the variability obtained when accounting for the different sea ice categories, but its average temperature is smaller.
2. One-year integrated effect of exchange grid fluxes on the ocean and sea ice evolution modifies, although marginally, the total ice volume in both Arctic and Antarctic regions. This is less significant for the case of the multi-ice category coupling. The experiments that were run to reach these conclusions are too short to exclude that the positive results that were obtained are not transient effects. The results could also depend on the horizontal resolution of the models used. Decade-long experiments with low and high-resolution models would hence be needed to increase our confidence in the results. However, the mechanisms are quite clearly explained and the effect is strong enough to be considered robust. More analysis, particularly including the coupling with the atmosphere model should be done before thinking about a modification of the reference version.

Regarding the representation of key processes such as snow over sea ice, we have shown that the modelling of surface processes at the sea ice-snow-atmosphere interface is essential for a realistic representation of the evolution of the skin (interface) temperature in coupled NWP. Not representing key processes such as snow over sea ice leads to model biases in the polar regions. For example, rapid variations in surface temperature cannot be reproduced if snow over sea ice is not included in the NWP model, because sea ice has a larger heat conductivity compared to snow (6 to 10 times), preventing a rapid response to changes in atmospheric forcing. The presence of snow leads to an effective thermal decoupling between the atmosphere and the sea ice underneath, therefore its top layer can rapidly respond to the atmospheric forcing, for instance during the advection of a polar air mass or a clear-sky period dominated by surface radiative cooling. Based on the experiments performed in WP2 of APPLICATE, the following conclusions can be drawn:

1. The representation of snow over sea ice is important for correctly capturing the coupling at the sea ice, snow, atmosphere interface and its impacts on near-surface predictions, even at short time ranges, and should therefore be included in NWP systems. However, work is necessary not only in terms of modelling the snow over sea ice and its coupling to the atmosphere, but also in terms of its initialization, and more precisely in order to ensure that the snow over sea ice can be initialized from realistic initial conditions. Deriving accurate initial conditions for snow over sea ice can be problematic given the very limited number of in situ or satellite observations.
2. There are obvious benefits of using both dynamic and thermodynamic information from the sea ice models included in NWP systems. This ensures the consistency between the atmospheric and sea ice models, and the inclusion of processes which are not represented with the dynamic (or 'ice-to-ice') coupling presently used in ECMWF's coupled forecasts (i.e. melting processes and snow over sea ice), and their impacts on the evolution of the atmosphere/sea ice interface. Again here, work is needed to ensure such a 'tightly' coupled system can be initialized in a satisfying manner. For this, a coupled data assimilation system is necessary.

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6. ACRONYMS

ARPEGE: Action de Recherche Petite Echelle Grande Echelle
GELATO: Global Experimental Leads and ice for ATmosphere and Ocean model
IFS: Integrated Forecast System
JULES: Joint UK Land Environment Simulator
LIM2: Louvain-la-Neuve Sea Ice Model 2
NEMO: Nucleus for European Modelling of the Ocean
NWP: Numerical Weather Prediction
RMSE: Root Mean Square Error