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PARAMETERISATION OF SEA ICE COVER IN SHORT-RANGE REGIONAL NUMERICAL WEATHER PREDICTION

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Academic dissertation

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Abstract

With the ongoing climate change economic activity in the Arctic steadily increases and it is expected to grow further in the coming years. However, harsh weather conditions of the present-day Arctic place strong demands for accurate and timely weather forecasts, which nowadays are obtained by means of numerical weather prediction. Sea ice covers a considerable part of the Arctic Ocean and numerical weather prediction systems operating in the region require a reliable and computationally-efficient representation of the sea ice cover in the model. Traditionally, simplified one-dimensional parameterisation schemes are applied for this task. However, implications of utilising such schemes in the context of contemporary high-resolution regional operational numerical weather prediction are not well studied. The present work aims to assess these effects through a series of numerical experiments in the operational-like environment. A new one-dimensional parameterisation scheme, allowing for varying level of complexity, implemented in the HARMONIE-AROME numerical weather prediction system, is used as the main research tool. The findings show that applying an over-simplified parameterisation scheme can result in considerable deterioration of the ice surface temperature field in the model. Errors in the modelled ice surface temperature influence the turbulent exchange between the ice surface and the model atmosphere, and, as a result, the near-surface atmospheric variables, such as the screen-level air temperature. Thus, improving the ice surface temperature in the model results in a positive impact on the atmospheric forecast of these parameters. Therefore, a sea ice scheme within an operational numerical weather prediction system should preferably include an explicit representation of the snow layer to accurately represent the surface energy budget of sea ice. Applying a sea ice data assimilation procedure to assimilate a near real time satellite ice surface temperature product in HARMONIE-AROME further reduces the root mean square error of the ice surface temperature and improves the screen-level air temperature forecast over Svalbard and Franz Josef Land archipelagos, however the positive effect in the ice surface temperature is short-lived and greatly reduced already after three hours of model forecast. Spatial resolution of contemporary regional numerical weather prediction systems allows some of the fine-scale features of the sea ice cover to be explicitly represented in the model. Numerical experiments show that introducing irregular structures within the marginal ice zone of the model ice cover results in both local and non-local responses in the atmospheric model. These findings indicate potential benefits of applying high-resolution ice cover in regional numerical weather prediction systems, for example, as a surface perturbation in ensemble prediction systems.

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The present thesis is based on the research conducted at the Norwegian Meteorological Institute over a time period of more than five years. Indeed, it was a long journey and being a PhD student at the University of Helsinki while physically staying and working in Norway added a fair share of complications, sometimes expected and sometimes not. Just ten years ago, sitting in a train and preparing to spend a year in the military service, I would never have imagined that one day I will be working as a researcher abroad let alone pursuing a degree. But nevertheless, here I am, sitting in my office in Oslo and typing these words while realising that soon this pursuit will reach its conclusion, and I must say, I would not be able to reach this far without help and encouragement from many people.

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Research can not be performed by sitting alone in a locked room and I would like to thank my coauthors Dr. Mariken Homleid, Dr. Malte Müller and Dr. Ekaterina Kurzeneva, whom I already mentioned, for all their support and fruitful collaboration. To all the current and former colleagues at the Development Centre for Weather Forecasting and at the Norwegian Meteorological Institute in general, thank you for sharing your expertise and helping, especially in the beginning, with all the issues I encountered when running numerical experiments. Separately, I would like to thank the director of the Development Centre for Weather Forecasting Dr. Jørn Kristiansen for finding ways to extend my position at the Norwegian Meteorological Institute and continue this project, and Dr. Teresa Remes for her friendly advice and encouragement. Special thanks to Dr. Andrew Singleton and Dr. Erin Thomas for their numerous suggestions on improving the language of the manuscripts. Additionally, I would like to thank all the colleagues outside the Norwegian Meteorological Institute, especially at the Swedish Meteorological and Hydrological Institute and at the Finnish Meteorological Institute, for their support and willingness. There are too many names to list all of them here, but in no case I deem your contributions and support less important.

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Finally, I would like to emphasise the importance of financial support provided to this PhD project throughout the years. Research presented in this thesis was funded through various external and internal projects at the Norwegian Meteorological Institute. Without the funding from such projects as ALERTNESS and the Nansen Legacy, to name a few, this study would not reach its current state.

Юрий Батрак
Осло, июль 2022 года

Acronyms and abbreviations

3DVAR	Three-dimensional VARiational analysis
ALADIN	Aire Limitée Adaptation dynamique Développement InterNational
AROME	Applications of Research to Operations at Mesoscale
CMEMS	Copernicus Marine Environment Monitoring Service
COSMO	Consortium for Small-scale Modeling
ECMWF	European Centre for Medium-Range Weather Forecasts
EKF	Extended Kalman Filter
ESTD	Standard deviation of errors
GFS	Global Forecast System
HARMONIE	HIRLAM-ALADIN Research on Mesoscale Operational NWP in Euromed
IFS	Integrated Forecasting System
LSMIX	Large-scale mixing
ME	Mean Error
MODIS	Moderate Resolution Imaging Spectroradiometer
NCEP	National Centers for Environmental Prediction
NPP	National Polar-orbiting Partnership
NWP	Numerical Weather Prediction
RMSE	Root Mean Square Error
SICE	Simple ICE scheme
SURFEX	SURFace EXternalisée
VIIRS	Visible Infrared Imaging Radiometer Suite

Contents

List of original publications

This thesis consists of an introductory review, followed by four peer-reviewed research articles. Papers **I–III** are reprinted under the terms of the Creative Commons Attribution 4.0 International license, and paper **IV** is reprinted under the terms of the Creative Commons Attribution Non Commercial No Derivatives 4.0 International license.

I. Batrak, Y., Kourzeneva, E. & Homleid, M. Implementation of a simple thermodynamic sea ice scheme, SICE version 1.0-38h1, within the ALADIN–HIRLAM numerical weather prediction system version 38h1. *Geoscientific Model Development* **11,** 3347–3368. DOI: `10.5194/gmd-11-3347-2018` (2018).

II. Batrak, Y. & Müller, M. On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice. *Nature Communications* **10,** 4170. ISSN: 2041–1723. DOI: `10.1038/s41467-019-11975-3` (Sept. 2019).

III. Batrak, Y. Implementation of an Adaptive Bias-Aware Extended Kalman Filter for Sea-Ice Data Assimilation in the HARMONIE-AROME Numerical Weather Prediction System. *Journal of Advances in Modeling Earth Systems* **13,** e2021MS002533. DOI: `10.1029/2021MS002533` (2021).

IV. Batrak, Y. & Müller, M. Atmospheric Response to Kilometer-Scale Changes in Sea Ice Concentration Within the Marginal Ice Zone. *Geophysical Research Letters* **45,** 6702–6709. DOI: `10.1029/2018GL078295` (2018).

Chapter 1

Introduction

Sea ice, these two short words are strongly associated with one of the harshest environments in the Northern Hemisphere, the Arctic. Indeed, even though the seasonal ice cover reaches as far as 40°N,[1,2] the vast area of the Arctic seas encrusted by seasonal and perennial ice outweighs the seasonally frozen mid-latitude seas by an order of magnitude. These frozen seas are covered by myriads of moving ice floes of all different shapes and sizes forming endless planes scarred by chaotic ridges or swiftly diverging in their constant motion creating narrow openings and wide polynyas. Sea ice, especially when covered by snow, has low thermal conductivity and high albedo insulating the ocean from the atmosphere and reducing the amount of absorbed shortwave radiation. All this creates a unique environment affecting the life on Earth on all scales: from providing a stable platform for various microorganisms,[3] primary producers[3] and animals[3] to moderating the climate[4–6] over millennia.[7]

Earth climate and Arctic sea ice are strongly connected, with ice influencing even the areas located thousands kilometres away from the polar regions. However, sea ice impacts not only the long-term evolution of the climate but also has a strong influence on the short-term atmospheric state – *weather*. Drastic difference in the physical properties of open water and sea ice results in a strong surface temperature gradient between ice-free and ice-covered parts of the Arctic Ocean and affects the turbulent energy exchange between the ocean surface and the atmosphere. This in turn has impact on weather not only over ice-covered regions but in remote areas as well. A simple example: *marine cold air outbreaks* or advection of cold air masses formed over ice-covered areas towards warm ice-free ocean which can result in formation of Arctic fronts and polar lows.[8,9]

Severe weather events can have disastrous consequences and socio-economic activities in any region on Earth require timely and accurate information about current and expected weather. Nowadays this information is provided by means of numerical models approximating the real processes on Earth surface and in the atmosphere. There is a wide range of NWP models used for operational weather prediction but fundamentally they can be divided in two classes: global and regional. The model domain of a global model covers the whole Earth

Earth and has an important advantage of not having discontinuities or boundaries in the model atmosphere, except for the surface and top of the atmosphere, thus such models do not require external forcing data to account for the unrepresented part of the atmosphere. Examples of such models are IFS by the ECMWF and GFS by NCEP. However, advantages of global grids lead to a serious limitation of such models – high computational and storage cost. Computational cost of global models is often a limiting factor and to alleviate it operational centres, which require timely weather forecasts, commonly use models with reduced spatial resolution and simplified representation of the atmospheric processes. From the other side, regional NWP systems do not cover the whole globe but rather provide weather forecast for a limited area. Thus, such systems require information from a global model or another regional model covering a larger region to define the atmospheric state over the model domain boundaries. Although, since these systems cover smaller areas, they are less computationally demanding and operational centres can afford using higher spatial resolution or more advanced representation of physical processes, for example, applying non-hydrostatic formulations.

Operational NWP systems routinely provide forecasts for any region on Earth, although some regions are proven to be more challenging for weather prediction than others. One of such regions is the Arctic, where lack of in-situ observations combined with simplifications applied in the weather models, usually tuned to perform best in the mid-latitudes, results in reduced forecast skill.[10] Quality of weather forecasts for the Arctic regions becomes more and more pressing issue with the recent climate change and increasing activity in the region.[11] The Arctic, which remained a deserted and isolated place for many centuries, experiences a more drastic warming than any other region on Earth.[12–14] For a long time the possible advantages of sea routes by the Arctic Ocean were only theorised upon;[15,16] and many brave men lost their lives trying to discover the North-West and North-East passages.[17–19] In the first quarter of the XXI century, with retreating ice cover and increasing ship traffic, importance of the Arctic Ocean to the world economy grows and it is predicted to increase in the following decades.[20] Growing activity in the region results in increasing demands on the quality of weather forecasts.

In NWP systems representation of surface processes plays an important role impacting the quality of the produced forecasts, and surface parameterisation packages become more and more advanced. Naturally, Earth surface forms the lower boundary condition for the model atmosphere where turbulent and radiative fluxes transfer energy between the surface and the atmosphere. All these fluxes should be accurately represented or parameterised in an NWP model to give a reliable forecast of near-surface parameters, such as screen-level air temperature (here *screen-level* denotes the air temperature modelled or observed at the height of a standard meteorological screen, which is situated at the 1.25 to 2 m height above ground[21]). A surface parameterisation package of an NWP system usually includes representation of various surface types including natural landscapes, urban areas and water bodies. Additionally, if an NWP system is designed to operate in high latitudes, its surface parameterisation package should include a numerical representation of the sea ice cover – a sea ice model.

Numerical modelling of sea ice went a long way from first semi-empirical formulations to contemporary

contemporary numerical models. Early studies focused mainly on the evolution of the ice thickness as a response to the atmospheric conditions[22,23] to derive a practical means of predicting the ice thickness from the air temperature series. However, these simple models, while being undoubtedly useful to practical men, do not resolve the evolution of the ice cover with enough level of detail for incorporating them in NWP systems. Following evolution of numerical sea ice models went along the two main directions, namely: thermodynamic and dynamic ice modelling. Thermodynamic sea ice models aim on representing the processes in ice column with maximum possible level of detail while dynamic models focus on the larger-scale evolution of the ice cover as a drift medium. Finally, these two types of sea ice models are merged into dynamic-thermodynamic models trying to accurately represent the full evolution of the sea ice cover. These models can use somewhat simplified representations of the thermodynamic processes to reduce the computational costs emerging when running the model on the basin scales.

Traditionally in numerical forecasting, NWP systems and ocean models are operated separately and represent sea ice cover with different level of detail. In ocean modelling one of the main products is the sea ice forecast which necessitates an advanced dynamic-thermodynamic sea ice model to be included. These forecasts focus mainly on such parameters as ice thickness and ice compactness while thermal properties of the ice cover are of less importance. From the other side, in NWP sea ice is often treated simply as the lower boundary condition of the atmospheric model and not as one of the main components of the system, therefore in these systems surface properties of the sea ice cover become the most important for a parameterisation scheme to accurately resolve since these parameters influence the energy exchange between surface and the atmosphere. As a result, sea ice models in NWP systems are often greatly simplified, sometimes to the point of prescribing the ice temperature by means of an external data set or climatology.[24]

Additionally, the so-called fully coupled NWP systems are in active development and become more common in operational applications.[25–27] These systems, in case of ocean–sea-ice–atmosphere coupling, include both an atmospheric and a three-dimensional ocean model with a dynamic-thermodynamic sea ice model allowing for a great detail of representing the interactions between these components. However, combining multiple models in a single system not only considerably increases the computational cost of model simulation, but also introduces additional degrees of freedom in the system making model tuning more complicated.

Contemporary short-range NWP systems operating over the Arctic model domains use various approaches to representing the sea ice cover. Even though prescribing ice temperatures in the model is becoming obsolete nowadays, it is still a relatively popular solution in the systems which are not focused on the high latitudes.[24,28] In models with prognostic sea ice schemes, complexity and design of the applied parameterisation also varies. Usual choices are single layer and multilayer schemes with prescribed ice thickness, snow layer is often missing or represented by modifying the albedo of the ice cover. However, whilst modern NWP systems use finer and finer resolution grids, with the grid cell dimensions nearing 1 km, and become more and more advanced in general, effects and limitations posed by traditionally-applied traditionally-applied simplistic sea ice parameterisation schemes are not well studied.

The aim of the present work is to develop a sea ice parameterisation scheme applicable to regional short-range high-resolution operational NWP and improve the understanding of the effects induced by simplified parameterisation schemes on model forecasts. Specifically, the following research questions are addressed throughout the thesis:

- *What are the effects induced by applying a thermodynamic sea ice scheme into a short-range regional NWP system operating in the Arctic?* Ice surface temperature in the model can be prescribed by means of an external observational or modelling data set, which potentially could have a higher quality than the field computed by a simplified parameterisation scheme. The aim is to investigate the benefits of applying a prognostic scheme in the model and assess whether a simplified parameterisation scheme is always a viable option compared to prescribing ice surface temperature in the system.

- *What are the consequences resulting from applying a simplified representation of the evolution of the sea ice cover and their impact on the near-surface atmospheric variables in the model forecast?* NWP systems apply a wide set of simplifications in their sea ice parameterisation schemes, such as prescribed ice thickness or binary ice cover, while some of them can be detrimental to the quality of the model forecast.

- *Should the state of the sea ice parameterisation scheme in an NWP system be constrained by observational data sets?* Ice surface temperature is seldomly constrained by the observations in operational NWP applications. However, applying a data assimilation procedure could potentially alleviate the modelling errors caused by the simplicity of the parameterisation scheme.

- *Are there potential benefits of applying high-resolution representation of the sea ice cover in a high-resolution convection-permitting NWP system?* Contemporary regional NWP systems typically define sea ice cover by means of low-resolution satellite or modelling products. Impacts of applying high-resolution sea ice cover on the evolution of the atmospheric variables are not well-studied in the context of operational NWP.

This thesis is organised as follows: Chapter 2 provides an overview of the used NWP system and applied sea ice parameterisation scheme, utilised external observational and modelling data sets, as well as design of the performed numerical experiments. Chapter 3 presents a summary of the main results, Chapter 4 discusses the obtained results and Chapter 5 concludes the thesis and highlights the prospects for future research. The introductory review is followed by the four reprinted articles, prefaced by a short summary of the published peer-reviewed articles with a description of author's contributions in case of joint publications.

Chapter 2

Methods

This chapter provides an overview of the applied numerical models and observational data sets. Additionally, a summary of the numerical experiments performed in the present work is given.

2.1 Numerical models

In this thesis the HARMONIE-AROME[29] NWP system is used as the main research tool for studying the effects of applying a sea ice parameterisation scheme in regional NWP systems. HARMONIE-AROME includes a regional non-hydrostatic convection-permitting atmospheric model and a selection of atmospheric and surface data assimilation procedures. Typical operational configurations use 3DVAR for atmospheric data assimilation and optimal interpolation for surface analysis. Surface processes in HARMONIE-AROME are represented by the externalised modelling platform SURFEX,[30] which provides parameterisation of various land surface types, such as inland water bodies, seas, urban areas, and natural landscapes. SURFEX is incorporated as a subcomponent of HARMONIE-AROME and resolves the energy exchange between the atmosphere and the underlying medium. In the present thesis HARMONIE-AROME is configured to run on a relatively dense grid with spatial resolution of 2.5 km and 65 vertical layers; the top-most model layer is located at the 10 hPa height, and the lowest model layer has the height of approximately 12.5 m above the model surface. For the model integration HARMONIE-AROME uses a semi-implicit numerical scheme which is combined with a semi-Lagrangian advection scheme, and a characteristic time step for a 2.5 km grid is 60 s.

Numerical experiments in this thesis are designed to resemble operational applications of HARMONIE-AROME where model integration is performed by applying the so-called cycling approach. With this approach, model output from a numerical experiment represents a set of overlapping model forecasts rather than continuous series of model states, which is usually the case in climate modelling, for example. Schematic on the Figure 2.1 provides details on the organisation of a typical HARMONIE-AROME experiment in NWP mode.

HARMONIE-AROME is a regional NWP system, therefore it requires boundary conditions to be provided from an NWP system covering a larger area. In the present work HARMONIE-AROME is forced by the global NWP system IFS-HRES operated by the ECMWF. Boundary conditions are provided with one hour temporal resolution.

Originally,

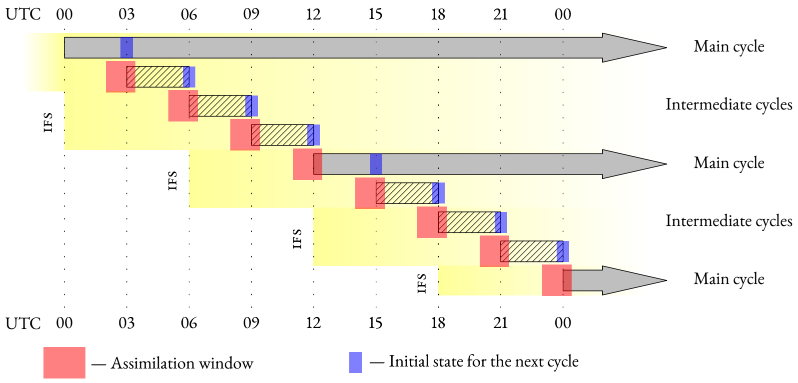

Figure 2.1: Schematic representation of running a HARMONIE-AROME model simulation in NWP mode. Model experiment consists of a series of analyses and model forecasts or *cycles*, where model forecast from the previous cycle is provided as the initial model state for the next cycle's analysis. Main cycles (00 and 12 UTC on the schematic) provide longer model forecasts, while forecast length at intermediate cycles is only enough to obtain the initial model state for the next analysis. Also on the schematic, a simplified representation of the cycling strategy of the host model, IFS-HRES, is outlined.

Originally, sea-ice covered areas in HARMONIE-AROME were represented in a very simplified way: the ice surface temperature, as well as the sea surface temperature, was prescribed by means of an external data set and remained constant during model forecast. To represent the effects of the evolution of the sea ice cover in the model, the prescribed ice surface temperature field was updated each cycle during the analysis step. **Paper I** introduces a new thermodynamic sea ice parameterisation scheme, SICE, in HARMONIE-AROME to resolve the evolution of the ice surface temperature during the model forecast. The scheme resolves the process of heat diffusion in the ice layer with constant salinity of 3 ‰. Additionally, the scheme allows for the snow cover over sea ice to be explicitly represented by an adapted version of one of the land snow parameterisation schemes provided by SURFEX.[31] However, the process of snow-ice formation, which is of less importance in the Arctic than in the Antarctic,[32] although indicated to become a more common phenomenon in coming years,[32–34] is not represented in the current version of the scheme. Turbulent fluxes over a partially ice-covered sea grid cell are computed as a weighted mean between sea-ice and open water fluxes with a discretionary form drag term.[35] Original implementation of SICE uses prescribed and constant ice thickness, and **Paper II** extends this implementation by adding the processes of ice growth, and ice melting from bottom and surface. The ice growth formulations in SICE use a prescribed constant ocean heat flux as a tuning parameter.

The

The SICE scheme does not resolve ice dynamics, and it is unable to freeze new ice from open water or melt the ice completely since NWP applications of SURFEX in HARMONIE-AROME use a prescribed sea surface temperature field in place of a prognostic parameterisation for sea grid cells. Thus, sea ice cover in HARMONIE-AROME is defined by the sea ice concentration field provided to the model from an external source, for example from the host model. The ice concentration field is updated each cycle at the analysis step and remains constant during the model forecast. Such approach, while allowing a considerable simplification of the sea ice component of HARMONIE-AROME, introduces inconsistencies between the existing and updated ice cover in the model. For initialisation of the new ice grid cells SICE applies a simple distance-weighted extrapolation procedure using the ice state from nearest grid cells with existing ice cover. If the model state from the previous model forecast has no ice-covered grid cells, new ice is initialised as a snow-free surface with predefined uniform ice thickness and temperature equal to the freezing temperature of the sea water.

The sea ice parameterisation scheme discussed in **Papers I, II, IV** of this thesis does not use any additional information to constrain the state of the sea ice model, thus ice temperature profile, as well as ice thickness and snow cover over sea ice (when applicable), evolve freely during the model integration and from cycle to cycle. **Paper III** further extends the SICE model by adding a data assimilation procedure correcting the thermal profile of the ice slab. This assimilation procedure uses the EKF to assimilate a near real time ice surface temperature product,[36] which provides estimated ice surface temperature only in cloud-free conditions. Therefore, before performing sea ice analysis within SURFEX, which operates with one-dimensional parameterisations, ice surface temperature product should be converted to gridded observations defined on the HARMONIE-AROME model grid. This step is preformed by applying the optimal interpolation procedure, which uses the surface temperature field from the previous cycle's forecast as the model background. For the ice-covered grid cells located at the considerable distance from the valid ice surface temperature product pixels the system reports missing observations and the analysis procedure does not update the SICE model fields, only propagating the background error covariance matrix.

2.2 Observational data

In this thesis various observations are used for studying and verifying the performance of the sea ice parameterisation in the HARMONIE-AROME NWP system, and for assessing its effects on the other components of the system.

The primary effects of applying the sea ice parameterisation scheme are observed in the ice surface temperature fields, and for verifying the performance of the scheme observational data sets of the ice surface temperature are required. However, in-situ observations are scarce and often report only local conditions[37] or do not directly measure surface temperature, making them less applicable for studying general effects of introducing a new parameterisation scheme. Thus, in this thesis a considerable amount of satellite remote-sensing product data is used for verification purposes. Given that ice surface temperature is a fast-evolving variable,[37,38] daily aggregated ice surface temperature fields are not optimal for verification purposes since they combine multiple

ple satellite swathes with different valid times, which would make the analysis considerably more difficult. Instead, in the present thesis L2[39] near real time products are utilised allowing for better temporal collocation of model and observational data.

The following satellite ice surface temperature products are used for verification purposes in **Paper I** and **Paper III**: MOD29[40] and MYD29,[41] derived from the data obtained by the MODIS instrument on-board the Terra and Aqua satellites, respectively. Additionally, **Paper I** uses the VNP30[42] product obtained from the VIIRS instrument on-board the Suomi NPP satellite for extended validation, and **Paper II** uses an L4[39] ice surface temperature product from CMEMS[43] for assessing the ice surface temperature of atmospheric reanalysis products in cloud-free conditions.

In-situ observations on the sea ice, though scarce, are a valuable source of local information which can not be obtained from spaceborne instruments. **Paper II** of the present thesis uses observations from the N-ICE2015 drift campaign[44] for assessing the ability of different sea ice parameterisation schemes to represent evolution of the ice surface temperature with focus on clear-sky events. Ice surface temperature along the N-ICE2015 drift trajectory is derived from the in-situ longwave radiation observations.

In-situ observations and remote sensing data sets providing information about the ice-covered regions are used to verify the direct effects of applying a sea ice parameterisation scheme as a component of an NWP system. However, the indirect effects, such as impact on the screen-level air temperature forecast in the surrounding regions, are also of high importance, especially since they represent the forecast quality over the populated areas (for example, the Svalbard archipelago with total population close to 2500 individuals as of 2021). Therefore, **Paper I** and **Paper III** use observations from the land meteorological (SYNOP) stations, which routinely report to the Global Telecommunication System, to verify the forecast quality of the screen-level air temperature and humidity, and 10 m wind speed.

State of the sea ice cover directly affects the energy exchange between the surface and the atmosphere thus modifying the state of the near-surface air masses, which in turn can have an impact on the evolution of the upper air variables. To assess these possible effects, accurate information about the vertical structure of the atmosphere is required, which is usually obtained by means of radio sondes. For example, **Paper III** uses soundings from the Ny Ålesund station located at the western coast of the Spitsbergen island to study the possible effects of different initial states of the sea ice cover on the atmospheric forecast. However, since there are only a few operational sounding stations in the European Arctic[45,46] and all of them are located over land, which limits the applicability of such observations, this type of observations is used only for the preliminary assessment of the induced effects. A more detailed study on the responses induced by the sea ice model in the upper levels of the atmospheric model would require considerably longer than discussed in the present work experimental periods for generating reliable statistics.

2.3 Model data

Different atmospheric modelling systems use different approaches to parameterising sea ice cover. Thus, comparing the products generated by various NWP systems against a reference

ence data set allows to estimate the quality of the represented evolution of the sea ice state with respect to applied sea ice parameterisation schemes. However, operational NWP systems are constantly evolving and do not provide long series of model forecasts produced with the same version of the model system. Additionally, timeliness constraints of an operational system pose strict limitations on the scheduled start time of a model cycle and operational systems routinely use only observations which arrive before the cut-off time in the analysis;[47] even though additional observations could become available later. To alleviate these limitations of operational NWP, dedicated non-real-time *reanalysis*[48] products are produced. An atmospheric reanalysis product is generated with a single version of an NWP system which is not modified throughout the whole time period covered by the product. Moreover, since reanalysis products are always generated for periods in past and not in real time they can use a much wider set of observations than operational systems. Thus, these products are often used as the best estimate of the surface and atmospheric state[49] for a specific date.

In this thesis, a limited set of contemporary reanalysis products is used to study the effects induced by simplifying assumptions applied in the sea ice parameterisation schemes. **Paper II** uses the following global atmospheric reanalysis products: MERRA-2,[50] ERA-Interim,[51] ERA5,[52] JRA-55,[53] and NCEP-DOE Reanalysis 2.[54]

2.4 Design of numerical experiments

In the present thesis effects induced by applying a sea ice parameterisation scheme in HARMONIE-AROME are studied through a series of numerical experiments and simulations. The experiments are configured to follow the design of the operational applications of HARMONIE-AROME and use model domains, which include considerable amount of ice-covered regions. A general overview of the model domains and conducted numerical experiments discussed in the present work is provided by Figure 2.2 and Table 2.1. On the Figure 2.2 AA denotes the AROME-Arctic domain which is used for operational weather forecasting[55] by the Norwegian Meteorological Institute. On the same figure, AM denotes the AROME-MetCoOp domain, which was used for operational weather forecasting jointly[56] by the Norwegian Meteorological Institute and the Swedish Meteorological and Hydrological Institute. The AROME-MetCoOp domain was extended multiple times over the years, the present work uses one of the earliest domain configurations which was in operational service before September 2017. The large size of the AA and AM model domains results in high computational and storage costs of running numerical experiments on these domains. Thus, to allow performing model simulations over longer time periods without using prohibitively expensive operational model configurations, a smaller model domain is used in a number of experiments presented in this thesis. This model domain, marked as AC on the Figure 2.2, includes a considerable amount of sea-ice covered areas, seasonal and perennial, as well as both Svalbard and Franz Josef Land archipelagos allowing for validation of model results against observations from the coastal SYNOP stations.

Operational NWP systems run on the AA and AM domains use data assimilation procedures in both the surface parameterisation package and the atmospheric model to constrain the model state by the observations. As of 2022 these systems use 3DVAR for atmospheric

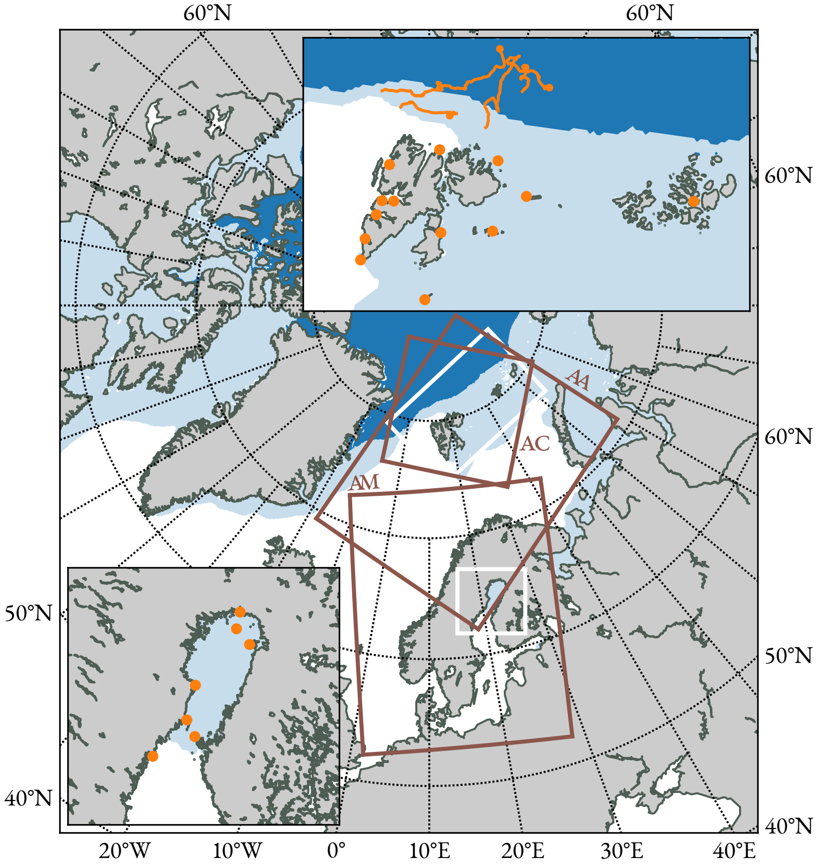

Figure 2.2: General overview of the study area and available in-situ observations. The map shows median March and September sea ice extent in the Arctic seas computed for the period from 2010 to 2020. Also on the figure, the positions of various model domains used for numerical experiments throughout this thesis are outlined. A summary of the land SYNOP stations located in the vicinity of the ice-covered areas, which were used for verifying the performance of HARMONIE-AROME is provided in the insets. Additionally, the top inset shows the drift trajectories of the four legs of the NICE-2015 drift campaign.

Table 2.1: Overview of the performed numerical experiments.

	Domain[a]	SICE[b]	Ice thk[c]	UA[d]	Time period	Notes
$\mathbf{I}^{\mathrm{AA}}_{\mathrm{REF}}$	AA	-	-	3DVAR	1 Mar 2013 – 30 Apr 2013	Binary ice cover, prescribed ice temperature
$\mathbf{I}^{\mathrm{AM}}_{\mathrm{REF}}$	AM	-	-	3DVAR	1 Mar 2013 – 31 Mar 2013	
$\mathbf{I}^{\mathrm{AM}}_{\alpha}$	AM	$^{0}/_{4}$	0.75	3DVAR	1 Mar 2013 – 31 Mar 2013	Prognostic ice temperature
$\mathbf{I}^{\mathrm{AA}}_{\alpha}$	AA	$^{0}/_{4}$	0.75	3DVAR	1 Mar 2013 – 30 Apr 2013	
$\mathbf{I}^{\mathrm{AA}}_{\beta}$	AA	$^{3}/_{4}$	0.75	3DVAR	1 Mar 2013 – 30 Apr 2013	As $\mathbf{I}^{\mathrm{AA}}_{\alpha}$ but with snow cover added
$\mathbf{I}^{\mathrm{AA}}_{\gamma}$	AA	$^{0}/_{4}$	clim	3DVAR	1 Mar 2013 – 30 Apr 2013	Climatological ice thickness
$\mathbf{I}^{\mathrm{AA}}_{\delta}$	AA	$^{0}/_{4}$	0.75	3DVAR	1 Mar 2013 – 31 Mar 2013	Form drag is applied
$\mathbf{II}^{\mathrm{AA}}_{\mathrm{REF}}$	AA	$^{0}/_{4}$	0.75	-	10 Jan 2015 – 20 Mar 2015	
$\mathbf{II}^{\mathrm{AC}}_{\alpha}$	AC	$^{3}/_{4}$	prog	-	1 Sep 2014 – 20 Mar 2015	Spin-up period until 10 January 2015
$\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF1}}$	AC	$^{12}/_{4}$	prog	LSMIX	1 Sep 2019 – 31 Jan 2020	
$\mathbf{III}^{\mathrm{AC}}_{\alpha}$	AC	$^{12}/_{4}$	prog	LSMIX	1 Sep 2019 – 31 Jan 2020	Assimilation of a sea ice temperature product
$\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$	AC	$^{12}/_{4}$	prog	3DVAR	1 Dec 2019 – 31 Dec 2020	Initialised from $\mathbf{III}^{\mathrm{AC}}_{\alpha}$ state on 30 November 2019
$\mathbf{III}^{\mathrm{AC}}_{\beta}$	AC	$^{12}/_{4}$	prog	3DVAR	1 Dec 2019 – 31 Dec 2020	Based on $\mathbf{III}^{\mathrm{AC}}_{\alpha}$, same initialisation as in $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$
$\mathbf{III}^{\mathrm{AC}}_{\gamma}$	AC	$^{12}/_{4}$	prog	3DVAR	1 Dec 2019 – 31 Dec 2020	As $\mathbf{III}^{\mathrm{AC}}_{\beta}$ but with surface analysis used in 3DVAR
$\mathbf{IV}^{\mathrm{AA}}_{\mathrm{REF}}$	AA	$^{0}/_{4}$	0.75	-	10 Jan 2015 – 30 Apr 2015	
$\mathbf{IV}^{\mathrm{AA}}_{\alpha}$	AA	$^{0}/_{4}$	0.75	-	10 Jan 2015 – 30 Apr 2015	Modified ice cover in the marginal ice zone

[a]) Model domain, following the definitions provided on the Figure 2.2.

[b]) Configuration of the SICE scheme, if used, where numerator denotes the number of snow layers and denominator denotes the number of ice layers.

[c]) Ice thickness in metres, in case of prescribed uniform ice thickness, or ice thickness computation/initialisation method (*clim* – prescribed climatological ice thickness; *prog* – prognostic ice thickness formulations of the SICE scheme).

[d]) Atmospheric data assimilation/initialisation procedure, missing value denotes a free-running atmospheric model where HARMONIE-AROME is forced only on the domain boundaries.

spheric data assimilation and optimal interpolation for surface analysis.[55,56] However, for numerical experiments and sensitivity studies applying computationally expensive 3DVAR is less beneficial, or even detrimental in situations where discontinuities introduced by the data assimilation procedure are undesirable. Thus, in the present thesis atmospheric data assimilation is applied only in the experiments $\mathbf{I}^{\mathrm{AA,AM}}_{\mathrm{REF}}$ and $\mathbf{I}^{\mathrm{AA,AM}}_{\alpha\text{-}\delta}$ assessing possible effects of applying a sea ice parameterisation scheme in the operational NWP environment, and in the experiments $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2},\beta,\gamma}$ studying the effects of sea ice analysis on the atmospheric data assimilation. Numerical experiments discussed in the **Paper II** and **Paper IV** were conducted without applying atmospheric data assimilation and these studies assess continuous series of weather forecasts generated by HARMONIE-AROME. Experiments $\mathbf{III}^{\mathrm{AC}}_{\mathrm{refi}}$ and $\mathbf{III}^{\mathrm{AC}}_{\alpha}$ use large-scale mixing to combine the model state of HARMONIE-AROME with atmospheric fields provided by the host model as the initialisation procedure for the atmospheric model. This approach allows saving computational resources in these considerably long experiments while still benefiting from the corrected initial state of the model atmosphere.[57]

When prognostic formulations for the sea ice thickness are applied in the SICE scheme, as in $\mathbf{II}^{\mathrm{AC}}_{\alpha}$ and experiments $\mathbf{III}^{\mathrm{AC}}_{\alpha\text{-}\gamma}$ discussed in **Paper III**, the scheme is initialised with uniform ice thickness of 0.75 m and ice temperature equal to the freezing point of the sea water (assuming the water salinity of 35 ‰). If SICE is configured to explicitly model the snow layer on top of the ice, HARMONIE-AROME starts from the snow-free state and SICE accumulates snow cover from model precipitations throughout the experimental period.

All the numerical experiments presented in this thesis, except the experiments discussed in the **Paper III** devoted to the problem of sea ice data assimilation, use the standard surface data assimilation procedure of HARMONIE-AROME which consists of a two-dimensional optimal interpolation procedure generating gridded observations[58] and a one-dimensional optimal interpolation procedure updating the prognostic fields in SURFEX. Additionally the surface analysis procedure updates the sea surface temperature and ice concentration (if applicable) fields using the lower resolution fields provided by the host model.

Boundary conditions in the discussed model experiments are provided by the global NWP system IFS-HRES in a manner simulating the operational applications. For example, in operational environments a HARMONIE-AROME forecast with valid time of 00 UTC can not use IFS boundaries with the same valid time, since the corresponding cycle of the host model is not finished by the time when HARMONIE-AROME starts. Thus, operational applications HARMONIE-AROME use the most recent and complete IFS forecast when generating boundary conditions for a model cycle. In the conducted numerical experiments this behaviour is achieved by introducing an at least six hour delay between the valid time of IFS-HRES and HARMONIE-AROME forecasts, see the Figure 2.1 for the details.

Chapter 3

Results

3.1 Effects of applying a sea ice model in a short-range regional NWP system

Presence of the sea ice cover within the model domain strongly affects the energy exchange between the surface and the lowest model levels of the atmospheric model since sea ice, unlike open water, quickly responds to the atmospheric forcing signal, and has much higher albedo. This results in great variations of the ice surface temperature within the time frame of a single model forecast. As a consequence, prescribed ice surface temperature in HARMONIE-AROME can not adequately represent these processes leading to underestimation of the diurnal cycle of the near-surface air temperature over sea-ice covered regions. Additionally, for main cycles starting when the ice temperature is low, for example for the 00 UTC cycle, prescribing the ice field by low nigh-time ice surface temperature leads to a cold bias in the screen-level air temperature forecast during the day-time in the model forecast. This situation is illustrated by the Figure 7a of the **Paper I** where prescribed ice surface temperature initialised at 00 UTC leads to a more than a 5 °C cold bias in the modelled screen-level air temperature after 12 hours of model forecast.

Introducing the SICE scheme in HARMONIE-AROME results in a responsive ice surface in the model, which freely evolves during the model forecast thus improving the diurnal cycle of the screen-level air temperature forecast over sea ice. This improvement is the most clear over the spring time in the Gulf of Bothnia where the diurnal cycle is prominent.

Another effect of applying a thermodynamic sea ice parameterisation scheme is the reduced error growth rate as a function of the forecast lead time. Figure 3.1 shows the performance of the SICE scheme in the operational application[55] of the HARMONIE-AROME NWP system over a one year period. As illustrated on the figure, in the reference configuration of HARMONIE-AROME the ice surface temperature RMSE computed against a near real time ice surface temperature product quickly grows with the increasing forecast lead time for all months, except the April–August period, when ice temperature is close to the melting point. Applying a simple thermodynamic sea ice scheme helps to reduce the error growth rates in the modelled ice surface temperature without deteriorating the model forecast. However, with a prescribed ice surface temperature field, HARMONIE-AROME shows smaller ice surface RMSE for short forecasts with lead time less than 12 hours. This can be explained by the fact that IFS-HRES, which is used

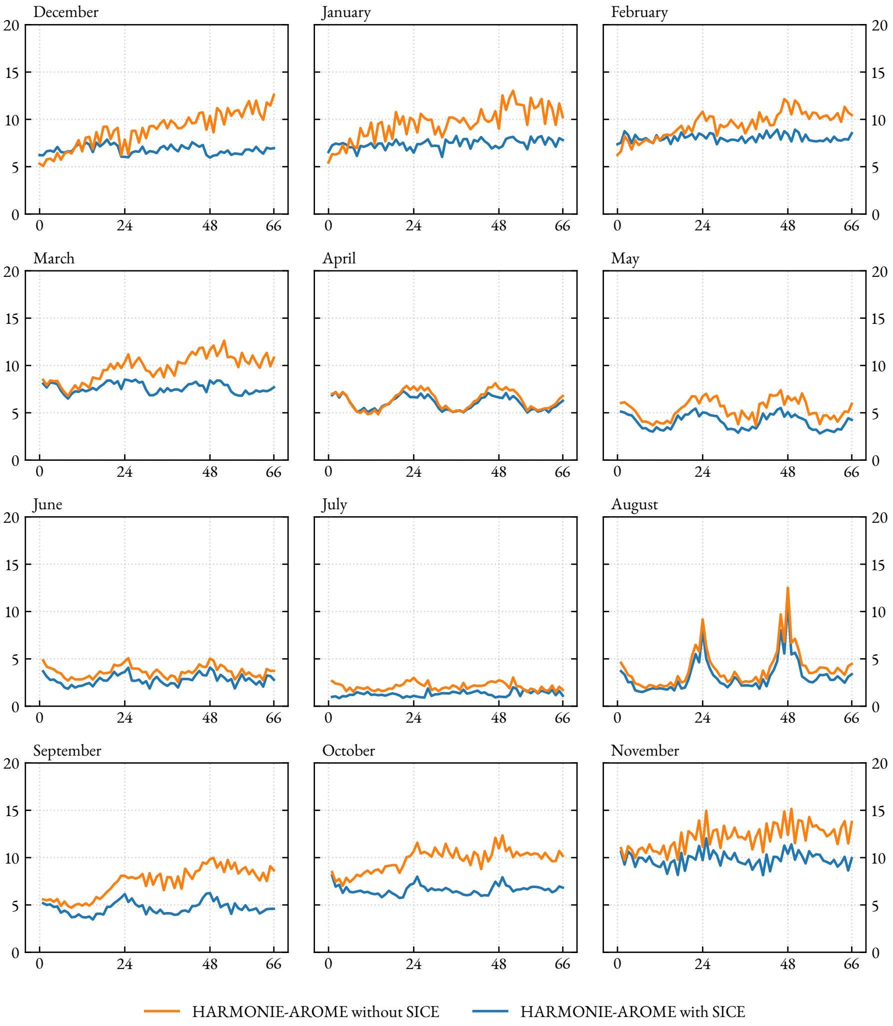

Figure 3.1: Ice surface temperature RMSE as a function of the forecast lead time computed over a one year period in two configurations of HARMONIE-AROME. On the figure, "HARMONIE-AROME without SICE" shows the simulated effect of prescribing the ice surface temperature in HARMONIE-AROME using the host model surface temperature field; "HARMONIE-AROME with SICE" represents the ice surface temperature in the operational system;[55] which uses sea ice scheme in the same configuration as in $\mathrm{I}_{\alpha}^{\mathrm{AA}}$. Scores are computed for the period from 1 December 2015 to 1 December 2016 for the forecast initialised at 00 UTC. On the panels, x axis: lead time in hours; y axis: RMSE in °C.

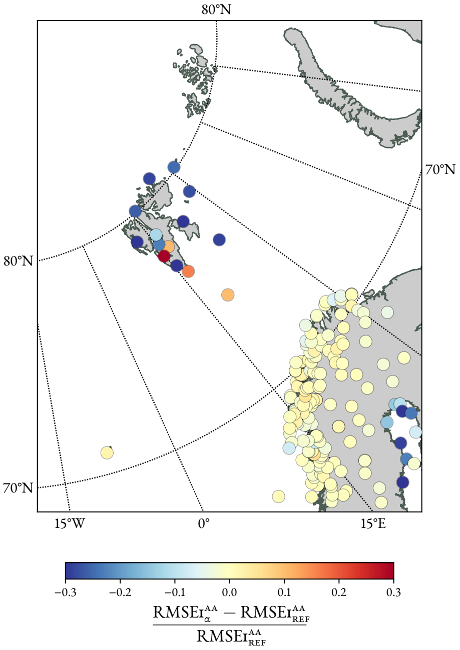

Figure 3.2: Relative change in the RMSE of the screen-level air temperature forecast resulting from applying a thermodynamic sea ice model in HARMONIE-AROME. RMSE is computed for up to 48 hour forecast lead time against in-situ observations.

used as a source of the prescribed ice surface temperature fields, while applying a similar to SICE sea ice parameterisation scheme with snow-free ice layer of prescribed and constant ice thickness;[59] uses the ice thickness of 1.5 m compared to 0.75 m in SICE. Having thicker ice cover, more suitable for a global NWP system, IFS-HRES reports lower ice surface temperature, which better corresponds to the actual temperature field, especially in the winter time.

Thus, for short-range NWP applications of HARMONIE-AROME applying a high-quality prescribed ice surface temperature field would outperform a simplified thermodynamic sea ice parameterisation scheme, but for model forecasts longer than 12 hours even a simplified sea ice model has a considerable positive effect. This result is in line with the findings of a similar study discussing the effects of applying a thermodynamic sea ice model instead of using prescribed ice temperature in the COSMO model.[28]

Effects of introducing a sea ice parameterisation scheme in HARMONIE-AROME can be traced also in the screen-level air temperature forecast for the stations located in the vicinity of the sea-ice covered areas. Verification scores computed against the SYNOP observations show that HARMONIE-AROME with SICE has lower air temperature RMSE than the reference model configuration for most of the stations located over the Svalbard archipelago and in the Gulf of Bothnia, as shown on the Figure 3.2. Other stations located within the model domain show a relatively weak response to introducing a thermodynamic sea ice model. However, there is a small number of Svalbard stations that show a considerable increase in the air temperature RMSE in the updated version of HARMONIE-AROME. This deterioration of the forecast quality is caused by the low resolution sea ice cover field provided by IFS-HRES, which is used to define sea-ice covered grid cells when SICE is used in HARMONIE-AROME. This low resolution ice concentration field, which uses a corresponding coarse land-sea mask, when interpolated to the 2.5 km grid of HARMONIE-AROME is unable to represent all the features of the coastal sea ice cover around Svalbard, such as fjords covered by the land-fast ice. As a result, in sensitivity experiments these fjords are ice-free, which causes

causes the warm bias in the modelled screen-level air temperature. The reference configuration of HARMONIE-AROME uses the surface temperature field produced by IFS-HRES to derive the prescribed ice surface temperature, thus in the areas with complex coast line of the Svalbard archipelago the resulting 2.5 km ice temperature field is interpolated from snow-covered land grid cells of IFS-HRES therefore showing no spurious warm bias.

Additionally, applying fractional ice cover in HARMONIE-AROME can result in deteriorated 10 m wind speed forecast. For example, experiments $\mathbf{I}^{\mathrm{AM}}_{\alpha}$, $\mathbf{I}^{\mathrm{AA}}_{\alpha}$, $\mathbf{I}^{\mathrm{AA}}_{\beta}$ and $\mathbf{I}^{\mathrm{AA}}_{\gamma}$ show a 0.4 ms^{-1} increase in the mean error of the wind speed forecast over the coastal SYNOP stations. This effect is caused by introducing a contribution of the low-roughness open-water part of an ice-covered grid cell to the average turbulent flux of momentum, which is present in case of ice concentration less than 100%. Applying the form drag term when computing the average drag coefficient over a sea-ice covered grid cell (experiment $\mathbf{I}^{\mathrm{AA}}_{\delta}$) alleviates the observed increase in the wind speed bias.

3.2 Importance of the evolving ice thickness and snow cover

So far the effects of applying a sea ice parameterisation scheme in HARMONIE-AROME were tested with using the simplified SICE configuration which has prescribed and uniform ice thickness without any snow cover. However, these simplifications greatly reduce the accuracy of the represented evolution of the sea ice cover in the system. As a consequence, SICE in this configuration tends to show a noticeable warm bias in the modelled ice surface temperature, which is apparent when comparing the model forecast with satellite data, as presented on the Figure 3.1.

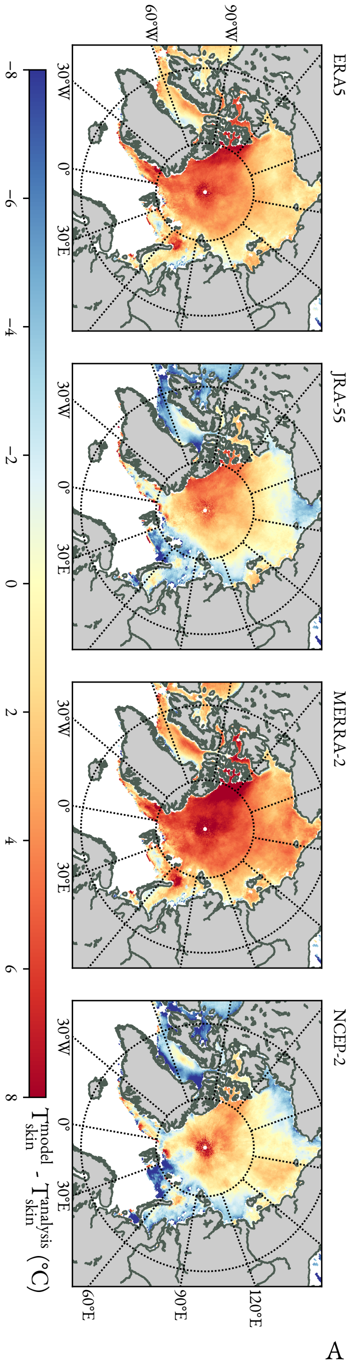

Figure 3.3: Ice surface temperature in various reanalysis products compared to a satellite-based clear-sky ice surface temperature product for years 2015–2017. None of the presented products has prognostic ice thickness nor insulating snow layer.

A popular approach to mitigating this limitation of the scheme is replacing the uniform prescribed ice thickness with non-uniform ice thickness,[60,61] for example, based on a climatological data set as in the experiment $\mathbf{I}^{\mathrm{AA}}_{\gamma}$. This varying in space prescribed ice thickness helps to somewhat reduce the warm bias in the model by the cost of introducing an additional external data dependency. However, applying a climatological ice thickness product still limits the ability of the system to adapt the ice cover state following the signals in the atmospheric forcing. Therefore, for operational applications a more preferable solution is extending the formulations of the SICE scheme to represent the processes of ice growth and melting. With this approach the ice scheme is able to represent the evolution of the ice thickness throughout the year while staying in balance with the state of the model atmosphere. Although, introducing a freely-evolving ice thickness in the system can lead to its unrealistic values, since it is not constrained by observations and a one-dimensional scheme can not represent sea ice as a drift medium.

Accurate and evolving ice thickness in the model, while being an important parameter, can not completely compensate other simplifications applied in the original configuration of the SICE scheme, most importantly the absence of the snow cover. Ice is almost always is covered by a layer of snow, which has different thermal properties and effectively insulates ice and underlying ocean from the atmosphere.[62,63] Thus, when snow cover is present, surface temperature can be lower than in cases of snow-free ice surface. Without the snow cover ice in the model should be unrealistically thick to allow such low surface temperatures but still unable to resolve extremely fast changes in the surface temperature resulting from the low thermal conductivity of the topmost layer of snow.

The original configuration of the SICE scheme discussed in the **Paper I** already provides an option to include a parameterisation of the snow cover in the system, however, initial tests showed that for the Svalbard stations applying the sea ice parameterisation with explicit representation of the snow cover does not result in clear improvement of the verification scores. This lack of clear positive impact, especially in the screen-level air temperature forecast, can be partly attributed to the configuration of the sensitivity experiment, which was performed over a two-month period in spring 2013 starting from the snow-free initial sate of the ice cover. Thus, snow cover accumulated from the model precipitations over the experimental period was considerably thinner than the snow cover in reality, which is close to its maximum thickness in the spring time before the snow melt starts. Nevertheless, comparison against the satellite ice surface temperature products shows that including the snow layer on top of the ice in the experiment $\mathbf{I}^{\mathrm{AA}}_{\beta}$ reduces the warm bias of the ice surface temperature forecast in HARMONIE-AROME (see, for example, Figure 9a in **Paper I**).

Further assessment of the effects of misrepresenting the sea ice state in simplified parameterisation schemes is performed by comparing different atmospheric reanalysis products. Results show that a parameterisation scheme with no snow layer and a prescribed and uniform ice thickness is unable to accurately represent the ice surface temperature field. As shown on the Figure 3.3 applying a parameterisation scheme with uniform ice thickness, especially when combined with binary ice cover, as in JRA-55 and NCEP-2, leads to strong biases over different parts of the Arctic ice cover. Notably,

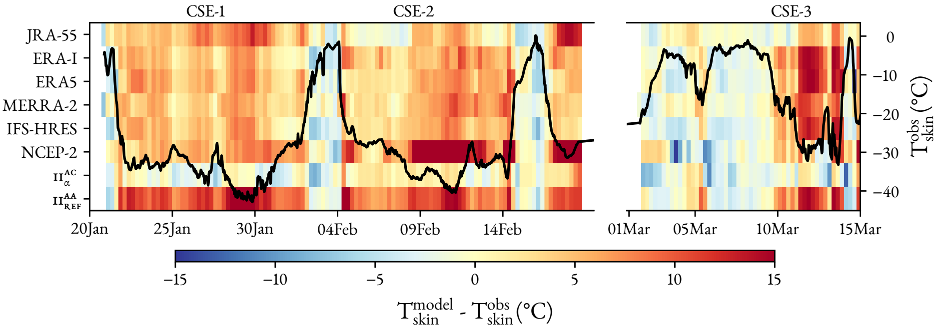

Figure 3.4: Ice surface temperature in various reanalysis products and in HARMONIE-AROME experiments compared to the NICE-2015 drift campaign data. Considerable errors in the ice surface temperature are observed during the clear sky events, three such events are marked on the figure as CSE-1, CSE-2 and CSE-3.

tably, JRA-55 and NCEP-2, which have the thickest ice cover suitable for the central Arctic show considerable cold bias over areas covered by the thinner first-year ice. Including the snow cover in a sea ice parameterisation scheme considerably reduces the heat flux from ocean to the atmosphere. Additionally, insulating properties of the snow layer of any considerable thickness are so good that actual thickness of the ice layer beneath the snow plays only a minor role in the evolution of the ice surface temperature[63] thus rendering the model less sensitive to misrepresentation of the ice thickness field.

Effects induced by the explicit representation of the snow layer in a sea ice parameterisation scheme are the most apparent during the winter clear sky events when fast radiative cooling results in very low ice surface and, as a consequence, screen-level temperatures. Comparing the surface temperature fields of various atmospheric reanalysis products, as well as the HARMONIE-AROME forecasts from the experiments $\mathbf{II}^{\mathbf{AA}}_{\mathbf{REF}}$ and $\mathbf{II}^{\mathbf{AC}}_{\alpha}$, against the in-situ observations from the drift campaign NICE-2015 shows that all the model configurations which do not include the snow layer on top of the sea ice suffer from the 5 to 10°C warm bias. As shown on the Figure 3.4, the only model version which does not show this considerable bias during clear sky events is HARMONIE-AROME when uses SICE with explicitly represented snow cover. In the experiment $\mathbf{II}^{\mathbf{AA}}_{\mathbf{REF}}$ SICE has no snow cover and uses the prescribed ice thickness of 0.75 m, which is thinnest amongst the compared products and results in the strongest warm bias during clear-sky events.

The findings presented in **Paper II** are in line with earlier studies[64] and indicate that contemporary atmospheric reanalysis products which are produced by models applying simplified representations of the sea ice cover tend to have warm bias of the ice surface temperature in certain conditions. Applying these data sets as a baseline or "best estimate" in model intercomparisons can lead to erroneous conclusions on the behaviour of compared systems. One example is the apparent "winter-time

time cold bias" observed in climate models[65] found when comparing their surface energy budget with estimates based on warm-biased model reanalysis products. Additionally, as supported by the findings presented in the **Paper I**, this intercomparison shows that snow-free state of the ice cover is a strong simplification, which degrades the quality of the lower boundary condition for the model atmosphere.

3.3 Necessity of constraining the ice state in the model

In a typical NWP application the state of the sea ice cover, when modelled by the SICE scheme, freely evolves forced by the model atmosphere of HARMONIE-AROME. This allows for a reasonable representation of sea ice in the model without introducing additional data streams or time constraints in the operational environment. However, SICE does not represent all the processes of ice evolution and the ice surface temperature field in the model, while evincing a positive impact when compared to the original sea-ice handling approach of HARMONIE-AROME, shows considerable errors and biases when compared against observational data sets.

Paper III addresses this issue by applying a data assimilation procedure in SICE to constrain the sea ice state by an observational ice surface temperature product. Introduced framework uses a near real time ice surface temperature satellite product as observations, complemented by the ice concentration field provided by the host model. Numerical experiments performed over a small experimental domain show positive impact of assimilating ice surface temperature product in SICE. Specifically, the RMSE of the ice surface temperature forecast in the model experiment $\mathbf{III}_{\alpha}^{\mathrm{AC}}$ computed against an independent satellite ice surface temperature product is reduced by 0.4 °C on average after analysis, or in other words, at 0 hour forecast lead time. However, ice surface temperature is a very fast-evolving variable and effects of surface analysis found in the model forecast quickly diminish as a function of the forecast lead time. After 3 hours of model forecast the effect of sea ice data assimilation is already considerably reduced, but still traceable with ice surface temperature RMSE reduced by 0.1 °C on average compared to the reference experiment $\mathbf{III}_{\mathrm{REFI}}^{\mathrm{AC}}$ without any sea ice data assimilation procedure applied.

Series of weekly model-domain-average ice surface temperature RMSE presented on the Figure 3.5 also show the generally positive effect of applying sea ice analysis in HARMONIE-AROME. RMSE values in both $\mathbf{III}_{\mathrm{REFI}}^{\mathrm{AC}}$ and $\mathbf{III}_{\alpha}^{\mathrm{AC}}$ are highest at the beginning of the experimental period with values of 8.26 and 6.15°C, respectively. These high initial RMSE values are attributed to the effects of model cold start from the snow-free state of uniform ice thickness. By January 2020 these errors are reduced to 5.71 and 4.74°C, respectively. Assessing the time series of the RMSE components, namely ME and ESTD, (see the Figure 7 of the **Paper III**) shows that constraining the sea ice state by assimilating an observational data set considerably reduces the ice surface temperature ESTD, which indicates that applied procedure reduces the uncertainty of the ice surface temperature state in the system. Additionally, ESTD growth over a three hour model forecast in the $\mathbf{III}_{\alpha}^{\mathrm{AC}}$ is higher than in the reference experiment $\mathbf{III}_{\mathrm{REFI}}^{\mathrm{AC}}$, which shows almost no change in the ESTD score. From the other side, the ME series of the ice surface temperature forecast does not show the same degree of improvement compared to the ESTD scores. Applying

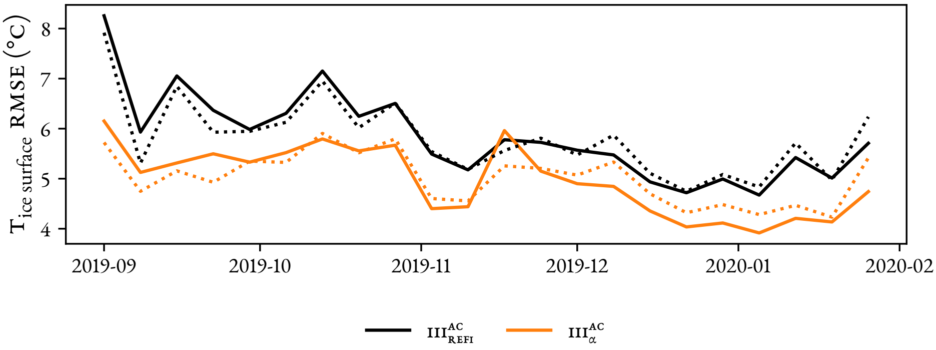

Figure 3.5: Series of weekly ice surface temperature RMSE in HARMONIE-AROME with (the $\mathbf{III}^{\mathrm{AC}}_{\alpha}$ experiment) and without (the $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REFI}}$ experiment) constraining sea ice parameterisation scheme by observations. RMSE scores are computed against an independent ice surface temperature product derived from MODIS data. On the figure, solid line represents the 0 hour forecast lead time; dotted line represents the 3 hour forecast lead time.

Applying the EKF-based sea ice analysis procedure was unable to completely remove the positive bias found in the ice surface temperature forecast of HARMONIE-AROME in certain conditions, although, this bias in the sensitivity experiment $\mathbf{III}^{\mathrm{AC}}_{\alpha}$ is smaller than in the reference run $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REFI}}$. This observed reduction of ME suggests that the applied bias-aware EKF is able to detect the presence of the model bias in the system. The apparent inability of the filter to completely remove the systematic error in the system can be attributed to several factors. Firstly, the strongest bias is observed at the beginning of the model experiments where crude initial conditions and scheme simplicity can not be fully compensated by adjusting the ice temperature. Secondly, incremental bias correction applied in SICE reduces the differences in the computed model bias at 0 and 3 hour forecast lead time. Finally, MODIS ice surface temperature products use infrared-sensitive channels of the instrument, thus they are available only in cloud-free conditions and mismatch in the cloud mask between HARMONIE-AROME and the product can lead to spurious biases.

Positive effects of applying a sea ice data assimilation procedure in HARMONIE-AROME can be also found in the near-surface atmospheric variables, for example, screen-level temperature. Assessing the screen-level temperature RMSE computed for the first 12 hours of model forecasts initialised at 00 UTC using observations from Svalbard and Franz Josef Land stations shows a considerable reduction of the error in the sensitivity experiment $\mathbf{III}^{\mathrm{AC}}_{\beta}$, compared to the reference model configuration $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$ which does not constrain the ice state with observations (see the Figure 3.6). This reduction is more apparent for the stations located close to, or surrounded by, ice-covered areas where it reaches up to 5% on average. For the Svalbard stations located further away from the ice edge effects of applying sea ice analysis are less pronounced and for three stations

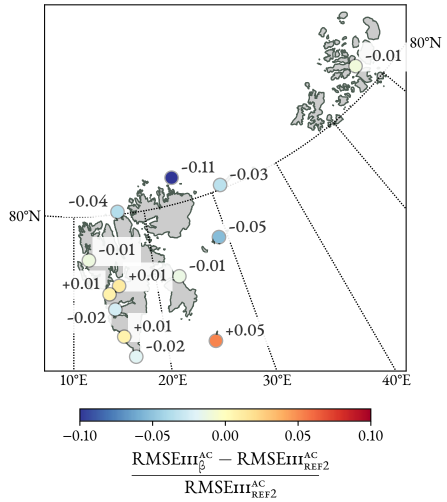

Figure 3.6: Relative change in the RMSE of the screen-level air temperature forecast resulting from applied sea ice data assimilation procedure in HARMONIE-AROME. RMSE is computed for up to 12 hour forecast lead time against in-situ observations.

tions the screen-level temperature RMSE of the sensitivity experiment is increased by 1% compared to the reference run. Similarly, for the station located in the marginal ice zone, applying sea ice data assimilation procedure leads to a considerable 5% increase of the air temperature RMSE. This reduction of the model forecast skill is attributed to reduced quality of the ice concentration field of HARMONIE-AROME near the ice edge combined with a similar feature of the assimilated ice surface temperature product.

Verifying the model forecasts of the near-surface variables as a function of the forecast lead time by combining all the SYNOP stations within the model domain shows that sea ice data assimilation helps to improve the screen-level temperature forecast for the forecast lead time of up to 24 hours. At the 0 hour forecast lead time the experiments $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$ and $\mathbf{III}^{\mathrm{AC}}_{\beta}$ show screen-level air temperature RMSE of 4.07 and 3.8°C, respectively. In both experiments RMSE grows as a function of the forecast lead time, however in the sensitivity experiment $\mathbf{III}^{\mathrm{AC}}_{\beta}$ RMSE grows faster and difference between the two experiments diminishes. After 24 hours of model forecast the screen-level temperature RMSE reaches 4.28 and 4.26°C in $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$ and $\mathbf{III}^{\mathrm{AC}}_{\beta}$, respectively. Similar analysis performed for screen-level specific humidity and 10 m wind speed shows no clear impact of constraining the sea ice state in the model (see the Figure 9 in **Paper III**).

Improving the ice surface temperature in the model by applying a data assimilation procedure has a direct effect on the near-surface variables over sea ice and in the adjacent regions. However, improved ice surface temperature can also induce indirect positive effects on the upper atmosphere in the model through the atmospheric data assimilation if the observation operator of the atmospheric data assimilation system uses surface temperature field as one of its input parameters. Thus, an additional experiment $\mathbf{III}^{\mathrm{AC}}_{\gamma}$ was conducted with providing the observation operator of the atmospheric data assimilation system of HARMONIE-AROME[66] with updated surface temperature field available after performing the surface analysis. A preliminary assessment of this effect showed that applying sea ice data assimilation procedure does not result in a clear positive impact on the model forecast of the upper atmosphere. However, updating the atmospheric data assimilation system to use the surface temperature analysis field as the model background in the observation operator

tor results in a response from the atmospheric model thus indicating potential benefits of this approach, which resembles a strongly coupled data assimilation procedure. For example, the difference between the reference experiment $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$ and the experiment $\mathbf{III}^{\mathrm{AC}}_{\gamma}$, which uses the updated surface temperature field in the observation operator of HARMONIE-AROME's 3DVAR data assimilation procedure, is greater than the difference between $\mathbf{III}^{\mathrm{AC}}_{\mathrm{REF2}}$ and the experiment $\mathbf{III}^{\mathrm{AC}}_{\beta}$. Additionally, providing the updated surface temperature field to the observation operator, increases period of significant RMSE reduction of the screen-level temperature forecast in $\mathbf{III}^{\mathrm{AC}}_{\gamma}$ to 12 hours compared to 5 hours in $\mathbf{III}^{\mathrm{AC}}_{\beta}$, which also indicates potential benefits of this solution.

3.4 Atmospheric response to small-scale features in the sea-ice cover

Numerical experiments and operational applications of HARMONIE-AROME use model grids with typical horizontal resolution of 2.5 km. This relatively high resolution allows explicitly representing some of the small-scale features of the ice cover, such as individual leads[67] and ice floes,[68,69] for example, in the marginal ice zone. However, ice concentration products retrieved from passive microwave satellite data and applied to define the ice covered areas in HARMONIE-AROME usually have nominal spatial resolution of $\mathcal{O}(10\ \mathrm{km})$[70,71] and even lower effective resolution.

Potential effects of applying high-resolution sea ice cover in regional NWP were assessed through a conservative modification of the ice concentration fields within the marginal ice zone in HARMONIE-AROME. It was found that presence of small-scale features in the experiment $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$ can have a well-pronounced effect on the near-surface atmospheric variables. Modifying the ice cover of HARMONIE-AROME to mimic the highly irregular structure of the real marginal ice zone results in a strong turbulent heat flux originated from introducing openings in the ice cover. However, the warm air plumes rising from these openings in the ice cover can not be fully reproduced by HARMONIE-AROME due to the coarse resolution of the model grid and simplified model physics. The turbulent flux can reach the values of up to 200 $\mathrm{Wm^{-2}}$ higher in the experiment $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$ than in the experiment $\mathbf{IV}^{\mathrm{AA}}_{\mathrm{REF}}$ with unmodified ice cover. This heat flux induces a response in the atmospheric model, which can be traced in the standard deviation of the difference in surface heat flux computed when comparing the reference experiment $\mathbf{IV}^{\mathrm{AA}}_{\mathrm{REF}}$ and the sensitivity experiment $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$. The computed standard deviation field, largest over the modified marginal ice zone with the values reaching 100 $\mathrm{Wm^{-2}}$ on average, also has high values over open sea, indicating that signals induced by the modified surface heat flux are advected to the regions located at the considerable distance downstream from the areas with modified ice cover.

Figure 3.7 shows similar features observed in the standard deviation of screen-level temperature and 10 m wind speed difference between the experiments $\mathbf{IV}^{\mathrm{AA}}_{\mathrm{REF}}$ and $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$. Both these fields indicate that signals induced by the modified marginal ice zone in the experiment $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$ propagate as far as the northern Norway, which is located about 1000 km away from the ice edge. However, response in the screen-level air temperature field tends to be considerably weaker over large open water regions of the model domain, compared to the response in the 10 m wind speed. This behaviour is attributed to the peculiar implementation of the open sea parameterisation scheme[72] of SURFEX

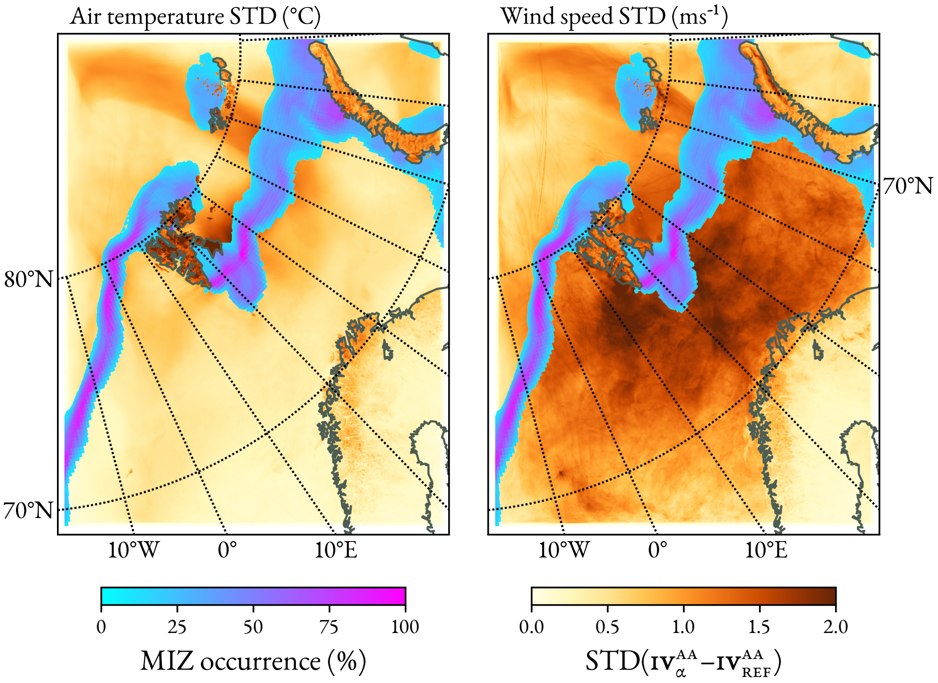

Figure 3.7: Non-local effects in the screen-level air temperature and 10 m wind speed forecast of HARMONIE-AROME presented as a standard deviation of difference between six-hourly output of $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$ and $\mathbf{IV}^{\mathrm{AA}}_{\mathrm{REF}}$ over the 3.5 month experiment. Also on the figure, location of the marginal ice zone, where kilometre-scale ice features were introduced in $\mathbf{IV}^{\mathrm{AA}}_{\alpha}$ during the model experiments, is highlighted.

FEX used in HARMONIE-AROME. This parameterisation scheme does not include a prognostic model of the sea surface temperature and only parameterises the turbulent exchange between the ocean surface and the atmosphere while the sea surface temperature field is prescribed by means of an external data set, which is provided by the host model in case of the discussed experiments. Thus, when air masses are advected over the open water parts of the model domain, the prescribed sea surface temperature field tends to behave like a filter and diminishes the anomalies in the lowest model levels. Conversely, for the 10 m wind speed atmospheric response over open sea was considerably more pronounced, with no strong filtering effect from the ocean surface.

These findings indicate the potential benefits of applying high-resolution sea ice cover in operational regional NWP systems. Additionally, the response in the atmospheric system to the modifications of the ice cover field suggests it as a candidate for applying perturbations in operational ensemble prediction systems.

Chapter 4

Discussion

Sea ice cover in an NWP system operating in the Arctic can be represented with different level of detail, from a simple prescribed temperature field to a complex model with a dedicated data assimilation system. As shown in the Chapter 3, the model atmosphere of HARMONIE-AROME is sensitive to changes in the representation of the lower boundary condition over the ice-covered areas, which results in a pronounced effect on the forecast quality.

Applying even a simplified parameterisation of the sea ice cover in a high-resolution limited area NWP system, compared to prescribing the ice surface temperature, can be beneficial for operational applications. The study performed in the **Paper I** shows that introducing a simple thermodynamic sea ice scheme improves the representation of the ice surface temperature in the system. However, extended comparisons of performance of the sea ice scheme in the operational application of HARMONIE-AROME suggests that for very short-range forecasts a high-quality prescribed ice surface temperature field in HARMONIE-AROME can potentially outperform a simplified sea ice parameterisation scheme. Such behaviour of the model system is attributed to applying an over-simplified sea ice parameterisation scheme which represented a snow-free ice layer of prescribed and uniform thickness. Conversely, for the forecasts longer than 12 hours using a parameterisation scheme, which can provide prognostic ice surface temperature, has clear advantages over prescribing the surface temperature field in the model. Verification against the land-based SYNOP stations shows that applying a prognostic sea ice scheme leads to a positive impact on the forecast skill of the near-surface variables, primarily the screen-level temperature, although the NWP system becomes sensitive to the quality of the prescribed sea ice cover, which tends to be lower in the areas with complex coast line such as Svalbard fjords. From the other side, the 10 m wind speed forecast in HARMONIE-AROME shows an increased ME when binary ice cover is replaced by the fractional ice cover, which can be compensated by taking into account the form drag when computing the drag coefficients over an ice-covered grid cell.

Performance of HARMONIE-AROME with a sea ice parameterisation scheme strongly depends on the level of simplification in the scheme. For example, **Paper I** uses a scheme which represents a snow-free surface with prescribed ice thickness of 0.75 m which results in a considerable positive bias of the ice surface

face temperature in the model. Applying a prescribed climatological ice thickness in the model reduces this bias but not completely. Initial experiments with representing the snow cover on top of the ice conducted in **Paper I** indicated potential benefits of extending the sea ice scheme by incorporating a snow model, although the results suggest insufficient spin-up time in the performed simulations. A more thorough study in **Paper II** shows that missing snow cover, which is a common feature of many contemporary reanalysis products, results in misrepresented surface energy budget in the system causing a noticeable warm bias of the ice surface temperature, especially during clear-sky events. Increasing the prescribed ice thickness in a snow-free parameterisation scheme can not completely compensate the missing snow layer, particularly in case of binary ice cover in the model. Thus, a regional NWP system operating over high-latitude model domains can strongly benefit from applying a thermodynamic sea ice scheme with explicit representation of the ice thickness and snow cover evolution. However, such sea ice scheme requires a considerable spin-up period (preferably with the model cold start date being close to the September minimum of the sea ice extent in the Arctic) if initialisation data sets for snow cover over sea ice are not available.

Utilising a more detailed sea ice model helps to improve the representation of the ice cover in the NWP system, however a one-dimensional scheme can not represent all the processes governing the evolution of the ice cover since it misses the ice dynamics. This deficiency can be compensated to some extent by constraining the sea ice state in the scheme by an observational product. **Paper III** assesses this approach by assimilating a L2 near real time ice surface temperature product in HARMONIE-AROME. Constraining the ice surface temperature in the model helps to reduce the RMSE of the ice surface temperature in HARMONIE-AROME after analysis, although this improvement is short-lived and quickly diminishes as a function of the forecast lead time. For the SYNOP stations results are also positive in general with improvement of the screen-level temperature forecast in terms of RMSE lasting for up to 24 hours, although some stations, for example, located near the ice edge, show degraded forecast scores suggesting that this region can be problematic for the applied analysis scheme. Additionally, assimilating a non-gap-free product results in strongly uneven observation coverage. Considering relatively high uncertainty of the ice surface temperature computed by a simplified one-dimensional parameterisation scheme further studies on the potential benefits of assimilation daily aggregated products should be conducted.

Timeliness of the near real time satellite products is a limiting factor for utilising them in operational applications. Introducing the so-called long cut-off cycle is a practical means to alleviating these constraints in an operational NWP system by the cost of performing an additional analysis and forecast each cycle. Effects of applying the presented sea ice data assimilation procedure in a long cut-off cycle under the timeliness constraints of operational applications of HARMONIE-AROME were not discussed in the present work and require further investigations.

Applying a sea ice data assimilation procedure opens a possibility of providing the updated ice surface temperature field to the atmospheric data assimilation procedure. Potentially, this approach can partially represent some effects of a strongly-coupled data assimilation

ilation system without costly modifications within both surface and atmospheric data assimilation components of an NWP system. Initial study performed within the **Paper III** shows that HARMONIE-AROME gives a noticeable response in the model forecast to updating the surface temperature field in the model background of the atmospheric data assimilation procedure. The identified response was not assessed for giving positive or negative impact on the quality of the model forecast due to lack of the observational data and small size of the experimental model domain. A more detailed study utilising a larger model domain is required to investigate the feasibility of applying the suggested approach in the operational environment.

Relatively high resolution of contemporary regional NWP systems allows for more and more detail of the ice cover to be explicitly represented. With increasing spatial resolution sea ice cover becomes less and less smooth and individual leads and openings in the ice result in the strong local turbulent heat fluxes from the ocean to the atmosphere. **Paper IV** investigated the consequences of applying a high-resolution sea ice cover in a regional NWP system in an idealised environment. The study found that modifying the marginal ice zone in a conservative manner, while preserving the total ice area within the model domain, results in both local and non-local responses from the atmospheric system. The non-local response in the screen-level air temperature and 10 m wind speed reaching all the way from the ice edge to northern Norway suggests that accurate representation of the high-resolution marginal ice zone in a high-resolution NWP system can potentially benefit the quality of the weather forecast. However, since misplaced ice leads could result in misrepresented turbulent exchange between surface and the atmosphere, and position of individual leads and ice floes is very dynamic, benefits of prescribing the lead positions in a deterministic NWP system are not clear. This issue is expected to become more pressing as developments pursue higher and higher spatial resolution of regional NWP systems.[73–75] A more viable approach could be using the sea ice leads products for developing sea ice perturbations in an ensemble prediction system. In this case, misplacement errors in high-resolution sea-ice cover of each ensemble member would become less important.

Chapter 5

Conclusions

Sea ice in the modern-day Arctic still covers a great part of the Arctic Ocean. Presence of the ice cover insulates the ocean surface from the atmosphere while high albedo of the snow-covered ice reduces the amount of absorbed shortwave radiation. As a result, the state of the sea ice cover is an important factor governing the weather and climate in the Arctic.[6] Recent drastic changes in the Arctic climate and diminishing of the ice cover result in increased economic activity in the region and this activity is expected to grow in the coming years.[76,77] With increasing economic activity a higher demand is placed on the accurate and reliable weather forecasts.[78] However, in the contemporary short-range regional NWP systems sea ice is often represented by simplified one-dimensional parameterisation schemes or even by prescribing the ice surface temperature field.[24] This thesis is devoted to implementing a one-dimensional sea ice parameterisation scheme in the high-resolution regional NWP system HARMONIE-AROME[29] and assessing the effects induced by applying a simplified scheme on the quality of model forecasts in the Arctic.

The present work introduces a new one-dimensional sea ice parameterisation scheme SICE within the surface parameterisation package of HARMONIE-AROME. SICE is configurable and allows representing the sea ice cover with various level of detail: from a snow-free ice surface with prescribed and uniform ice thickness, to explicitly modelled evolution of the snow cover and ice mass balance. Further, the thermal profile of sea ice in the scheme can be constrained by means of assimilating a remote-sensing observational product. A series of numerical experiments with applying different configurations of SICE in HARMONIE-AROME was conducted to improve the understanding of the effects induced by the sea ice scheme in the atmospheric forecast. Additionally, sea ice parameterisation schemes of several contemporary atmospheric reanalyses were studied. These schemes have different levels of complexity, allowing to assess the effects of applying a simplified model on the quality of the ice surface temperature in further detail.

The findings presented in Chapter 3 show that applying a prognostic sea ice parameterisation scheme has a positive effect on the model forecast of near-surface variables resulting from the reduced error growth rate of the ice surface temperature in the system. This effect becomes more pronounced with increasing forecast length, whilst in operational NWP systems with short forecast lengths, for example

ple nowcasting systems, a high-quality prescribed ice surface temperature can outperform a simplified prognostic sea ice parameterisation scheme.

When a sea ice scheme does not explicitly represent the snow layer on top of the ice, the ice surface temperature in the model tends to have a considerable positive bias. Misrepresenting the ice thickness, for example by replacing it with a prescribed and uniform field, also leads to biases in the ice surface temperature. Although, in the presence of the snow cover contribution of errors in the ice thickness to the evolution of the ice surface temperature in the model is greatly diminished. When sea ice scheme utilises fractional sea ice cover, the quality of the sea ice concentration data becomes one of the most important parameters affecting the energy exchange between ice-covered grid cells and the model atmosphere. For example, missing the land-fast ice over the Svalbard fjords results in a considerable warm bias in the screen-level air temperature forecast. From the other side, applying binary ice cover can result in a considerable negative bias of the ice surface temperature in the regions with low ice compactness.

Applying a data assimilation procedure to constrain the sea ice state in the system can help to further reduce the errors in the ice surface temperature, however the observed positive effect is rather short-lived and already greatly reduced after three hours of model forecast. Nevertheless, the impact on the screen-level air temperature forecast is pronounced for extended forecast lengths.

Resolution of the contemporary regional NWP systems allows for explicit representation of the small-scale features in the sea ice cover. HARMONIE-AROME shows a pronounced non-local response to presence of small scale features in the sea ice cover. Observed effects suggest that perturbing sea ice cover in the highly uncertain marginal ice zone can be beneficial for ensemble prediction systems operating in the Arctic.

This thesis presented a simple one-dimensional sea ice parameterisation scheme suitable for operational short-range regional NWP applications. However, the main limitation of such schemes, absence of the ice dynamics, reduces potential benefits of applying them in NWP systems. From the other side, coupling with a complex dynamic-thermodynamic sea ice model could introduce unwanted complexity and require considerable development efforts. Some alternative approach, for example, modifying prognostic fields of a one-dimensional sea ice parameterisation scheme according to an externally provided sea ice drift data set, could be a pragmatic short-term solution, however, feasibility of such model configurations requires further investigation.

Problems of coupling a short-range regional NWP system with complex dynamic-thermodynamic sea ice models, as well as potential benefits of such coupled systems over applying simplified one-dimensional parameterisation schemes, were not discussed in the present work. The next logical step would be assessing the applicability limits of simplified parameterisation schemes and their performance compared to dynamic-thermodynamic sea ice models in the context of short-range operational NWP. However, implementing and tuning a high-resolution regional coupled sea-ice–atmosphere NWP system is out of scope of the present work and these studies are left to the future research.

Chapter 6

Summary of the original publications

I. Batrak, Y., Kourzeneva, E. & Homleid, M. Implementation of a simple thermodynamic sea ice scheme, SICE version 1.0-38h1, within the ALADIN–HIRLAM numerical weather prediction system version 38h1. *Geoscientific Model Development* **11,** 3347–3368. DOI: `10.5194/gmd-11-3347-2018` (2018)

Paper I discusses the problem of parameterisation of sea ice in a regional high-resolution NWP system. A new sea ice parameterisation scheme is implemented and validated against in-situ and remote-sensing observational data sets. Numerical experiments show that applying the newly developed sea ice scheme, SICE, reduces the mean absolute error of the screen-level air temperature forecast by 0.5 °C, but increases the wind speed bias by 0.4 ms^{-1} on average in the areas close to sea ice. Validating the performance of HARMONIE-AROME with SICE against the satellite ice surface temperature products shows reduced error growth rates. However, the snow-free configuration of the scheme tends to have a considerable warm bias of the ice surface temperature.

The author developed and implemented SICE in HARMONIE-AROME, ran the major part of the numerical experiments, performed the verification of the model forecasts against the satellite ice surface temperature products, and wrote a major part of the manuscript.

II. Batrak, Y. & Müller, M. On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice. *Nature Communications* **10,** 4170. ISSN: 2041–1723. DOI: `10.1038/s41467-019-11975-3` (Sept. 2019)

Paper II investigates the performance of various contemporary atmospheric reanalysis products in terms of quality of the represented ice surface temperature. Validating the reanalysis products and two experimental configurations of HARMONIE-AROME against the data from a drift campaign shows that during Arctic winter clear-sky events missing representation of the snow layer in sea ice parameterisation schemes leads to a considerable 5–10°C warm bias of the modelled ice surface temperature. Additionally, detrimental effects of using

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a binary representation of the sea ice cover in an NWP system, as well as relative contributions to the errors in the ice surface temperature of the misrepresented ice thickness and snow depth over sea ice are discussed.

The author developed and implemented prognostic formulations for the evolution of the ice thickness within the SICE scheme, ran the numerical experiments, contributed to the analysis of the results and writing of a considerable part of the manuscript.

III. Batrak, Y. Implementation of an Adaptive Bias-Aware Extended Kalman Filter for Sea-Ice Data Assimilation in the HARMONIE-AROME Numerical Weather Prediction System. *Journal of Advances in Modeling Earth Systems* **13,** e2021MS002533. DOI: `10.1029/2021MS002533` (2021)

Paper III implements a new data assimilation procedure in the surface parameterisation package of HARMONIE-AROME for sea ice data assimilation. Initial assessment shows that constraining the sea ice model by assimilating a satellite observational product helps to reduce the errors in the modelled ice surface temperature. The reduction in ice temperature RMSE is strongest right after the analysis, when it reaches 0.4 °C on average, and quickly diminishes as a function of the forecast lead time. However, these effects are still traceable after 3 hours of model forecast. Positive effect of sea ice data assimilation is also found in the screen-level air temperature forecast over the Svalbard and Franz Josef Land archipelagos. A new approach of using the output from surface analysis in atmospheric data assimilation of HARMONIE-AROME is discussed.

IV. Batrak, Y. & Müller, M. Atmospheric Response to Kilometer-Scale Changes in Sea Ice Concentration Within the Marginal Ice Zone. *Geophysical Research Letters* **45,** 6702–6709. DOI: `10.1029/2018GL078295` (2018)

Paper IV studies the response of an atmospheric NWP system to presence of fine-scale features in the sea ice cover. Numerical simulations show that applying conservative modifications within the marginal ice zone by introducing artificial openings in the ice cover results in both local and non-local responses in the atmospheric model. A pronounced atmospheric response with the 2 °C and 2 $\mathrm{ms^{-1}}$ standard deviation of the differences in air temperature and wind speed, respectively, reaching as far as 500–1000 km from the ice edge indicates a potential benefit of applying high-resolution sea ice cover in operational NWP applications, ensemble and deterministic.

The author performed the numerical experiments discussed in the study, contributed to the analysis of the results and writing of a considerable part of the manuscript.

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