Abstract

Introduction

Arctic is warming two to three times faster than the rest of the world (Serreze and Barry, 2011) and the Southern Ocean at all depths is warming at a rate higher than the global average ocean warming (Sallée, 2018). An unprecedented decline of sea ice cover (Screen and Simmonds, 2010; Comiso et al., 2008) is a major evidence of those dramatic changes. Increasing ocean heat uptake and above–average atmospheric temperatures lead to the thinning of remaining sea ice and the gradual disappearance of multiyear ice (Kwok et al., 2009; Bitz and Roe, 2004). In the Southern Ocean the atmospheric warming trend has been most pronounced in the western Antarctic, in particular the Antarctic Peninsula (King and Comiso, 2003). The regional and global effects of those changes are not fully understood, as demonstrated by our inability to fully reproduce them in numerical modeling results (Stroeve et al., 2007; Hodson et al., 2013). Edwards et al. (2020) show that atmospheric boundary layer (ABL) processes over snow and sea ice are one of the most poorly observed and understood. Sparse network of observations, the multiplicity of processes and interactions, varying surface conditions and strong diurnal and annual cycles make the development of accurate physical parameterizations for polar regions a major challenge (Seo and Yang, 2013; Steeneveld, 2014a; Tjernström et al., 2005).

Particularly problematic for numerical weather prediction (NWP) models is the atmospheric response to the non–uniform spatial distribution of sea ice within a model grid cell. Sea ice is a critical component of the polar climate system, interconnected with the ocean and atmosphere. Presently, most of the operational models are initialized with satellite sea ice concentration products that are available daily and at the resolutions of tens of kilometers, not taking into account subgrid variability of sea ice cover. In consequence, the relevant surface variables, e.g. moisture and heat fluxes, roughness, albedo, are calculated as the weighted average of the respective values over sea ice and open water. Therefore, various effects of different spatial distributions of sea ice floes and leads (narrow, linear cracks in an otherwise continuous sea ice) are disregarded in the NWP models simulations, whereas numerous studies show that the presence of open water within the uniform sea ice cover considerably changes the properties of the atmosphere. In winter, a large temperature difference between open water and the air above (up to 20 - 30 K) results in the rapid exchange of heat and moisture (Andreas, 1980) and development of convection (Pinto. et al., 1995; Andreas and Cash, 1999). Released moisture transforms into rapidly dissipating steam fog, and mixed–phase cloud plumes that persist and extend in the downwind direction from the crack (Burk. et al., 1997). The intensity of the open water–atmosphere interactions depends on wind speed (Glendening and Burk, 1992), lead width (Marcq and Weiss, 2012), spatial orientation of the cracks (Esau, 2007; Dare and Atkinson, 2000) and, as indicated by my research, floe size distribution (Wenta and Herman, 2019). Wind influence is most pronounced when the flow is perpendicular to the crack as then surface fluxes are even 2–3 times higher on the downwind side of the lead than on the upwind one (Ruffieux et al., 1995). Furthermore, it is often assumed that numerous narrow leads tend to produce stronger area–averaged turbulent exchange of heat and moisture than a few wide ones (Burk. et al., 1997; Marcq and Weiss, 2012). However, recent studies indicate that this assumption might not be relevant when the Arctic as a whole is considered, where a larger contribution from small leads is probably associated with their high density, length and frequency occurrence (Qu et al., 2019) rather then increased efficiency. Additionally, Dare and Atkinson (2000) point out that apart from the width of open water areas in the sea ice cover, their spatial arrangement and size should also be considered as it affects the magnitude of vertical heat transfer.

To resolve the heterogeneity of sea ice cover at scales smaller than the model grid cell, the large scale NWP models have to rely on parameterizations and estimations of relevant processes. The non-linear relationship between surface and lower atmosphere variables, together with spatial correlations between them, makes this task particularly difficult. This is true especially in the case of surface turbulent heat fluxes – main focus of this thesis – as they vary significantly with different surface types. In general, there are several different ways of surface turbulent heat fluxes computation in the NWP models. The most basic one is called an "aggregation process", where only one, most dominant surface type is taken into account. In this approach, all relevant surface and atmospheric properties are represented as one number, and used for the calculation of cell–representative surface fluxes, not taking into account the non–uniform character of sea ice cover and thus producing biased results. The erroneous character of this approach has long been recognized (Vihma, 1995; Arola, 1999), thus it is only used in standard versions of some low–resolution global climate models (Rockel et al., 2008) where surface heterogeneity within the grid cell can be neglected. Another way of fluxes calculation in NWP models, a mosaic method (Avissar and Pielke, 1989), tries to overcome the issue of subgrid surface variability by independently coupling each surface type in a grid cell to the overlying atmosphere. Surface specific fluxes are, as previously, calculated from area–averaged atmospheric properties but with the consideration of the parameters specific for each surface type. Grid cell averaged fluxes are then obtained by summing the fluxes from different surfaces, weighted by their fractional coverage. This method, adopted in a number of studies (Claussen, 1990; Heinemann and Kerschgens, 2005; de Vrese et al., 2016; Frech and Jochum, 1999), includes to some extent the effects of surface heterogeneity but disregards the spatial structure of surface–atmosphere interactions. The research presented in my thesis demonstrates that the spatial structure of non–uniform sea ice plays an important role in the surface–atmosphere interactions and its absence in global climate models might be responsible for some of the observed biases.

The limitations of NWP models are particularly important now, when the sea ice cover is becoming more and more vulnerable to fragmentation due to external forcing (Rampal et al., 2009). Leads, cracks, variously shaped sea ice floes and sea ice concentration below 90% are typical features of the marginal ice zone (MIZ). However, with the ongoing decrease of sea ice extent and thickness, those characteristics can now be used to describe large areas of the Arctic ocean, including its central regions. In recent years many studies of sea ice cover evolution in the MIZ focused on floe size distribution (FSD), defined as the number of the floes in different size categories in a given region, divided by the total number of the floes in that region. Numerous publications examined various effects associated with FSD, including its influence on sea ice lateral melting (Steele, 1992; Bateson et al., 2020), the internal stresses and dynamics of sea ice (Zhang et al., 2015) and oceanic (Horvat et al., 2016) and atmospheric boundary layers (Wenta and Herman, 2018), as demonstrated in my thesis. The growing interest in various FSD related processes is reflected in the efforts to introduce FSD into global sea ice and climate models. Particularly interesting is a joint floe size and thickness distribution model developed by Horvat, Tziperman and Roach (Horvat and Tziperman, 2015, 2017; Roach et al., 2018) and implemented into the global coupled ocean–sea ice model. Apart from FSD scientists are also looking into the detection of sea ice leads in the Arctic from satellite images (Reiser et al., 2020; Wernecke and Kaleschke, 2015) and modeling of their distribution in sea ice (Wang et al., 2016). Those new advancements in the modeling of non-uniform sea ice provide a basis for the development of coupled ocean–sea ice–atmosphere models that would take into account effects associated with FSD and leads in compact sea ice, thus emphasizing the importance of increasing our understanding of the interactions between the atmosphere and heterogeneous sea ice cover.

Research motivation and summary of the results.

This section briefly describes the results from publications contributing to this thesis and the motivation behind my research. The first part presents an outcome of numerical modeling simulations of atmospheric boundary layer–sea ice interactions. In the second one, a study of ABL response to katabatic winds and polynya development based on unmanned aerial vehicle observations is described, together with a summary of a field campaign carried out in the Bay of Bothnia in winter 2020.

Numerical modeling of atmospheric response to inhomogeneous sea ice cover.

The aim of my thesis is to contribute to the ongoing efforts toward better understanding and modeling of the ABL processes and properties above the sea ice. In particular, one of the main goals is to analyze the influence of the floe-size distribution on heat and momentum fluxes at the sea surface, as well as on turbulence, mixing processes and vertical stability in the atmospheric boundary layer. Moreover, the goal is to take the first steps toward developing a method to implement above-mentioned effects related to FSD in the algorithms suitable for practical application in NWP models. Those objectives are addressed in the following two publications:

- **Publication 1**: Wenta, M., & Herman, A. (2018). The influence of the spatial distribution of leads and ice floes on the atmospheric boundary layer over fragmented sea ice. *Annals of Glaciology*, 59(76pt2), 213-230. doi:10.1017/aog.2018.15

- **Publication 2**: Wenta, M. & Herman, A. (2019). Area-averaged surface moisture flux over fragmented sea ice: floe size distribution effects and the associated convection structure within the atmospheric boundary layer. *Atmosphere*, 10, 654. doi:10.3390/atmos10110654

In the first one, a hypothesis is formulated that at a given ice concentration atmospheric boundary layer response to sea ice surface inhomogeneities differs, depending on different spatial distributions of floes and leads. An idealized version of the Weather Research and Forecasting (WRF) model is launched multiple times with various leads and sea ice floes layouts and two sea ice concentrations (50% and 90%). Three–dimensional structure of the atmospheric circulation, atmospheric moisture content, surface turbulent fluxes, as well as the influence of small scale atmospheric variability on domain–averaged properties of the ABL are analyzed. It is demonstrated that the domain–averaged values are sensitive not only to sea ice concentration but also to subgrid–scale spatial arrangement of ice floes and leads. The results clearly show that spatial distribution and strength of downdraft and updraft regions associated with convective motion within the ABL are related to underlying features of ice cover. Thus, it is demonstrated that point measurements within the ABL over sea ice might not provide data representative for larger domains. Furthermore, a possibility of parameterization formulation is suggested, which would include effects of subgrid–scale structure of the atmospheric circulation within the ABL over ice–covered areas.

In **Publication 2**, which is an extension of the above described study, the model results obtained in **Publication 1** are examined further, with a focus on convective structures within the ABL and the surface turbulent moisture heat flux. The differences in area–averaged values of turbulent fluxes, total water vapor and liquid water content found in the first article are explained, based on the fact that FSD determines the spatial arrangement and intensity of convective cells, which in turn controls the exchange of heat and moisture. Moreover, the problem of the high variability of local atmospheric conditions due to surface heterogeneity is addressed further. I propose a method, in the form of coefficient denoted with α, to integrate the effects of FSD into the calculation of surface moisture heat flux. The value of α depends on mean wind speed, sea ice concentration and the median floe radius from particular FSD. In view of the fact that models do not include FSD or the size of the floes in a particular grid cell and that presented results have not been validated with observational data, the proposed coefficient is not yet applicable for the global climate models (GCMs). However, with the development of models like the one proposed by Horvat et al. (2016); Roach et al. (2018) described solution, which includes the effects of different spatial arrangement and sizes of the floes may soon become adequate for use in NWP simulations.

It must be stressed that my studies are based on the idealized modeling results and must be validated with observations in the future. However, crucial aspects of the simulated processes in obtained results are realistic and have been observed in other modeling and observational studies in the polar regions (Tetzlaff et al., 2015; Marcq and Weiss, 2012; Zulauf and Krueger, 2003; Esau and Sorokina, 2010). Furthermore, the research described in both **Publication 1** and **Publication 2**, provides a fresh perspective on the atmospheric boundary layer response to sea ice fragmentation and can serve as a basis for field campaigns planning.

Unmanned Aerial Vehicles observations of the atmospheric boundary layer over sea ice.

It is disappointing that as yet, the obtained results cannot be validated with observations. While several campaigns have been carried out in winter Arctic that measured atmospheric properties over leads in compact sea ice cover and sea ice floes (e.g. Uttal et al., 2002; LeadEx Group, 1993), none of them obtained observations over fragmented sea ice that could be used for the evaluation of the performed simulations. Proper validation would require high resolution atmospheric measurements from various positions relative to sea ice i.e. open water, close to floes edges, in the central part of large floes, collected simultaneously over a large area. It is very likely that the recently completed MOSAIC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) expedition will provide that type of information, but considering the vast amounts of data collected, their processing and analysis are likely to take several years. The scarcity of observations in the polar regions have long been recognized as one of the main reasons behind errors in NWP models predictions (Jung et al., 2016) in high latitudes. Fragmented or newly formed sea ice presents a particularly dangerous location for measurements due to the instability of non-uniform/thin sea ice and harsh atmospheric conditions. However, a new approach, the usage of unmanned aerial vehicles (UAVs) (also called unmanned aerial systems (UAS)) (Gaffey and Bhardwaj, 2020), makes this environment much more accessible. UAVs, commonly known as drones, provide a unique opportunity to reach previously inaccessible areas and obtain three-dimensional observations of the ABL. The polar ABL and sea ice properties have already been a subject of several UAV campaigns focusing on the marginal sea ice zone (MIZOPEX; Zaugg et al., 2013), coastal sea ice (ISOBAR; Kral et al., 2018), polynyas (Knuth. et al., 2013; Cassano et al., 2015), ABL structure offshore (deBoer et al., 2018) and high latitude glaciers (Lamsters et al., 2019). Those, and numerous other studies, demonstrated that UAVs are highly flexible, can be operated in changing weather and surface conditions and are advantageous in performing high resolution atmospheric measurements, making them suitable for the observations of the ABL over fragmented sea ice.

In regard to the potential of UAVs for the studies of atmosphere–sea ice interactions, the second part of my thesis consists of two publications, in which drone observations play a key role.

- **Publication 3**: Wenta, M. & Cassano, J.J (2020). The atmospheric boundary layer and surface conditions during katabatic wind events over the Terra Nova Bay Polynya. *Remote Sens.*, 12, 4160. doi:10.3390/rs12244160
- **Publication 4**: Wenta, M., Brus, D., Doulgeris, K., Vakkari, V., and Herman, A. (2021). Winter atmospheric boundary layer observations over sea ice in the coastal zone of the Bay of Bothnia (Baltic Sea), *Earth Syst. Sci. Data*, 13, 33-42. doi:10.5194/essd-13-33-2021

Publication 3 focuses on the ABL over Terra Nova Bay, a bay located in the western Ross Sea, between Cape Washington in the North and the Drygalski Ice Tongue in the south, along the coast of Victoria Land, Antarctica. An ice-free stretch of sea persists there throughout the winter—the Terra Nova Bay Polynya (TNBP), forced by sea ice removal from the coast by strong offshore winds and maintained due to the presence of Drygalski Ice Tongue, which blocks the transport of ice from the south (Kurtz and Bromwich, 2013). Extreme winds on the coast of the Antarctic are a result of the combined influence of the forcing from temperature inversion over sloping terrain and synoptic scale pressure gradients (Parish and Bromwich, 2007; Turner et al., 2009; Wenta and Cassano, 2020). The development of katabatic winds begins in the interior of the Antarctic due to intensive radiative cooling of the surface and a consecutive buildup of the near-surface inversion layer, which has a lower temperature than the air downslope. This cold, negatively buoyant air is driven downward through the valleys of the Transantarctic Mountains, due to gravitational pull and thermodynamic forcing. Once the katabatic wind reaches the shore, it spreads laterally over the ocean and can propagate over a long distance, depending on the duration and intensity of the flow. The gradual removal of sea ice from the coast and the interaction of relatively warm open water with cold katabatic flow results in the strong atmosphere–surface coupling. In consequence, heat and moisture are exchanged upward and momentum is transferred downward (Parish and Bromwich, 1989). As the energy from the surface is absorbed by the atmosphere, the formation of new sea ice takes place, which is then transported further away from the coast by offshore winds. A continuous formation of sea ice and resulting rejection of salt increases the density of near-surface water (Minnett and Key, 2007) and produces the densest water in the ocean – the Antarctic Bottom Water (AABW). Studies indicate that TNBP may contribute about 10% of all AABW formed in the Ross Sea (VanWoert, 1999) and therefore plays a crucial role in the global thermohaline circulation, whereas the total ice production in TNBP has been estimated at 53 ± 5 km^3/year (Ohshima et al., 2016).

The aim of my research was to analyze surface-atmosphere coupling and ABL transformation during the katabatic wind events between 18 and 25 September 2012 in Terra Nova Bay using observations from Aerosonde unmanned aircraft system (UAS), satellite data, numerical modeling results and Antarctic Weather Station (AWS) measurements. It is important to mention that atmospheric data obtained with Aerosonde UAS was one of the first collected in late winter in Terra Nova Bay (Cassano et al., 2015). Although short, the analyzed period covered extreme variations of wind speed, from few m/s to more than 35 m/s and changes of Terra Nova Bay Polynya extent from several tens of km^2 to more than 2000 km^2, thus providing unique information about atmospheric properties during different stages of polynya development.

Analysis of UAV atmospheric measurements, together with satellite images of the surface, revealed how complex are the relationships between the surface, ABL and the flow from the interior of the continent in Terra Nova Bay. Changing intensity of downslope flow causes consecutive opening and closing of the polynya, reflected in significant fluctuations of sea ice concentration and atmospheric conditions. High sea ice concentration at the beginning of the analyzed period results in a relatively homogenous structure of the ABL. However, the subsequent opening of the polynya leads to increased variability of atmospheric conditions across the bay. What is more, the atmosphere is not only affected by varying surface conditions, but also by the location and intensity of the katabatic flow path, which changes throughout the studied period. For instance, very strong winds are accompanied by low level inversions, which disappear or move to higher altitudes when the wind speed decreases. The more opened and larger is the polynya, the more intensive is the heat exchange between the surface and the atmosphere, which leads to deeper mixing in the ABL. Both closing and opening of the polynya, accompanied by an increase/decrease of sea ice concentration, can occur within a few hours, leading to rapid changes in atmospheric conditions. Furthermore, my results agree with other studies (Jolly et al., 2016; Ebner et al., 2014; Parish and Cassano, 2001) in terms of synoptic scale pressure gradient role in determining the surface wind field in the Terra Nova Bay and thus polynya appearance. UAV measurements indicate that different origins of the flow, either purely katabatic, synoptically-forced or mix of both, result in different properties of the ABL above the polynya. Such complex interactions and rapid fluctuations are very hard to simulate in NWP models and most of the global ones cannot correctly resolve extreme katabatic events on the coast of the Antarctic. Antarctic Mesoscale Prediction System forecasts, evaluated in **Publication 3**, perform this task much better but with some substantial errors. The path of the simulated flow might in some cases be too narrow or too wide, leading to high overestimation (e.g. Fig. 1, b) or underestimation of wind speed.

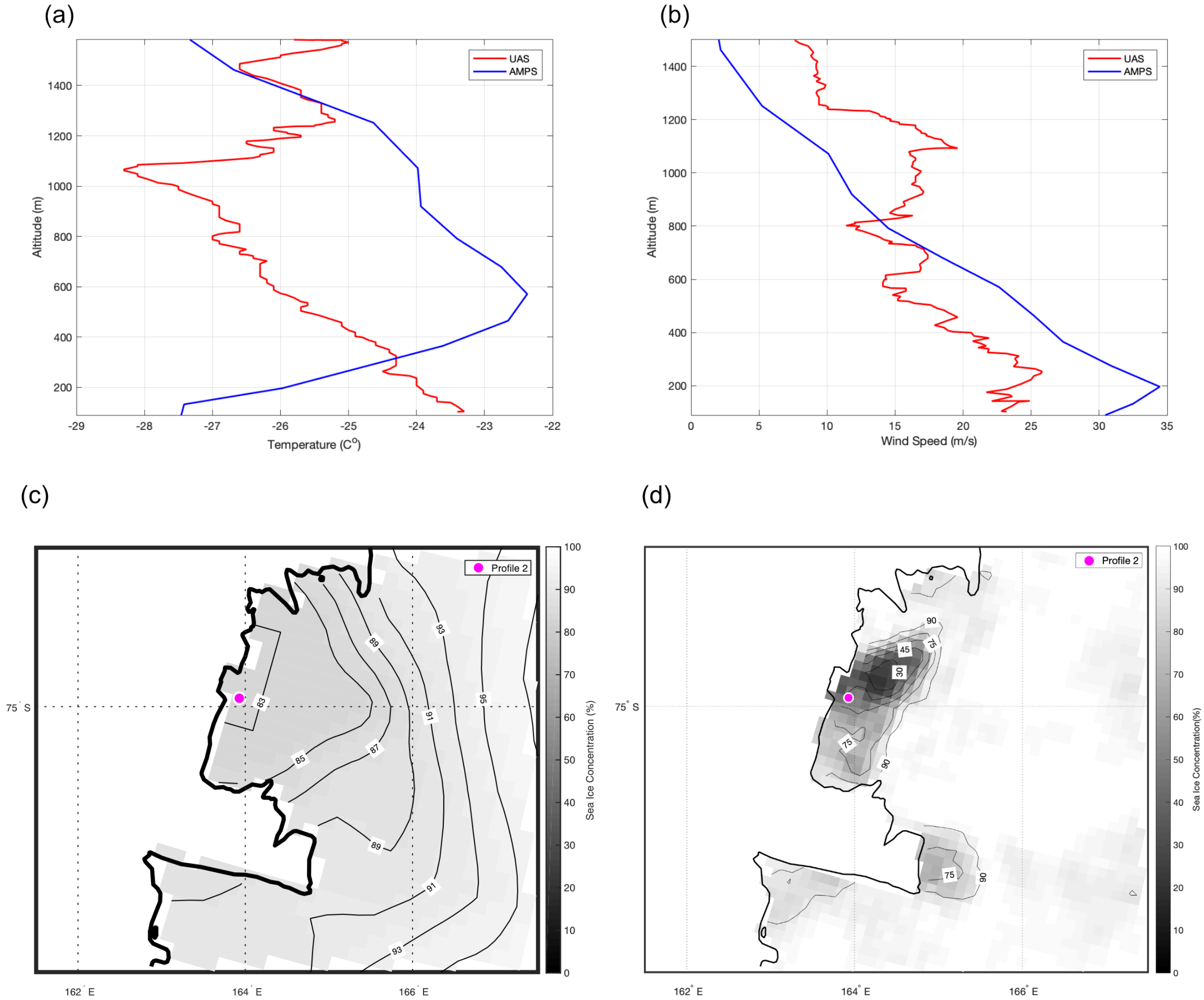

Figure 1 Illustration of typical problems of NWP models over inhomogeneous sea ice: incorrectly reproduced vertical structure of the ABL and insufficient information on surface conditions. The plots show the situation over the Terra Nova Bay polynya on 18 September 2012: observed (UAS; red) and modeled (AMPS; blue) vertical profiles of air temperature (a) and wind speed (b), as well as sea ice concentration maps used as AMPS input (c) and from the high-resolution AMSR2 satellite product provided by the University of Bremen (d). Magenta dots in (c,d) show the location of profiles in (a,b). See text for more details.

Inadequate surface conditions, particularly the lack of SIC variations throughout the day in Terra Nova Bay and low spatial resolution of SIC data (Fig. 1, c), causes errors in both temperature and wind speed simulation, often leading to unrealistic shape of the vertical profiles of those variables (Fig. 1, a-b). Furthermore, good/poor correlation for modeled wind speed profiles is not, in many cases, related to good/poor correlation for temperature profiles. Therefore, the errors in model results are related to both misrepresentation of katabatic flow intensity and surface conditions.

Overall my research indicates that surface conditions and properties of the downslope flow are interconnected and together affect temperature and wind speed throughout the ABL over the bay. Considering that the presented study focuses on just a few days, it only gives us a glimpse into the processes taking place in Terra Nova Bay in response to katabatic wind events and changing synoptic conditions. More observations are needed to fully understand the extreme winds and atmosphere–surface interactions in TNBP and improve predictions made by numerical weather prediction models. Furthermore, as indicated by other studies in my thesis (**Publication 1, 2**), the realistic representation of sea ice cover, particularly its heterogeneous character might substantially improve NWP simulations.

The last publication included in my thesis, also focuses on the application of UAVs in the studies of ABL over sea ice. **Publication 4** describes the outcome of HAOS (Hailuoto Atmospheric Observations over Sea Ice) field campaign carried out under my initiative in the Bay of Bothnia (Baltic Sea) between 27 February and 2 March 2020. The primary goal of HAOS was to obtain detailed measurements of the atmospheric boundary layer over sea ice, in particular non-uniform, thin sea ice, as well as to test the equipment and to develop methodology and procedures for subsequent, more extensive campaigns in the future. The westernmost point of Hailuoto island was chosen for the campaign due to its exposed location, outside of continuous landfast ice zone, and the presence of drifting pack ice within the short distance off the harbor (∼1 km). Every day throughout the 27 February and 2 March, a series of UAV flights were undertaken off the Marjaniemi harbor to obtain measurements of the lower ABL properties (temperature, humidity, pressure), together with high resolution photographs of the underlying surface. Additionally, an automatic weather station (AWS) and Halo Doppler Lidar were installed on the shore to continuously collect meteorological observations. Overall, the dataset obtained during HAOS (Wenta et al., 2020) provides a thorough description of the atmospheric conditions over newly formed sea ice near Hailuoto island. Furthermore, detailed orthomosaic maps give us a unique and extremely detailed view of the newly formed sea ice and its changes in the span of 4 days. Considering the scarcity of high resolution, three-dimensional ABL observations over sea ice cover in the Bay of Bothnia, and the Baltic Sea in general, the presented dataset may be considered as a valuable source of information and the basis for further studies on sea ice–atmospheric interactions in this region.

Discussion and conclusions.

Summary of the main findings.

Main motivation behind the studies presented in my thesis was NWP models incapability to correctly resolve the properties of the atmosphere in high latitudes, in particular in terms of the ABL vertical structure (Steeneveld, 2014b; Sandu et al., 2013) and near–surface properties (Køltzow et al., 2019; Jung et al., 2016). Poor results are often found in the simulations of the stable boundary layer, which is governed by submesoscale processes like radiative cooling, vertical fluxes, and turbulence, that cannot be directly resolved by the models or in the MIZ, where extreme variations of surface conditions occur (Batrak and Müller, 2018). While some of those problems will be overcome by increasing resolution of NWP models (Edwards et al., 2020), many small scale, sub-grid processes will need to be parameterized (Vihma et al., 2014). In order to develop accurate parameterizations that would improve models forecasts, we need to increase our understanding of subgrid processes at the interface of ocean–sea ice–atmosphere. This task is a central motivation of my thesis.

In the first two publications, an idealized version of the WRF model is used as a laboratory for experiments and hypothesis testing. Atmospheric response to various sea ice cover types, with randomly distributed floes or leads, is studied and analyzed thoroughly. The main outcomes of the research described in **Publication 1** and **Publication 2** are:

- Domain-averaged properties of the atmosphere, as shown on the example of surface turbulent heat and moisture fluxes or total liquid and water vapor content, depend on spatial arrangement and size of floes and leads in the sea ice cover.
- Floe size distribution determines the spatial arrangement of convective structures and the intensity of convection in the atmosphere over sea ice, and thus, the net values of surface turbulent fluxes and moisture content.
- A correction factor, that includes the effects of FSD, for the calculation of surface moisture heat flux from area averaged surface and atmospheric variables is developed.

To my knowledge those are the first studies focusing on the FSD influence on the atmospheric boundary layer and attempting to develop parameterizations of the associated effects for NWP models. They are thus innovative and provide a basis for future research, which should focus on the further development of the proposed correction factor (to a wider range of conditions, FSD types etc.) and its implementation into newly developed NWP models. Simultaneously, obtained results should be verified with observations. Given the sparseness of field measurements in polar regions, in particular in a highly dynamic environment of fragmented sea ice, it is a challenging task. What makes my goal to validate obtained model results more achievable is the emergence of UAVs in numerous field campaigns carried out in high latitudes (Knuth. et al., 2013; Cassano et al., 2015; Bhardwaj et al., 2016; Knuth et al., 2013). In fact, the increasing popularity of drones and my motivation to obtain observations relevant for conducted numerical modeling studies inspired us to carry out the HAOS campaign described in **Publication 4**. Unfortunately, dynamic weather conditions during HAOS resulted in unfavourable sea ice conditions for the evaluation of simulations from **Publication 1** and **Publication 2**. Nevertheless, the campaign gave me an opportunity to study NWP models performance over uniform, coastal sea ice and inspired me to plan future projects focusing on UAV observations and verification of models biases in high latitudes.

In order to explore the capabilities of UAVs in the polar regions (in preparation for the HAOS campaign), and to study the atmospheric boundary layer over sea ice in an extreme environment related to katabatic winds, a study focusing on Terra Nova Bay was conducted (**Publication 3**). Aerosonde UAS observations from late winter 2012 were analysed and used for the verification of Antarctic Mesoscale Prediction System forecasts. I found that although model managed to reproduce katabatic winds, a challenging task for global climate models (Bintanja et al., 2014; Barthélemy et al., 2012), it struggled with a correct representation of near–surface temperature, wind speed and vertical changes of atmospheric properties. It is suggested that inaccurate representation of sea ice cover variations might be partially responsible for those errors, especially taking into consideration the dynamic environment of Terra Nova Bay and the fact that in AMPS sea ice concentration data is implemented into the model at the beginning of every simulation and do not change throughout the forecast. In Fig. 1 an example of such a situation is shown, where the model misrepresents the intensity of downslope winds and vertical stability of the atmosphere. Comparison of sea ice concentration maps (Fig, 1, c–d) reveals substantial differences in surface conditions in the model and the satellite based image. This takes us back to the conclusions from the first two publications included in my thesis, which highlighted the importance of accurate representation of sea ice conditions in regional and global NWP models. To summarize the outcome of the study described in **Publication 3**, I would point out the following:

- The intensity and duration of the katabatic flow, surface conditions in the bay and regional sea level pressure fluctuations create a dynamical, interconnected system that regulates polynya development. All components of that system have to be taken into account in order to reproduce in a model the ABL evolution over the polynya and the polynya itself.
- Incorrect representation of the vertical and near–surface ABL properties over Terra Nova Bay Polynya in the Antarctic Mesoscale Prediction System results are partially caused by low temporal and horizontal resolution of sea ice concentration maps used as model input.

Current research and plans

UAV and ABL related research continued throughout and after the field campaign carried out in winter 2020 in the Bay of Bothnia. As already mentioned, decreasing air temperatures and low wind speeds during HAOS resulted in the consolidation of drifting pack ice off the westernmost point of Hailuoto – our hope for non–uniform sea ice conditions, that might have been relevant for verification of numerical modeling simulations from **Publication 1, 2**. Hence, proving how hard it is to obtain observations suitable for the verification of specific model results from the polar regions. Nevertheless, observations from HAOS provided an extensive and valuable dataset describing surface and atmospheric conditions over coastal sea ice (Wenta et al., 2020; Wenta et al., 2021), that can be used in various studies related to sea-ice covered regions. As part of the ongoing research, the purpose of which is to assess the potential of acquired data and provide a basis for our future campaigns in the Bay of Bothnia, I decided to verify several regional NWP models forecasts with the measurements from HAOS UAV and automatic weather station (AWS) (similar to the study from Terra Nova Bay described in **Publication 3**). The results of the following models were used in this study: AROME (Application of Research to Operations at Mesoscale) Arctic (Bengtsson et al., 2017) - run by Norwegian Meteorological Institute, HIRLAM (High Resolution Limited Area Model Unden et al., 2002)- run by Finnish Meteorological Institute and two models launched by Interdisciplinary Centre for Mathematical and Computational Modelling at University of Warsaw: WRF (Wang et al., 2017) and United Kingdom Met Office Unified Model (UM ICM Walters et al., 2017). The evaluation of the models results was carried out based on the following statistics: Pearsons's correlation coefficient (R), mean bias (MBE) and root mean square error (RMSE). My analysis reveals that in the coastal sea ice zone models tend to underestimate near–surface temperatures (Fig. 2, c), overestimate humidity (Fig. 2, d) and struggle with the representation of low level winds variations (Tab. 1). In terms of UAV measurements, too low temperatures in the lowest layers result in too strong

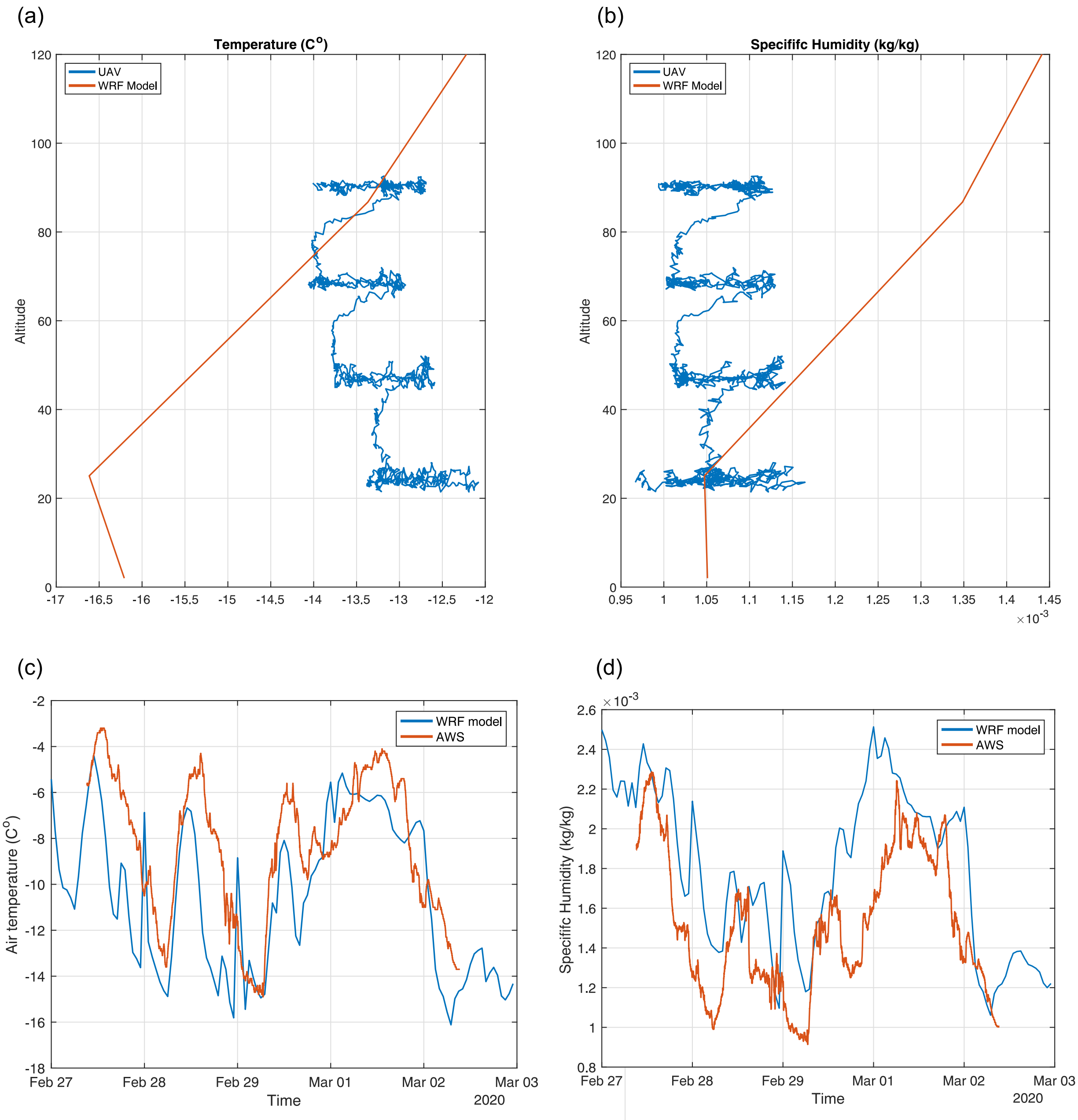

Figure 2 Measured (HAOS UAV) and modeled (WRF) vertical air properties off the coast of Hailuoto Marjaniemi on the 1st of March 2020, (a) temperature (b) specific humidity, and AWS measurements and WRF model results for the period of HAOS campaign (27 February- 2 March 2020) of (c) air temperature and (d) specific humidity 2 m above the surface.

inversions and erroneous simulation of atmospheric stability (Fig. 2, a-b). Furthermore, best results are found in the highest analyzed altitudes (Tab. 2), thus underlining models struggle with atmospheric properties in the lowest part of the ABL. In terms of surface conditions, in all of the studied models, sea ice cover is represented by fractional coverage. UAV images (**Publication 4**) show that throughout the campaign the area of conducted observations was entirely covered with sea ice. However, in the results from AROME-Arctic sea ice concentration does not exceed ~75%. In this model surface conditions are assimilated from ECMWF HRES (European Center for Mesoscale Weather Forecast Higher Resolution forecast), which uses high resolution satellite

Table 1 Statistics for the comparison of AWS measurements and results of four models for the period between 27th February and 2nd March 2020 (T-air temperature, WS- wind speed, Q- specific humidity, R- Pearson's correlation coefficient, MBE-mean bias error, RMSE- root mean square error). The hypothesis of no correlation was tested and the pValue for all correlations was below the level of significance (0.05).

	T–RMSE (°C)	T–R	T–MBE (°C)	WS–RMSE (m/s)	WS (R)	WS–MBE (m/s)	Q–RMSE (kg/kg)	Q (R)	Q–MBE (kg/kg)
AROME-Arctic	1.93	0.85	1.08	1.35	0.54	0.68	0.0004	0.82	0.0003
HIRLAM	2.97	0.79	-2.13	1.45	0.64	0.88	0.0003	0.86	0.0001
UM (ICM)	4.67	0.61	-3.51	1.11	0.55	-0.49	0.0003	0.78	0.0001
WRF (ICM)	2.96	0.73	-1.82	1.20	0.45	0.22	0.0004	0.74	0.0003

Table 2 Statistics for the comparison of UAV measurements and results of four models for the period between 27th February and 2nd March 2020 (T-air temperature, Q- specific humidity, R- Pearson's correlation coefficient, MBE-mean bias error, RMSE- root mean square error). The hypothesis of no correlation was tested and the pValue for all correlations was below the level of significance (0.05).

	Altitude (m)	T–R	T–RMSE (°C)	T–MBE(°C)	Q–R	Q–RMSE (kg/kg)	Q–MBE (kg/kg)
WRF (ICM)	25.00	0.90	3.10	-2.54	0.86	0.0002	0.0001
	86.00	0.97	1.32	-0.97	0.81	0.0003	0.0001
AROME-Arctic	37.50	0.66	2.82	-0.85	0.82	0.0002	0.0001
	63.00	0.67	2.80	-0.85	0.82	0.0002	0.0001
	89.40	0.73	2.32	-0.48	0.73	0.0003	0.0001
UM (ICM)	21.67	0.74	3.53	-2.63	0.82	0.0004	0.0003
	45.00	0.87	2.17	-1.32	0.88	0.0004	0.0004
	75.00	0.89	1.81	-0.61	0.82	0.0004	0.0003

images to determine surface conditions in the Bay of Bothnia. During HAOS campaign large areas of sea ice off the coast of Hailuoto were snow–free and resembled open water, which probably resulted in erroneous interpretation of sea ice conditions by satellite sensors. In HIRLAM, WRF and UM ICM sea ice concentration is assimilated from lower spatial resolution data and varies between 98-100%. The differences in real and simulated sea ice fraction might be partially responsible for the errors found in AROME-Arctic interpretation of vertical ABL properties (Tab. 2), thus emphasizing the importance of accurate representation of sea ice conditions in the NWP models. Nevertheless, it could seem that consolidated, relatively uniform sea ice present throughout HAOS campaign, should not be problematic for atmosphere modeling. However, as described above, consistent biases are found in the results (Tab. 1, 2). This is in agreement with various other verification studies (Køltzow et al., 2019; Jung et al., 2016; Pithan et al., 2016; Holtslag et al., 2013; Steeneveld, 2014b), that highlighted the problem of accurate representation of stable boundary layer over sea ice, due to complexity of numerous processes involved (e.g. surface-atmosphere coupling, surface-energy balance, radiative cooling). Overall, described analysis confirmed the statement, repeated throughout my thesis, that modeling of the atmosphere over sea ice, both uniform and non-uniform, remains problematic for numerical weather prediction models, thus emphasizing the importance of further observations and numerical modeling studies. In accordance with this statement, the results obtained during winter 2020 and presented analysis will be used for the preparation of future campaigns in the Bay of Bothnia, planned for consecutive winters. It is important to mention once more that while valuable, HAOS 2020 served as a preliminary step for those subsequent campaigns and helped us gain essential experience and perspective. In a nutshell, research carried out throughout the HAOS campaign and described in detail in **Publication 4**, allowed us to:

- Test the capabilities of the UAVs, designed specifically for our project, in harsh winter conditions over the sea ice in the Bay of Bothnia.

- Better prepare future campaigns, including the one planned for March 2021. In detail, to add surface temperature and lidar measurements from drones, in order to better asses what processes govern the structure of atmospheric boundary layer over both uniform and non–uniform sea ice.

In summary, my research expands our understanding of sea ice-atmospheric boundary layer interactions in various surface conditions, including idealized floe size and leads distributions, polynya opening due to extreme katabatic winds and over coastal, newly formed sea ice. Included publications answer several important questions, regarding the hypothesis of FSD–ABL interactions or numerical models performance in the polar regions and leave many of them open. Furthermore, my research provides a solid basis for the planning of future numerical modeling and observational studies focusing on the atmosphere over the sea ice. Many of models biases, including the ones found in the analysis of HAOS results, remain poorly understood and require new parameterizations. Therefore, I plan to continue the research described above and further contribute to the ongoing efforts to develop better parameterizations and improve NWP models forecasts. In fact, a comprehensive study focusing on extensive UAV measurements from both hemispheres, including the ones collected during MOSAIC expedition, reanalyses results and numerical modeling have already been planned and will begin after the completion of my doctoral degree. The objectives of this future project include: to determine where the errors in predictions of near–surface atmospheric properties and ABL stability are the biggest and explain the possible reasons behind it, to indicate how the choice of models resolution (horizontal and vertical), parameterizations and initial conditions affect the results of the simulations and to suggest optimal model configurations for accurate simulations of the polar ABL. In general, my goal is to help us understand some of the complex processes, such as turbulence, surface coupling and low-level jets, that dominate polar ABLs and present a challenge for NWP models and to validate results described in the presented thesis.