FULL DESCRIPTION OF THE PROJECT

1 Research Project Objectives

The subject of the project are interactions between the atmospheric and oceanic boundary layers and sea ice, with special interest in fragmented, strongly heterogeneous sea ice cover typical of, but not limited to the so-called marginal ice zone (multiple ice floes of different sizes; leads and cracks), as well as first stages of sea ice formation. The overarching leitmotiv integrating the individual project tasks are larger-scale effects of local, small-scale processes related to the spatial and temporal inhomogeneity of sea ice properties. Several of those effects have been studied by the team of the Principal Investigator in the last years, and therefore many aspects of the proposed research are a natural continuation of the already completed and ongoing work. In particular, on the list of the project objectives below (and further throughout this document) reference is made to the results obtained within the currently running project "Discrete-element sea ice modeling – development of theoretical and numerical methods" (funded by the Polish National Research Centre; 07.2016–07.2019; project number 2015/19/B/ST10/01568).

The main objectives of the proposed project are:

- To apply Unmanned Aerial Vehicles (UAVs) to collect a wide range of observational data from the ice/water surface and the atmospheric boundary layer (ABL) over fragmented sea ice in the Baltic Sea. To perform the UAV surveys in different ice and weather conditions in order to obtain data suitable for validation of numerical models and for an analysis of the dynamical processes within the ABL related to different spatial distributions of ice floes and open water areas.
- To use the collected observational data and the validated WRF (Weather Research and Forecasting) model to improve our understanding of the interactions between nonhomogeneous sea ice and lower atmosphere; in particular, to investigate how the size and spatial distribution of different sea ice features determine the ABL structure.
- To verify the hypothesis – formulated based on the results of idealized numerical modeling obtained within the project currently under realization – that sea ice concentration alone is not sufficient to determine the area-averaged properties of the ABL and the turbulent ocean–sea ice–atmosphere heat and moisture exchange. To the contrary, the subgrid-scale spatial distribution of sea ice floes, cracks and leads, through its influence on the three-dimensional (3D) ABL circulation and on details of convective processes, heat and momentum fluxes, turbulence, vertical stability etc., modifies area-averaged ABL characteristics.
- To develop parameterizations, similar to the existing so-called mosaic methods, of the surface heat fluxes through a fragmented sea ice cover, suitable for implementation in WRF and other Numerical Weather Prediction (NWP) models.
- To develop the code of a 'multi-phase' model suitable for high-resolution simulations of coupled ocean–sea ice–atmosphere dynamics, based on the models developed within the currently running project and the available open-source Computational Fluid Dynamics (CFD) models. To use the coupled model to analyze the dynamics of the upper ocean/lower atmosphere during initial stages of sea ice formation, with particular interest in formation of so-called frazil streaks – elongated bands of high concentration of frazil cristals – and their role in turbulent ocean–atmosphere momentum and heat exchange. Thus, to improve our understanding of a process that is only rudimentarily taken into account in present sea ice models.
- To implement new features in the coupled sea ice–wave model, developed within the current project, and to apply this model to analyze various mechanisms of wave attenuation in the Marginal Ice Zone (MIZ), including floe–floe collisions, under-ice skin and form drag, inelastic dissipation within the ice, and turbulence.

In a wider perspective, the project will provide valuable experience in *in situ* data collection in extreme, winter conditions over fragmented and highly mobile sea ice. As we are planning more extensive observational campaigns in the future (in collaboration with other Polish and international partners), the experience in operating UAVs and in applying them to ABL monitoring will help in planning and realization of later projects.

After the completion of this project, the observational data will be published and made available to the scientific community. As with the present versions of the Discrete-Element bonded-particle Sea Ice model (DESIgn;

Herman, 2016), developed by the Principal Investigator, the code and documentation of all models will be freely available to everyone to use and modify.

2 Significance of the project

2.1 State of the art and justification for the choice of scientific problems

2.1.1 Introduction – a broad perspective

In recent years, sea ice (and the cryosphere in general) in both hemispheres has been undergoing changes that fully deserve to be called dramatic. In the Arctic, significant negative trends in sea ice extent (Fig. 1), area, thickness and age have been observed over many years. The changes appear to occur increasingly fast, suggesting intensifying response to the oceanic/atmospheric forcing (e.g., Stroeve et al., 2012; Serreze and Stroeve, 2015, and references there). Almost every new ice season breaks new records, brings previously unobserved phenomena and events, or 'normal' processes taking place at untypical times of the year. The unusual polynya opening north of Greenland between the middle of February and the first week of March 2018, related to the longest winter period of above-freezing air temperatures ever recorded[1], is a good example. Similarly worth mentioning are large open-water areas in the Chukchi Sea and unprecedentedly low sea ice extent in the Bering Sea in Spring 2018 that allowed large waves to propagate without significant dissipation up to the coasts, usually protected from storms at this time of the year.[2] Strong, large-scale deformation of the sea ice cover in the Beaufort Sea (Fig. 2), taking place in February and March instead of late spring/early summer, is not exceptional any more. In the Southern Hemisphere, the trends in sea ice extent were opposite to those in the Arctic, i.e., positive – until 2014, when a rapid, spectacular retreat occurred (Fig. 1). The following years will show if this is a shift to a new normal state of the Antarctic sea ice or a very strong, but short-lived fluctuation.

Current state-of-the-art large-scale (global and regional) climate models generally fail to reproduce those changes. For example, they do predict a decline of the Arctic sea ice extent during the 21st century, but the observed negative trend in the period in which observations are available is roughly three times faster than the ensemble mean of the models, and none of the individual models is able to reproduce the observed trend value (Stroeve et al., 2007). The problem remains in spite of significant progress in our understanding of various feedbacks between the ocean, sea ice and atmosphere that influence the state of the Earth's climate. Those feedbacks are very complex, operate at a very wide range of spatial and temporal scales, and include mechanisms that are extremely challenging for direct measurements. Therefore, notwithstanding the very fast

[1] see a series of images by J. Stroeve, National Snow and Ice Data Center, at `http://nsidc.org/arcticseaicenews/2018/05/arctic-winter-warms-up-to-a-low-summer-ice-season/`

[2] see *Shock and thaw – Alaskan sea ice just took a steep, unprecedented dive* by A. Thompson (Scientific American), `https://www.scientificamerican.com/article/shock-and-thaw-alaskan-sea-ice-just-took-a-steep-unprecedented-dive/`; or *Historic low sea ice in the Bering Sea* at `https://earthobservatory.nasa.gov/IOTD/view.php?id=92084`

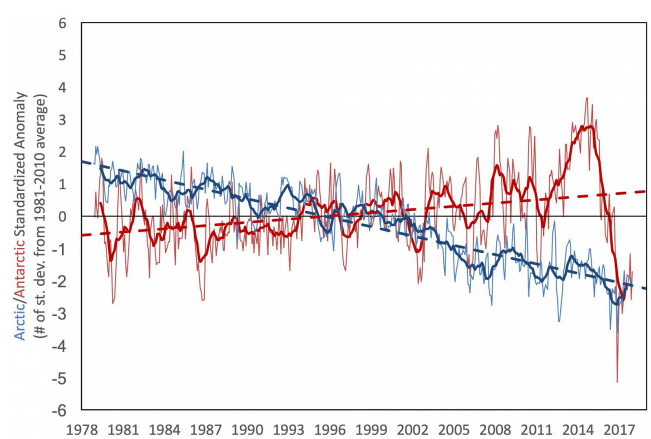

Figure 1: **Sea ice extent anomalies.** Trends in the observed sea ice extent in the Arctic (blue) and Antarctic (red) in the period 1979–2017. Thick lines indicate 12-month running means, and thin lines indicate monthly anomalies. Source: U.S. National Snow and Ice Data Center, University of Colorado, Boulder.

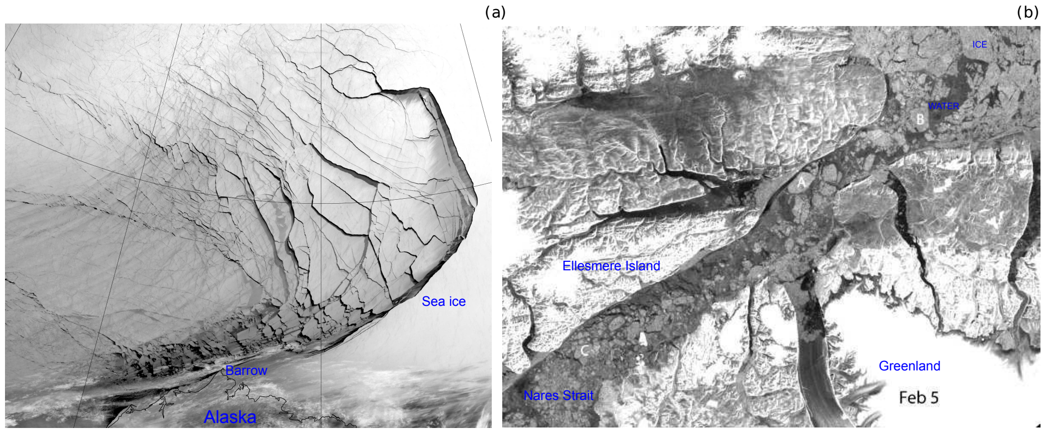

Figure 2: **Fragmented sea ice.** Extensive sea ice fracturing off the northern coast of Alaska on 23. Feb. 2013 (*a*; from Visible Infrared Imaging Radiometer Suite, VIIRS), and sea ice fractures in the Nares Strait on 5. Feb. 2015 (*b*; from Sentinel-1, ESA). Dark areas in the images may represent open water or new, thin sea ice.

development of the available observational technology and computational power, it is not surprising that many local processes with larger-scale effects remain poorly understood.

Many of those feedbacks involve both sea ice dynamics and thermodynamics. In particular, due to lower effective strength of the thinning, fragmented ice, it gets more easily deformed and transported by winds and currents (e.g., Rampal et al., 2009; Gimbert et al., 2012). Higher deformation rates of sea ice generally lead to the increase of the total sea ice volume in winter (due to increased new ice production in leads; but see Stroeve et al., 2018) and to the decrease of the total sea ice volume in the summer (due to increased lateral melting). Positive feedbacks between sea ice fragmentation and sea ice loss in the summer have been analyzed recently by Asplin et al. (2012, 2014), who pointed out that decreasing sea ice extent and the associated larger areas of open water lead to larger storm-induced waves, which can penetrate deeper into the weakening ice cover and lead to faster melting and even larger waves in subsequent storms. Thus, the overall trend in the Northern Hemisphere sea ice is towards conditions typical for the MIZ: ice concentration lower than 90%, small floe sizes, patchy distribution of floes on the sea surface, etc. All that means that wave–ice interactions play an increasingly important role not only close to the ice edge, but over vast areas of the ice cover (see, e.g., Asplin et al., 2012, 2014; Thomson and Rogers, 2014; Thomson et al., 2016). Recent progress in modelling of sea ice–waves interactions is described in section 2.1.3.

2.1.2 Recent progress in sea ice modelling

Substantial progress has been made in recent years in terms of modeling of sea ice response to deformation. For example, the elasto-brittle rheology proposed by Girard et al. (2011) and the Maxwell-elasto-brittle rheology of Dansereau et al. (2016, 2017) significantly improve the ability of large-scale sea ice models to produce realistic deformation patterns. New numerical-modeling techniques have been proposed as well, like for example the neXtSIM model (Rampal et al., 2016; Williams et al., 2017), based on the Lagrangian dynamics, which enables to preserve sharp boundaries and highly localized features in the ice cover (leads, pressure ridges etc.). Even though all these recent achievements bring us closer to reproducing the observed intermittent, localized, multifractal character of sea ice deformation (see, e.g., Marsan et al., 2004; Weiss and Marsan, 2004; Hutchings et al., 2011; Herman and Glowacki, 2012), making the large-scale models both accurate and computationally efficient remains a challenge.

A very important recent achievement is the formulation of prognostic equations for the joint ice-thickness and floe-size distribution, suitable for continuum sea ice models (Horvat and Tziperman, 2015) and analogous to the well established equations for the ice-thickness distribution. They provide a universal, consistent framework in which new parametrizations of various floe-size dependent processes can be directly incorporated (Horvat and Tziperman, 2017; Roach et al., 2018).

After many years of relative stillstand, last years brought also a revival of interest in discrete-element sea ice models, not least thanks to the work of the Principal Investigator of this project, who used this approach to analyze the influence of the floe-size distribution on 'herding' of ice floes on the sea surface, on the response of the ice to shear deformation, on the properties of force networks and jamming phase transition in various conditions (Herman, 2011, 2012, 2013a,b), as well as wave-induced sea ice breaking and collisions of ice floes (Herman, 2017, 2018). A review of discrete-element and related methods in sea ice modeling can be found in Herman (2016, 2017, 2018). Other recent works in which DEM approach is used are by Rabatel et al. (2015) and Yulmetov et al. (2016). The study by Herman (2017) is an example of a coupled model, in which a DEM is run together with a hydrodynamic wave model.

Finally, appreciable effort has been made in recent years towards developing parameterizations of wave–ice interactions for large-scale continuum models (Dumont et al., 2011; Doble and Bidlot, 2013; Squire et al., 2013; Williams et al., 2013, 2017; Bennetts et al., 2017). However, development of those parameterizations is hindered by lack of data and our limited understanding of many aspects of wave–ice interactions, as described in the next section.

2.1.3 Sea ice–waves interactions

In terms of our ability to model sea ice dynamics with sufficient accuracy, the marginal ice zone (MIZ) is particularly challenging. Because of strong fragmentation of the ice into many small floes, and highly energetic environment due to the presence of waves, it is a very difficult, unstable and dangerous location for field work. The amount of *in situ* observational data from the MIZ is therefore very limited, and many crucial processes and their large-scale effects remain only poorly understood. This is the case if sea ice interactions with waves are concerned, i.e., *the* defining processes of the MIZ. Most observations and models consistently show/predict exponential attenuation of waves propagating into the MIZ (e.g., Dumont et al., 2011; Kohout et al., 2011; Stopa et al., 2018; Sutherland et al., 2018, and references there). (Note that although recent observations by Kohout et al. (2014) suggested a different picture, with approximately linear decay for waves exceeding 3 m in height, subsequent analyses of the same data by Meylan et al. (2014) showed that when analyzed in terms of individual components rather than the total energy, the exponential-decay model successfully explained the observed attenuation.) However, the individual processes contributing to the observed wave attenuation are hardly known. In the very recent study by Stopa et al. (2018), based on unprecedentedly high number (2237) of SAR satellite images from the Antarctic, the estimated values of the attenuation coefficient covered a few orders of magnitude, from under 10^{-6} m^{-1} to over 10^{-3} m^{-1} (for waves of comparable length). Thus, in some situations swell waves can propagate hundreds of kilometers into the ice cover without much dissipation, whereas in other situations rapid attenuation occurs over a distance of just a few kilometers. Mechanisms contributing to wave attenuation in sea ice are scattering (energy conserving) and various dissipation processes, including ice–water friction, under-ice turbulence, floe–floe collisions, inelastic and viscous deformation within the ice and ice breaking, rafting and friction between rafted floes, or migration of liquid brine through the ice. The intensity of those processes strongly depends on the ice properties, including ice thickness (and its variability), mechanical properties, presence of ridges, and floe sizes. Many of those characteristics are modified by waves themselves, as is the case for the floe-size distribution. Sea ice breaking by waves has been recently studied numerically by Herman (2017) and experimentally by Herman et al. (2018). Herman (2018) showed numerically that at large ice concentrations and with floe sizes comparable with wavelength, substantial amplitudes of drag forces occur at the ice–water interface (even for small values of drag coefficients) – and thus, this mechanism likely has significant contribution to wave attenuation.

There is growing evidence that wave–sea ice interactions have significance for the global climate. Arguably the most important finding of the already mentioned study by Kohout et al. (2014) was the existence of strong correlation between the trends in the sea ice extent and those of significant wave height at various sections of the Southern Ocean during both ice growth and melting seasons. Stopa et al. (2018) showed that the average wave stress acting on the ice, related to the convergence of momentum flux due to the wave motion, is comparable to the wind stress, and thus should not be omitted in large-scale numerical models.

2.1.4 Modelling of sea ice interactions with oceanic and atmospheric boundary layers

In the sea ice covered regions, the oceanic and atmospheric boundary layers influence and are influenced by sea ice dynamics and thermodynamics. Type and properties of the surface may change rapidly as a result of sea ice drift and deformation (Schulson, 2004), as well as melting and freezing. Fractures, leads, as well as ice floes with a wide range of sizes can be found in the Arctic in all seasons. Particularly the Beaufort Sea ice is frequently fragmented by strong winter storms. Intense cyclones can extensively fracture the sea ice over very large areas, creating multiple leads (Fig. 2); close to the shores and in straits, small floes with power-law size distributions are common (Barber et al., 2001, Fig. 2).

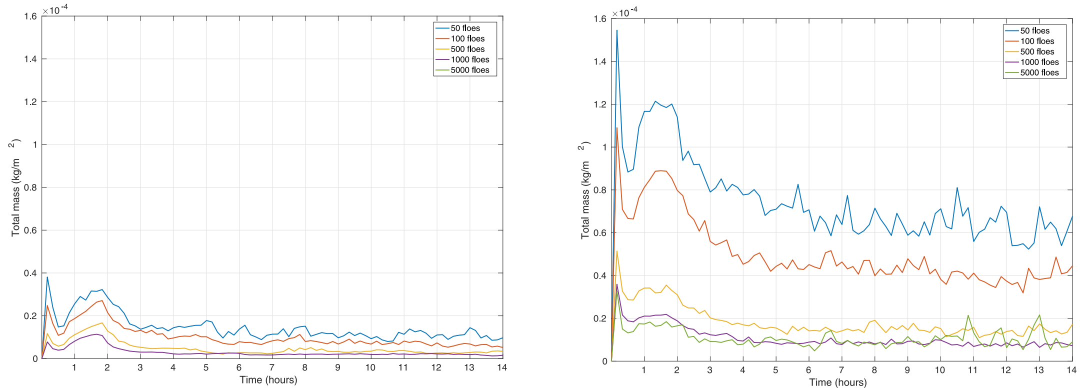

Figure 3: **Example results of WRF simulations over fragmented sea ice.** Area-averaged cloud liquid water content $Q_{c,tot}$ (kg/m^2) for ice concentration $c = 90\%$, different number of floes N_f and different wind profiles (*left*: weak ambient wind, *right*: strong ambient wind). See Wenta and Herman (2018) for details.

In large-scale and mesoscale NWP models, sea ice cover is typically represented by grid-cell-averaged ice concentration and thickness. Consequently, as the typical model resolution equals a few kilometers, all smaller-scale variability related to sea ice fracturing within model grid cells cannot be taken into account. Furthermore, because the large scale effects of the processes taking place at the level of the individual floes are largely unknown, very few parameterizations for NWP models are available. However, there is a growing observational and theoretical evidence that floe-level processes have significant influence on the dynamics and thermodynamics of the lower atmosphere and upper ocean, as well as the ice cover itself. Horvat et al. (2016) demonstrated that purely thermodynamically generated effects related to heat flux gradients at floes boundaries are responsible for formation of eddies and, through a number of feedbacks, for faster ice melting, with melting rates dependent on the size of the floes within the model area. Although these results are based on idealized model simulations, they clearly demonstrate the sensitivity of boundary layer processes to the FSD.

On the one hand, many general aspects of the ABL response to the intense heating over leads and cracks in sea ice are known and relatively well studied both observationally and numerically (see, e.g., Alam and Curry, 1995; Andreas and Cash, 1999). These effects include changes of the ABL stability over and downstream of open water (Lüpkes et al., 2008; Tetzlaff et al., 2015), the role of the prevailing wind conditions (Alam and Curry, 1995; Ruffieux et al., 1995), generation of thermal updrafts and turbulent eddies (Glendening and Burk, 1992; Ruffieux et al., 1995), formation of steam fog and cloud plumes (e.g., Burk. et al., 1997), or initiation of gravity waves (Mauritsen et al., 2005). Similarly, the role of the lead's width on the strength of the atmospheric response has been studied as well (e.g., Marcq and Weiss, 2012; Lüpkes et al., 2012, and references there). On the other hand, however, many studies are limited to the analysis of single leads, and systems of leads are analyzed only rarely. Moreover, none of those works was related to the ABL over strongly fragmented ice cover composed of many individual floes of different sizes.

Numerical analysis of the influence of the spatial distribution of leads and floes on the ABL circulation is one of the main research tasks in the already-mentioned project "Discrete-element sea ice modeling – development of theoretical and numerical methods". The hitherto results are described in detail in the recent paper by Wenta and Herman (2018). The study is based on idealized simulations with the WRF model, which was launched over a square domain with periodic horizontal boundaries for several lead layouts, as well as for different floe size distributions with sea ice concentrations of $c = 50\%$ and $c = 90\%$. Three-dimensional structure of the atmospheric circulation, atmospheric moisture content, surface heat flux, as well as the influence of small-scale atmospheric variability on domain-averaged properties of the atmospheric boundary layer were analyzed. It was demonstrated that the domain-averaged values are sensitive not only to sea ice concentration, but also to subgrid-scale spatial arrangement of ice floes. The results clearly show that the spatial distribution and strength of updraft and downdraft regions associated with convective motion within the ABL are related to the underlying features of the ice cover (distribution of floes and leads). Figure 3 shows example results of the analysis.

The modeling results of Wenta and Herman (2018) have not been validated against observational data. The goal was to obtain estimates of spatiotemporal variability of the ABL processes associated with submesoscale variability of sea ice properties. Obviously, although the model behavior is consistent and the results agree

Figure 4: **Frazil streaks in the Terra Nova Bay, Antarctica.** *Left*: photographed from a ship during the PIPERS cruise on May 4, 2017 (photo courtesy Steve Ackley); *right*: captured by the Advanced Land Imager on NASA's EO-1 satellite on Sep 16, 2009.

well with those of other studies, some aspects of the results may turn out unrealistic. Also, values of the analyzed quantities may differ considerably between different real-world situations. However, the results of the simulations – incomparably cheaper and easier to perform than field observations! – provide invaluable guidelines to subsequent measurements *in situ*, like those planned within the proposed project.

A very different type of situation in which interactions of sea ice with the oceanic and atmospheric boundary layers play a crucial role is during initial stages of sea ice formation. A typical location where those situations occur are latent-heat polynyas formed by strong offshore winds (e.g., very cold catabatic winds generated over snow- and ice-covered land). If the turbulence in the atmosphere and upper ocean is sufficiently strong and the temperature sufficiently low, streaks of frazil ice tend to form on the sea surface. Observations[3] show that the streaks have several remarkable features: their spacing is irregular; there are sharp boundaries between regions with high and low frazil concentration; neighboring streaks tend to merge into larger ones, but they never split; and turbulence within streaks is much less intense than in surrounding open water areas (Fig. 4). These features make the Langmuir circulation, arguably the most often proposed mechanism of frazil streaks formation, a controversial explanation (see, e.g., Thorpe, 2009; Dethleff et al., 2009; Matsumura and Ohshima, 2015). Other mechanisms have been proposed, but the issue is far from solved. A related, unresolved question is whether the formation of frazil streaks is solely a result of upper-ocean turbulence, with ice crystals behaving as a positively buoyant, but otherwise passive tracer that accumulates in surface convergence zones, or, alternatively, whether the presence of the ice itself affects the turbulence patterns and wave propagation in a way that further reinforces streak formation. These questions are important, because the presence of ice crystals on the sea surface (as opposed to their presence within the water volume) modifies the ocean–atmosphere momentum and heat exchange, thus influencing further ice formation, mixing, vertical stability of the water column, and so on. Large-scale models that assume a uniform distribution of the newly formed sea ice on the sea surface (as most models do) may produce biased results (e.g., underestimated total volume of sea ice).

2.1.5 Polar ABL observations and application of UAVs

So far, only a few measuring campaigns concentrated on the properties of winter ABL over fragmented sea ice, including SHEBA (Surface Heat Budget of the Arctic Ocean), AIDJEX (Arctic Ice Dynamics Joint Experiment) or LEADEX (Lead Experiment) projects. Even fewer campaigns measured the temperature, heat and moisture fluxes or wind speed simultaneously at a number of locations within a relatively small area, situated at various positions relative to sea ice features, i.e., over open water, close to floe edges, in central parts of large floes, etc. (e.g., Ruffieux et al., 1995). Although there are some exceptions (SHEBA, LEADEX), the spatial and temporal resolution of available observational data, e.g., that from arrays of drifting buoys, typically located many kilometers apart from each other, is often not sufficient for this kind of analysis, as the differences between data from neighboring buoys may result from both small-scale and larger-scale (mesoscale, synoptic) variability, and it is very hard to distinguish between those two effects.

[3] see, e.g., the recent PIPERS ("Polynyas, Ice Production and seasonal Evolution in the Ross Sea") project, http://www.utsa.edu/signl/pipers/; http://adsabs.harvard.edu/abs/2017AGUFM.C33C1220A

Fragmented sea ice is a particularly dangerous location for data collection. Constant motion of the floes, along with low temperatures and rapidly changing wind conditions effectively discourage from conducting field campaigns. Therefore, as mentioned above, most measurements focused on single leads within an otherwise compact ice cover, so that the danger of instrumentation loss or damage was much smaller than in MIZ. An approach that allows to avoid the exposure of scientific equipment to highly energetic environment of fragmented sea ice is based on Unmanned Aerial Vehicles (UAVs), which are becoming increasingly popular in atmospheric measurements (Lothon et al., 2014; Reuder et al., 2016; Greatwood et al., 2017, to name just a few examples). UAVs provide a space–time view of the ABL on the basis of various sensors that can be attached to the aircraft and allow to partially avoid the problem of harsh surface conditions on the sea ice cover. Undoubtedly, UAVs specifically adapted to winter conditions have great potential for polar research and are capable of providing large amounts of valuable data along multiple horizontal and vertical profiles through the atmosphere, from just a few meters above the surface up to the top of the ABL, thus filling the gap between data provided by sensors mounted on surface floats and those operated on meteorological balloons. UAVs are also incomparably cheaper than meteorological airplanes, operated by human pilots. The focus at present is on the development of vehicles capable of data collection in demanding weather conditions (Cassano et al., 2016; Goetzendorf-Grabowski and Rodzewicz, 2017) and on the verification of the validity of measured properties (Reuder et al., 2016; Martin et al., 2011). Although there are still some limitations in UAVs' usage in atmospheric measurements, they have a potential to significantly expand weather observation capabilities.

In the sea ice covered regions the usage of UAVs is also becoming more and more frequent (Williams et al., 2016). They have been successfully applied in various campaigns to measure surface albedo (Podgorny et al., 2018), snow depth (Tan et al., 2017), sea surface temperature (Castro et al., 2017) and many other variables. However, only few of the hitherto applications focused on the atmospheric boundary layer and none of them concentrated specifically on the ABL over fragmented sea ice. Cassano et al. (2016) examined the factors driving the formation of large polynya in the Terra Nova Bay (Antarctic). They conducted several flights (130 flight hours in total) covering an area of several square kilometers. The quality control of the collected data has shown that the results were reliable: 98% of the pressure, temperature, humidity, wind speed, and wind direction values, as well as all of the GPS data were suitable for further processing. Similarly, Jonassen et al. (2015), who studied the application of small remotely operated aircraft system in the ABL over Antarctic sea ice, demonstrated that the UAVs are more flexible than previously used measurement methods and that they can be operated in changing conditions. Moreover, they are advantageous in performing high-resolution temperature profiles compared to the widely recognized radiosonde and tethersonde systems.

2.2 Pioneering nature of the project and impact of its results

The proposed project focuses on the processes that are not fully understood and only recently attracted attention of the scientific community. Achieving the objectives of this project is possible only by applying the best existing and by developing new numerical modeling and observational methods. By combining field measurements, data analysis and numerical simulations, new insights will be gained into local (floe-scale, sub-mesoscale) interactions between the upper ocean, lower atmosphere and sea ice. The results will help answer the practically relevant question which of those interactions are important only locally, without producing any significant larger-scale effects, and which are linked to processes at larger temporal and spatial scales and therefore affect area-averaged properties of the ocean and/or atmosphere. In other words, the long-term goal is to be able to distinguish processes that can be omitted in large-scale models from those that should be parameterized in order to improve the performance of those models. The results of the proposed project will be a small step in that direction, fitting into the efforts of many research groups working on sea ice and related problems.

Apart from their potential influence on climate and large-scale weather patterns, there is another aspect related to smaller-scale atmosphere–sea ice–ocean interactions, including those studied in the present project. With sea ice in the polar and subpolar regions retreating, those regions become increasingly attractive for shipping, fishing, mining and other branches of industry. Low sea ice extent during the summer season have recast Arctic shipping routes as emerging international seaways for transport of resources and as potential alternative pathways for Atlantic–Pacific trade (e.g., Gascard et al., 2017). Obviously, instantaneous, local conditions and precise, short-term predictions are more relevant for those activities than long-term statistics and large-scale patterns. Better understanding of processes acting at those scales is crucial for correct interpretation of available observational (*in situ* and remote sensing) data, for reliable prediction of weather, wave and sea ice conditions, route planning, etc.

As already mentioned a number of times, this project is a natural continuation of previous works by Principal

Investigator and her collaborators. All our results are regularly presented to the international scientific community and widely consulted with other researchers during conferences, workshops and other events, in order to make sure that our efforts are directed toward problems that are relevant and interesting to a wide group of scientists. In particular, the results of the ABL modelling over fragmented sea ice have been presented at the 97th AMS Annual Meeting (14th Conference on Polar Meteorology and Oceanography, 23-28 January 2017, Seattle, Washington), at the International Glaciological Society Symposium “Polar Ice, Polar Climate, Polar Change” (14–19 July 2017, Boulder, Colorado), and the “Polar2018” conference in June 2018 (Davos, Switzerland). Many aspects of the proposed research related to numerical ABL models and observations have taken shape during discussions with conference participants, and have been influenced by their comments and suggestions. Similarly, the Principal Investigator spent over three months in 2017 at the Isaac Newton Institute for Mathematical Sciences (Cambridge, UK), participating in the “Mathematics of Sea Ice Phenomena” programme[4]. The four large workshops on “Multi-scale Modelling of Ice Characteristics and Behaviour”, “Ice-Fluid Interaction”, “Ice-Structure Interaction” and “Ice Fracture and Cracks” (the Principal Investigator co-organized one and gave talks in two of them[5]), as well as several accompanying events, were a perfect opportunity for discussions with the top sea ice researchers on the most important topics, key unanswered questions and future directions in sea ice research. The parts of the proposed project related to wave–ice interactions and frazil streaks formation are a result of those discussions, and much of the preliminary research in that direction (see section 3.1) has been done during PI’s stay in Cambridge.

In short, during planning of this project care has been taken that the investigated problems remain within the scope of the most actively pursued sea ice research directions. Moreover, as is the case of the project currently under realization, the Principal Investigator will continue participating in interdisciplinary conferences and meetings, actively carrying the fascinating problems of sea ice dynamics to researchers working outside of the Earth science community, at the same time keeping up-to-date with the latest achievements of the relevant disciplines (particle-based methods, CFD, coupled CFD–DEM, etc.). As already mentioned, this strategy is a prerequisite to the successful completion of the project objectives.

Apart from new theoretical and numerical developments regarding modelling of sea ice and its interactions with atmospheric and oceanic boundary layers, the observational part of the project includes several pioneering aspects. As has been already mentioned in the previous section, very few studies have been dedicated to UAV-based measurements within the ABL over fragmented sea ice. Many practical aspects of operating UAVs in this type of environment (low air temperature and high humidity) are not well established, and each new experience provides valuable insights for future campaigns. Our project will be a great opportunity to exchange this kind of experience with other researchers: scientists from the University of Gothenburg in Sweden and Finnish Meteorological Institute expressed their interest in our results and in sharing their expertise with us.

As already stated, the codes of the models developed within this project will be made freely available to the scientific community, and the observational data will be published after the completion of the project. The results will be presented at a number of international conferences and published in high-impact scientific journals.

3 Work plan

3.1 State of preliminary and initial research

As already mentioned in the first parts of this proposal, several aspects of this project are a continuation of previous works, including those within the project “Discrete-element sea ice modeling – development of theoretical and numerical methods” that ends in July 2019.

As far as the high-resolution ABL modelling over sea ice is concerned, the planned tasks are motivated by the results of idealized WRF model simulations, described in Wenta and Herman (2018). The analysis of the results obtained with different model parameters and under different forcing and boundary conditions (ambient wind speed, ice concentration, floe size, etc.) provides a very useful estimates for expected variability of the relevant quantities and thus is a very important prerequisite in planning the observational part of the proposed project and in further numerical simulations.

Similarly, the first version of a DEM sea ice model coupled to the NonHydrostatic Wave model NHWAVE, has been developed within the ongoing project. It has been applied to an analysis of sea ice breaking by waves, as described in Herman (2017). This first model version is suitable only for compact sea ice at concentration close to 100%, in which the vertical component of the wave-induced motion predominates over the horizontal component.

[4] https://www.newton.ac.uk/event/sip

[5] see: https://www.newton.ac.uk/seminar/20170911114512301 and https://www.newton.ac.uk/seminar/20171110133014301

The model is currently being developed further by replacing the very simple DEM with the Discrete-Element bonded-particle Sea Ice model (DESIgn), developed by the Principal Investigator (Herman, 2016)[6]. This new version, which should be completed by the end of the present project (i.e., in the middle of 2019), will allow simulations with the full contact mechanics model, i.e., with wave-induced floe–floe collisions. This is going to be a starting point for further model developments within the proposed project, including a range of alternative boundary conditions at the ice–water interface (partial-slip, no-slip etc.) and two alternative turbulence models (based on the Smagorinsky viscosity and the full $k - \varepsilon$ equations).

The tasks related to the modelling of frazil streaks require a coupled model of three "phases": water, air and frazil. In the preparatory phase for this project, very simple test simulations have been performed with OpenFOAM (`https://openfoam.org/`), which is a very general, open-source software for computational fluid dynamics. The choice of OpenFOAM was justified by a number of factors: it is very flexible and easily extendable; it contains a lot of so-called solvers, including those for multi-phase fluids; and it can be run together with the LIGGGHTS DEM model thanks to a CFD-DEM coupler, allowing for simulations of coupled particle–fluid problems. (Note that the DESIgn sea ice model is written as a toolbox for LIGGGHTS, making OpenFOAM a natural choice as the accompanying CFD programme.) In the simple preliminary simulations, two approaches to the frazil-ice simulations were considered. First, in which frazil was treated as a fluid phase that has high viscosity and can mix with water, but not with the air. And second, in which frazil crystals were treated as particles and modelled with a DEM. At present, none of the approaches gave fully realistic results, as the configurations used were oversimplified and several important features are missing from the code, but the numerical experiments allowed to identify the main problems and to define changes to the programmes and algorithms that are necessary.

Finally, the planning of the observational part of the project has been done in cooperation with scientists from the Department of Marine Sciences of the University of Gothenburg (UoG, Sweden) and from the Finnish Meteorological Institute (FMI), who have experience in operating UAVs in oceanographic research in general and in performing UAV surveys over sea ice in particular. Most importantly, we discussed with those researchers problems and difficulties associated with UAV missions in the polar environment, possible solutions to those problems, and – crucially – costs of the equipment and logistics.

3.2 Outline of the work plan

The planned tasks within the project have been divided into 5 thematic groups:

3.2.1 UAV measurements of the ABL over sea ice

This group of tasks includes the observational part of this project, i.e., collecting *in situ* data from the atmospheric boundary layer and the underlying sea ice/water surface. The specific tasks are:

1. Conducting measurements from the Swedish icebreaker "Oden", operating in the Baltic Sea, using the UAVs and sensors of the University of Gothenburg (1–2 campaigns, each approx. 2-weeks long)

2. Conducting two land-based measuring campaigns in the northern Baltic Sea with UAVs purchased for this project (task supported by an external company/institution providing assistance in operating the drones).

Both kinds of measuring campaigns involve a detailed analysis of the instantaneous weather and sea ice conditions, preparation and testing of the equipment, planning of the flight routes, and the actual measurements.

3.2.2 Analysis of observational data

This group of tasks includes analysis of data (both collected during the project and from other available sources), as well as preparation of the data for later dissemination. Specifically, the tasks in this group include:

1. Processing of the raw data, synchronizing data from different sensors, quality control and other technical operations necessary for later usage of the data.

2. Collecting and processing of available data from other sources (satellite, results of weather models, etc.).

3. Statistical analysis of relationships between the observed variables, their range of variability and dependence on larger-scale forcing.

4. Estimation of the influence of the measurement methods on the measured variables (e.g., assessment of the role of drone-induced turbulence on measured wind speeds and temperature).

[6]`http://herman.ocean.ug.edu.pl/LIGGGHTSseaice.html`

3.2.3 ABL modelling over sea ice

These tasks, related to WRF modelling, are dependent on tasks from sections 3.2.1, 3.2.2 above. They include:

1. Preparation of boundary condition data (sea ice, lateral boundary conditions etc.) in WRF format.
2. Configuration and calibration of the model parameters based on comparisons with observational data.
3. Reconstruction of situations observed *in situ*.
4. Verification of the hypothesis on the role of spatial distribution of sea ice features in shaping area-averaged ABL properties (see the list of project objectives in section 1).
5. Formulation of parameterizations of the analyzed effects for large-scale NWP models.

3.2.4 Sea ice–waves interactions

This group of tasks includes development of the coupled wave–ice model. Specifically, the tasks are:

1. Implementing and testing of new model features, including ice–water friction and turbulence models.
2. Improving the present numerical scheme for computing bond deformation in the DEM model in order to reduce spurious numerical wave attenuation in sea ice.
3. Performing a series of computations with different model parameters in order to assess the relative role of various wave attenuation mechanisms under various model configurations.
4. Use the model to laboratory case studies from the LS-WICE project (Cheng et al., 2017; Herman et al., 2017; Tsarau et al., 2017).

3.2.5 Modelling of frazil streak formation

Tasks in this group are related to modeling of frazil ice dynamics coupled to the ocean and the atmosphere. They include:

1. Analysis of possible methods of treatment of frazil crystals in the coupled model (see section 3.1), their advantages and disadvantages.
2. Implementation of necessary features in OpenFOAM (and possibly LIGGGHTS and CFD-DEM coupler), modifications of the multi-phase solvers to the conditions relevant for air–water, air–frazil and water–frazil interfaces and mixing.
3. Tests of the model for simple configurations (periodic domain, prescribed upper-boundary wind, etc.).
4. Application of the model to assess the role of different factors on frazil streaks formation.

4 Research Methodology

4.1 Methods used in the observational part of the project

4.1.1 Plan of the field work and data analysis

The first part of the field work, planned for winter 2019/2020, does not require purchasing of any equipment. As already mentioned, it will be done in cooperation with the University of Gothenburg and will be performed using their equipment (small Phantom 4 pro+ UAVs with sensors for temperature, humidity, wind, pressure, and with an infrared camera), operated by their employee. Additionally, similar temperature and humidity sensors available at our Department can be used as backup in the case of failure or loss of the first-choice sensors mentioned above. The UAVs will be operated from the Swedish icebreaker "Oden", adapted for research tasks and operated jointly by the Swedish Polar Research Secretariat and the Swedish Maritime Administration, during the cruise through the marginal sea ice zone of the northern Baltic Sea. It is a very valuable opportunity: the University of Gothenburg team is interested in testing their equipment before applying it in the Antarctic rather than in obtaining particular scientific results, and therefore the measurements can be specifically adjusted to the needs of this project. Due to the limited flight time (30 minutes), single flights will be carried out in helical flight patterns along the wall of an imaginary cylinder, as in Reuder et al. (2016). Straight-line profiles of atmospheric properties will be generated as well, at a few different heights. It is planned to perform one two-week-long campaign of this type in early 2020, and – if it turns out successful – to repeat it in winter 2020/2021 (exact period depending, among other factors, on sea ice conditions in the Baltic). The only costs for this project will be travel costs of the participants. Apart from data for further analysis, these flights will provide invaluable experience in selecting optimal flight parameters (height, speed, trajectory, etc.). In particular, it is extremely important to adjust the speed of the drone to the spatial gradients of the properties of the environment and to the reaction times of the sensors, so that zones of rapid changes can be properly captured.

The second part of the field work will consist of land-based campaigns based on two UAVs purchased specially for this project. The UAVs will be operated from a provisional, "mobile" land base, selected according to the actual sea ice conditions. It is planned to perform those campaigns in the Gulf of Bothnia (the colleagues from FMI will assist in acquiring necessary permissions), but in the case of the sea ice presence at the Polish Baltic Sea coast, this locations will be preferred due to cheaper and easier logistics. As in the case of the first block of measurements, the flight trajectories will be planned so as to obtain an optimal 3D view of the atmosphere considering limited operation time of the drones.

As previously, the exact time periods for the land-based measurements will be determined at a later time depending on sea ice and weather conditions. Preliminary plans consider late winter 2019/2020 and 2020/2021. Each individual campaign will take ∼1–2 weeks, and two campaigns are planned in total, with successive ones planned based on the results of previous ones. Importantly, the analysis of data collected in the field will be performed directly after each campaign (or even, in a basic form, after each flight), so that the results can be used in planning/modifying/correcting plans for the following observations.

It is planned to engage experienced staff from FMI and possibly another external company to assist in those field campaigns. (We obtained an official letter of intent from FMI expressing their interest in supporting our research project; the costs of equipment have been planned with their help as well.)

If time and other resources permit, and if relevant conditions will be found during the field campaigns, data from the ABL over sea surface covered with frazil streak will be collected as well.

4.1.2 Observational equipment

As mentioned in the previous section, the first part of the field work, done in cooperation with the University of Gothenburg, will be performed using their equipment: a small Phantom 4 pro+ UAV, equipped in the sensors for temperature and humidity (Sparvio T/RH sensor), wind, pressure, and with a Parrot Sequoia infrared camera. The drone is equipped with a Sparvio kit with logging and telemetry with radio receiver RR2. The usage of this equipment won't generate any costs for the present project. In the case of loss or failure of the UoG temperature and humidity sensors, it will be possible to replace them with the same type of sensors that are at the disposal of our department.

For the second part of the field work, two UAVs will be purchased, including: (i) drone frames (Talon mini, Skywalker or similar); (ii) flight controller (Pixhawk or similar); (iii) propulsion systems (motor and ESC); (iv) batteries >5000 mAh; (v) battery charger; (vi) radio and receiver; (vii) FPV (first person view) electronics with accessories; (viii) long-range system (for flight distance >2 km; e.g., Dragon link, TBS crossfire or similar); (ix) data loggers (Raspberry Pi 3 or similar). The costs per one UAV should not exceed 2500 euros. Two drones are necessary to increase the chance of success of the campaign, as the probability of losing a AUV during operation in such demanding conditions is relatively high. On the other hand, assistance from an experienced company/institution should minimize the risk associated with improper operation.

It is also planned to purchase a small notebook that can be used in the field. No additional computational equipment is necessary, all simulations will be performed on the servers available at the Department of Physical Oceanography at our Institute.

4.2 Methods used in the computational part of the project

The numerical methods that will be used in the project tasks 3, 4 and 5 have been already mentioned a number of times throughout this document. The tasks in group 2, including the analysis of observational data, will be performed with Matlab, ArcGIS and other software at the disposal of the project participants.

The tasks in group 3, related to the ABL modelling, will be performed with the WRF model, either in idealized configurations similar to that used in the previous works, or nested in larger-scale models. Two possible sources of boundary conditions are considered: (i) Regional Arctic System Model (RASM)[7], which has the atmospheric component based on WRF, making the technical aspects of nesting particularly straightforward; or (ii) the weather model run operationally at the Interdisciplinary Computer Centre in Warsaw, Poland[8], covering the area of Poland and the Baltic Sea. The decision will be made at the later stage. As described in previous sections, the Principal Investigator and her team have experience in working with the WRF model from the currently running and earlier projects.

In the tasks from group 4, the two main tools will be the Discrete-Element bonded-particle Sea Ice model DESIgn, and the nonhydrostatic wave model NHWAVE (a version extensively modified by the Principal Investigator). After implementation of new model features (first of all, turbulence models), it is planned to use the model for a case study based on data collected during the LS-WICE (Loads on Structure and Waves in Ice) laboratory experiment[9], which took place in 2016 and in which the Principal Investigator was responsible for tests of ice breaking by waves. Combining numerical modelling and analysis of observational data should provide a detailed picture of processes contributing to wave attenuation in those laboratory tests.

Finally, as already mentioned in section 3.1, OpenFOAM software will be the basis for numerical modelling in tasks from group 5, either standalone (if frazil will be treated as one of three liquid phases, apart from air and water), or coupled with a DEM model through the CFD-DEM coupler (if frazil will be treated as particles in a particle-laden flow of water). In either case, several modifications and extensions to the existing multi-phase solvers will be necessary. The goal is, first, to reproduce one of the published results, obtained with other types of models, and then to run the model several times with different parameters to analyze their role in formation of frazil streaks. Observational data from PIPERS and other projects will be used for verifying the modelling results.

4.3 Division of the work among the project participants

Apart from the costs of equipment and logistics, personal costs are the main component of the overall budget of this project. The PI believes that investing in young researchers is the most valuable kind of investment in the future development of sea ice research. It is planned to engage two PhD students, with background in physical oceanography and/or physics, and with programming and numerical-modeling skills. Additionally, one person with experience in operating UAVs in oceanographic/atmospheric observations will be engaged to assist in field measurements (only for short periods in which surveys will be conducted).

The tasks of the individual project participants are:

1. Principal Investigator:
    - coordinating the project,
    - supervising of the PhD dissertations of Co-investigators no. 1 and 2,
    - leading and participating in the observational and numerical work in all project tasks,
    - performing the majority of theoretical and numerical work within task 4,
    - dissemination of project results on the Internet.
    - preparing of publications and conference presentations, presenting the results at international conferences and workshops.
2. Co-Investigator no.1 (PhD student):
    - participating in the field work in task 1,
    - performing the majority of work within tasks 2 and 3, which will be the crucial contribution to his/her doctor thesis,
    - preparing of publications and conference presentations, presenting the results at international conferences and workshops.
3. Co-Investigator no.2 (PhD student):
    - participating in the tasks related to numerical modeling,

[7] http://www.oc.nps.edu/NAME/RASM.htm

[8] http://www.meteo.pl/

[9] report available online at https://zenodo.org/record/1067170#.Wxf4ooppxpg; see also Herman et al. (2018) and Herman et al. (2017)

- performing the majority of theoretical and numerical work within task 5, which will be the main subject of his/her doctor thesis,
- preparing of publications and conference presentations, presenting the results at international conferences and workshops.

4. Co-Investigator no.3:

   - participating in field work within task 1.

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