Quantifying ice floe size distribution and its influence on the Arctic climate

Background and aims

The Arctic has warmed nearly four times faster than the global average [1], which remarkably affects the local and global biodiversity, ecosystem, and livelihoods through direct and indirect feedback [2,3]. However**, current climate models have systematic biases in the Arctic, with the largest biases in the marginal ice zone** (MIZ) [4], i.e., the transitional zone between the open sea and pack ice. Sea ice floes in the MIZ, with sizes ranging from centimetres to hundreds of kilometres, can significantly alter many physical processes, for instance, ice melt rate [5], wave decay [6], surface turbulent fluxes [7], etc. Meanwhile, the size of ice floes is a critical parameter describing those processes. For instance, compared with larger ice floes, smaller ice floes have a larger lateral melt rate since they have a larger perimeter per unit area of sea ice cover [8]. Furthermore, those ice floe-related processes will have positive/negative feedback on Arctic warming by, for instance, increasing radiative flux to the upper ocean by enhancing ice melting. However, **those processes associated with ice floes are misrepresented in current climate models, which is likely the key contributor to the model biases in the Arctic**.

The ice floe size distribution (FSD), i.e., the number of floes in different size categories in a region, is widely used when parameterizing the influence of ice floes on different processes. The power-law FSD is the popular scheme, in which the power-law exponent is the most important tuning factor. A large range of the power-law exponent (between 0.91 and 5 [9]) has been reported based on different measurements. Furthermore, some measurements show that two power exponents cover different floe size ranges [10]. The power-law distribution is not even supported by some studies [11]. The divergence in these results indicates that some other environmental conditions may control the FSD. Meanwhile, one needs to note that the previous results are derived based on limited measurements. Thus, the proposed project aims to **explore the sea ice FSD in the Arctic MIZ and quantify their influence on the Arctic climate.** The specific aims of the project include

1. exploring sea ice FSD in the Arctic MIZ using deep learning approaches.
2. investigating the variation of FSD with environmental conditions.
3. quantifying the influence of ice floes on surface turbulent fluxes and atmospheric mixing
4. implementing the results from 3) into a regional climate model and quantifying the role of ice floes in the Arctic climate.

The expected results from the project **have a high potential to improve the performance of climate and weather models in the Arctic and beyond**. The implementation of the project is ***necessary and urgent*** since 1) the dramatically increasing Arctic activities need accurate weather prediction to reduce the damages from potential weather hazards, and 2) the role of MIZ in the Arctic and global climate is becoming more important with the increase of the MIZ width [12]. Meanwhile, the project is ***timely and feasible*** since 1) the measurements from satellites and recent high-profile field campaigns provide adequate data to fill the current knowledge gaps on the sea ice FSD in the MIZ, and 2) the recently developed air-wave-ocean-ice (AWOI) fully coupled model, UU-CM, by the applicants provides a numerical tool for the project implementation.

Project description

WP1: Algorithm for extracting ice FSD from satellite images

To reduce the inconsistency of the FSD caused by different methods and limited measurements, **we will develop a more efficient and accurate method to extract the ice floe information from images using data-driven approaches**. The steps of the method are shown in Fig. 1. The Synthetic-Aperture Radar (SAR) images and optical images from satellites and field campaigns will be explored, including the SAR images from Sentinel-1 and TerraSAR-X, the optical images from Sentinel-2, etc.

- **Ice-water segmentation:** Images will be converted into ice-water binary images according to the grey colour level. The high noise level of the SAR images introduces significant uncertainties when producing water-ice binary images. Here, the Multi-Scale Attention-Guided Neural Network developed by one of the applicants [14] will be used to adaptively estimate the noise map and blindly remove the random noise. The visual image quality could be significantly improved with the preservation of meaningful geometrical features. Then, we will use support vector machines (SVMs) to separate the ice pixel from the water and produce the water-ice binary images. SVMs a promising approach to separating the water pixel from the ice when the fresh ice colour value is close to the water value since SVMs can embed the data into higher-dimensional space and is more accurate to separate two groups of data [15]. In comparison, traditional linear separation approaches, i.e., thresholding methods, have difficulties to distinguish water from fresh ice and ice with melting ponds.

- **Floe detection**: Several methods have been proposed to generate the floe split images, including the superpixel algorithm [15], parametric kernel graph cuts algorithm [16], the gradient vector flow snake algorithm with modified contour initialization [17], and the approach which combination of distance transformation, watershed and simple rule-based boundary revalidation processing [13]. Meanwhile, the U-Net has the potential to generate floe split images with high accuracy, which is widely used for medical and ore image segmentation [18]. These methods will be carefully tested under different ice conditions, in particular under conditions with seemingly connected ice floes. Then, we will either choose one or make a combination of several of these methods for the following tasks.
- **Floe size & shape distribution**: The floe split images will be used to explore the floe size and shape distribution. We will carefully deal with the influence of the cutoff, i.e., the resolution and the coverage area of the images, on the FSD. If FSD does not follow a power-law distribution, we will propose a new FSD scheme based on the measurements. Meanwhile, the shape of the floe may significantly alter the ice melting and the turbulent flux (tested in WP3). If important, we will propose a floe-shape distribution, e.g., based on the roundness.

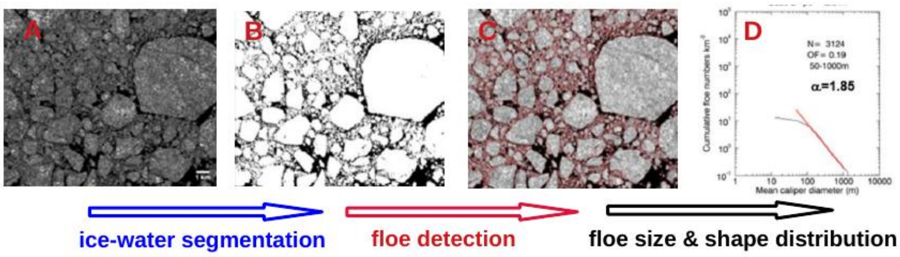

Fig. 1: Schematic of the steps to extract the FSD (Figure is adapted from [13]).

WP2: FSD under different environmental conditions

The environmental conditions may control the FSD due to the variation of mechanical and thermodynamic processes in the MIZ. The method developed in WP1 will be applied to more than 5 years of satellite images in the Arctic. Accordingly, we can get the variation of the tuning parameter in the FSD (floe shape distribution). Meanwhile, the FSD-related environmental parameters will be retrieved at the corresponding time and location of the images. Those parameters include wind speed from ERA5, ice thickness from SMOS, ice fraction from AMSR-E/AMSR2, air-sea temperature difference from ERA5, wave height from ERA5, the ice age (multiyear ice or first-year ice), etc. Based on those data, we can **derive the variation of the tuning parameters in FSD and floe shape distribution with environmental conditions**.

WP3: Parameterize the impacts of ice floes on turbulent fluxes

In current climate models, the turbulent fluxes in the MIZ are the weighted average of the fluxes over water and ice in proportion to their surface areas. However, this approach has significant uncertainties compared with measurements. The turbulence altered by the convective plum triggered by the ice and water patches is a potential reason for the uncertainties. In this WP, the ice FSD will be introduced into the parameterization of turbulent fluxes based on the analysis of the in-situ measurements and Large-Eddy simulations which explicitly resolve ice floe influences. Accordingly, **we can develop new turbulent flux parameterizations considering the influences of sub-grid ice floes.** The parameterizations will be implemented into UU-CM [19] and explore its influence on the Arctic climate.

Interdisciplinary aspects and involved actors

In this project, we will use machine learning (ML) to extract the ice floe information from the satellite images, which conquers 1) the scarcity of the in situ measurements in the Arctic, and 2) the poor understanding of the detailed ice-ice floe dynamical processes (since we are focusing on their large scale influence). The statistical methods will be used to extract useful information from massive satellite images. Combined with the knowledge from ML and statistics, the conventional numerical models will be further developed for improving our climate prediction and enhancing our understanding of the Arctic climate. Meanwhile, the project will develop new ML models for image processing based on the method developed by the applicant members, which will be accessible to the public for relevant research. In summary, the project is highly interdisciplinary with aspects from ML, statistics, meteorology, and oceanography. The supervisor teams and collaborators are experts in those topics which makes the project highly feasible.

Supervisors: Associate Prof. Lichuan Wu from the Dept. of Earth Sciences (main supervisor); Associate Prof. Shaobo Jin from Dept. of Mathematics and Dept. of Statistics (co-supervisor); Associate Prof. Ryan Wen Liu from Wuhan University of Technology (co-supervisor).

In addition to the daily supervisors, the PhD student will closely collaborate with Dr Alex Lars from the Swedish Meteorological and Hydrological Institute (a government agency) and Prof. Oyvind Brevik from Norwegian Meteorological Institute (a government agency) during the conduction of the project. The results can be implemented into their forecast models to improve the daily forecasts.

Host department and funding

The Dept. of Earth Sciences will host the PhD student. The LUVAL programme within the Dept. of Earth Sciences will co-finance an additional 25%. L. Wu's research group will cover 25% of the PhD salary from the ongoing VR project (2020-03190). CIM fund is applied to cover the remaining 50% of the PhD's salary.

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