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Summer sea ice floe size distribution in the Arctic: High-resolution optical satellite imagery and model evaluation

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Abstract. The sea ice floe size distribution (FSD) is an important component for sea ice thermodynamic and dynamic processes, particularly in the marginal ice zone. Recently FSD-related processes have been incorporated in sea ice models, but the sparsity of existing observations limits the evaluation of FSD models, so hindering model improvements. In this study, three FSD models are selected for the evaluation – Waves-in-Ice module and Power law Floe Size Distribution (WIPoFSD) model and two branches of a fully prognostic floe size-thickness distribution model: CPOM-FSD and FSDv2-WAVE. These models are evaluated against a new FSD dataset derived from high-resolution satellite imagery in the Arctic. The evaluation shows an overall overestimation of floe perimeter density by the models against the observations. Comparison of the normalized distributions of the floe perimeter density with the observations show that the models exhibit much larger proportion for small floes (the radius < 10–30 m) but much smaller proportion for large floes (the radius > 30–50 m). Observations and the WIPoFSD model both show a negative correlation between sea ice concentration and the floe perimeter density, but the two prognostic models (CPOM-FSD and FSDv2-WAVE) show the opposite pattern. These differences between models and the observations may be attributed to limitations of the observations (e.g., the image resolution is not sufficient to detect small floes), or limitations of the model parameterisations, including the use of a global power-law exponent in the WIPoFSD model, as well as too-weak floe welding and enhanced wave fracture in the prognostic models.

1 Introduction

Over the past decades, the extent and concentration of Arctic sea ice have been dramatically declining (Perovich et al., 2020). This results in the changing marginal ice zone (MIZ), defined as the ice-covered region affected by waves and swell (WMO, 2014; Horvat et al., 2020, Brouwer et al., 2021) or a sea ice-covered area with sea ice concentration (SIC) of 15%–80% (e.g., Strong and Rigor, 2013; Aksenov et al., 2017; Rolph et al., 2020; Bateson et al., 2020; Horvat, 2021). One of the

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major characteristics of the MIZ is the presence of discrete ice floes in different sizes and shapes, forming the floe size distribution (FSD) (Rothrock and Thorndike, 1984).

Previous studies have suggested the FSD is important for sea-ice processes in the MIZ. The FSD is linked to the total perimeter of the ice floes in the fragmented sea ice field, which is an important parameter influencing the sea ice melt occurring around the side of floes and ocean eddy processes (Steele, 1992; Tsamados et al., 2015; Arntsen et al., 2015; Horvat et al, 2016). Floe size influences ocean surface heat budget and affects sea ice rheology (Shen et al., 1986; Feltham, 2005; Rynders, 2017), which in turn can affect lead dynamics. The FSD also affects the atmosphere-ocean momentum transfer (Tsamados et al., 2014). In the MIZ, small ice floes (the diameter < 100 m) significantly increase the floe edge contribution to form drag and surface roughness (Steele et al., 1989; Herman, 2010; Lüpkes et al., 2012; Tsamados et al., 2014; Rynders et al., 2018; Brenner et al, 2021). This increases the momentum transfer between the atmosphere and the ocean (Steele et al., 1989; Birnbaum and Lüpkes, 2002; Herman, 2010; Martin et al., 2016). The FSD affects the ocean surface waves propagation and attenuation through the ice, i.e., floes smaller than a characteristic wavelength of swells attenuate wave energy through viscous dissipation, while larger floes attenuate the wave energy through scattering (Kohout and Meylan, 2008; Williams et.al., 2013a; Thomson and Rogers, 2014; Montiel et al., 2016; Meylan et al., 2021; Dumas-Lefebvre and Dumont, 2021; Horvat and Roach, 2022).

Given the crucial role of the FSD in various processes within the MIZ, a proper treatment of the FSD-related processes has become a key issue in simulating sea ice. Recently FSD parameterisations have been incorporated into sea-ice models (Horvat and Tziperman, 2015; Zhang et al., 2016; Bennetts et al., 2017; Rynders, 2017; Roach et al., 2018a; Bateson et al., 2020). For example, current FSD prognostic models consider the FSD evolution driven by thermodynamic and dynamic processes, including lateral melt (Horvat and Tziperman, 2015; Zhang et al., 2015; Roach et al., 2018a), ice ridging and ice fragmentation (Zhang et al., 2015; Horvat and Tziperman, 2015), wave-induced fracture (Horvat and Tziperman, 2015; Bennetts et al., 2017; Roach et al., 2018a), new ice formation (Roach et al., 2018a), floes welding (Roach et al., 2018a) and brittle fracture (Bateson et al., 2022). Some other modelling studies assumed a particular shape of FSD (e.g., Bennetts et al., 2017; Rynders, 2017; Bateson et al., 2020), for example fixing the FSD as following a truncated power law (Burroughs and Tebbens, 2001), i.e., a straight line in logarithmic axes.

Accurate model projections of Arctic climate change are needed to guide research and the response to climate change. The development of the FSD models is therefore essential to improve confidence in sea ice models. A major difficulty is the lack of the FSD observations, especially high spatial resolution data to constrain the model parameters and evaluate model performance. Hence, we derived a new FSD dataset from 1-m resolution MEDEA imagery and 0.5-m resolution Worldview imagery products and used the dataset to assess the performance of three selected FSD models. The new FSD data can resolve small floes (up to a few meters), providing a unique opportunity to evaluate the FSD model performance in the Arctic.

In this study, the three FSD models are evaluated against the new FSD dataset. The three models are a diagnostic Waves-in-Ice module and Power law Floe Size Distribution (WIPoFSD) model (e.g., Bateson et al., 2020; Bateson et al., 2022) and two fully prognostic FSD models branched from the FSTD model of Roach et al. (2018a, 2019), hereafter FSDv2-WAVE and CPOM-FSD. The FSDv2-WAVE model is developed by Roach et al. (2019), and CPOM-FSD is a branch of this model developed by the Center for Polar Observation and Modelling (CPOM) with additional features. This paper is organized as follows. The study regions are shown in Sect. 2. In Sect. 3, we introduce the FSD models and the new FSD dataset, and the methods applied to process satellite images to derive FSD and the metrics used to evaluate the models are described. Section 4 presents the model evaluation results. The discussion and conclusion are given in Sect. 5.

2 Study regions

Two study regions were selected for the model evaluation (Fig. 1). The Chukchi Sea region covers an area of 66°N–80°N, 156°W–180°W (blue box in Fig. 1), and the Fram Strait region covers an area of 77°N–87°N, 20°W–20°E (red box in Fig. 1). These regions are where the model outputs were extracted and analysed. The satellite images were acquired over a small area of 70°N and 170°W in the Chukchi Sea (black dot within the blue box in Fig. 1) and 84.9°N and 0.5°E in the Fram Strait region (black dot within the red box in Fig. 1). Compared to the satellite observation, much larger model study regions were selected. In this way, we minimize the bias caused by a lower resolution model outputs and ensure that the model outputs include the ice edge, so better representing the mean state of FSD in the models. Although both regions represent early-to-late spring sea ice conditions, the observations from the Chukchi Sea region captures a more dynamic and fragmented ice condition (e.g., Fig. 1b), while the observations from the Fram Strait capture a less dynamic environment (e.g., Fig. 1c).

3 Data and Methods

3.1 Observations

3.1.1 Satellite imagery

In this study we use two types of satellite imagery data. The first is 1-m resolution visual-band panchromatic images provided by Measurements of Earth Data for Environmental Analysis (MEDEA) group (Kwok and Untersteiner, 2011; Kwok, 2014). The images were accessed from the Global Fiducials Library (GFL) (http://gfl.usgs.gov/) of the United States Geological Survey (USGS), also known as Literal Image Derived Products (LIDPs). A total of 54 MEDEA images were acquired during May to August over the study period of 2000-2014 at the two fixed locations of the Chukchi Sea and the Fram Strait (Fig. 1). The original MEDEA images were cropped to remove cloud-covered areas and missing data. The size of the cropped images ranges between 30 km^2 and 250 km^2. We also collected one WorldView-1 (WV1) and four WorldView-2 (WV2) images with spatial resolution $\delta \approx 0.5$ m at the Chukchi Sea and Fram Strait sites (Fig. 1). The size of the WorldView (WV) images is ~40 km^2.

3.1.2 FSD retrieval from satellite image

Both MEDEA and WV images were processed to derive the FSD using the algorithm developed by Hwang et al. (2017a). The algorithm combines speckle filtering, Kernel Graph Cutting (KGC) for the segmentation of water and ice regions, distance transformation and watershed transformation, a rule-based boundary revalidation to split ice floes boundaries and final manual validation. The minimum size of floes that can be resolved by the algorithm is dependent on the resolution and type of the images. For 1-m resolution MEDEA images, retrievable floe size ranges between tens of meters to a few kilometres. Small floes with radii less than 5 m can be difficult to resolve due to the limitation in splitting the floe boundaries, so the number of small floes are generally underestimated when applying the algorithm to MEDEA images (Hwang et al., 2017a).

For the FSD retrieval, we first applied combined filters: median, bilateral and Gaussian filter (Hwang et al., 2017a) by using the same filter parameter as in Hwang et al. (2017b). The smoothing term, KGC algorithm parameter, was set as 0.0001 to slightly reduce low-intensity spots. To produce water-ice binary images by the KGC algorithm, one cut-off threshold is set to segment water and ice pixels. The SIC was calculated by counting the number of ice pixels out of the total number of image pixels. Segmented water-ice images were then used to split boundaries of sea ice floes using distance transformation and watershed transformation described by Ren et al. (2015).

3.1.3 Sea ice concentration

Two types of SIC products were used in this study: National Snow and Ice Data Center (NSIDC) SIC (Meier et al., 2017; Peng et al., 2013) and ARTIST Sea Ice (ASI) SIC (Spreen et al., 2008; Melsheimer and Spreen, 2019, 2020). The collected SIC data cover between May and July over the analysis period of 2000–2014. The SIC data were extracted for the study areas of the Chukchi Sea and Fram Strait (blue and red boxes in Fig. 1) to compare them with the SIC outputs from the FSD models.

3.2 Sea ice models with floe size distribution

In this study, three FSD models are evaluated. An overview of the configuration of these three FSD models is given in Table 1. The FSDv2-WAVE model uses the Los Alamos Sea Ice model CICE version 5.1 (Hunke et al., 2015) and is an upgraded version of FSDv2 by coupling with a wave model. On the other hand, the CPOM-FSD model is not coupled with a wave model but instead retain the internal wave scheme from Roach et al. (2018a) and uses 3-hourly ERA-Interim reanalysis as ocean surface wave forcing. Both CPOM-FSD and WIPoFSD models are applied within a modified version CICE v5.1.2 for sea ice simulation (hereafter referred to as CPOM-CICE) (Hunke et al., 2015). FSDv2-WAVE model has the displaced 1° (gx1v6, 320 × 384) grid over a global domain. The other two models are initiated with the ice-free Arctic and run with the tripolar 1° (129 × 104) grids for 37 years from 1 January 1980, followed by a 10-year period spin-up in a pan-Arctic domain

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excluding Hudson Bay and the Canadian Arctic Archipelago. In Sects. 3.2.1–3.2.3, we will briefly introduce the major differences between the three models in simulating FSD related processes.

3.2.1 FSDv2-WAVE model

FSDv2-WAVE model is based on a sub-grid scale floe size and thickness distribution (FSTD) model by Horvat and Tziperman (2015, 2017). Roach et al. (2018a) further implemented this FSTD model into a global ocean-sea ice model. This is the first global model that simulates emergent floe size evolution by physical processes, including lateral melt/growth, new ice formation, floes welding, and wave-induced fracture. FSDv2-WAVE uses the slab ocean model (SOM) (Bitz et al., 2012) coupled with the ocean surface wave model Wavewatch III v5.16 (WAVEWATCH III Development Group, 2016), and incorporates a new wave-dependent ice production scheme (Roach et al., 2019). Among the three selected models, FSDv2-WAVE is the only one that has a fully coupled ocean surface wave model to improve the modelling of wave attenuation in the open ocean and ice-covered area and wave-ice interactions and the associated ice thermodynamic/ dynamic processes in the MIZ (Roach et al., 2019).

3.2.2 CPOM-FSD model

CPOM-FSD model is adapted from the global FSTD model developed by Roach et al. (2018a, 2019) and built on CPOM-CICE v5.1.2 (Table 1). CPOM-CICE is an updated version by CPOM at the University of Reading to include (i) a modified prognostic mixed-layer ocean model to better capture sea ice-ocean feedbacks resulting from lateral and basal melt rate (Petty et al., 2014; Bateson et al., 2022), (ii) a form drag scheme for a better simulation of turbulent heat and momentum fluxes between the sea ice, ocean and atmosphere interface and representing the FSD effects on the form drag scheme (Tsamados et al., 2014; Bateson et al., 2022) and (iii) further amendments to alter maximum meltwater and snow erosion and add the “bubbly” conductivity formulation (Pringle et al., 2007; Schröder et al., 2019). A description of detailed differences between CPOM-CICE and standard CICE is available in Bateson et al. (2022). CPOM-FSD incorporates the in-plane brittle fracture and the associated FSD processes, which was shown to improve model performance in simulating the FSD (Bateson et al., 2022).

3.2.3 WIPoFSD model

WIPoFSD is a diagnostic power law FSD model (Bateson et al., 2020, 2022). The WIPoFSD model implements the wave-in-ice model (WIM), originally based on the ice-wave interaction process described by Williams et al. (2013a, 2013b) and updated to coupled ocean–waves–in–ice model NEMO–CICE–WIM at the National Oceanography Centre (NOC), UK (Hosekova et al., 2015; Rynders, 2017; Aksenov et al., 2022). Unlike the two prognostic models (FSDv2-WAVE and CPOM-FSD), WIPoFSD model simulates an FSD following a power law with a fixed exponent of $\alpha = 2.56$ to constrain the FSD shape over a variable range of floe sizes. The fixed power-law exponent is determined from the FSD data derived from 2-m resolution MEDEA images acquired at three locations: Chukchi Sea (70°N, 170°W), East Siberian Sea (82°N, 150°E) and Fram Strait (84.9°N, 0.5°E). In addition to the exponent, the model also simulates FSD evolution through the floe size parameter r_{var}, varying between minimum floe radius r_{min} and maximum floe radius r_{max}. r_{var} evolves according to four FSD processes: lateral melt, wave-induced fracture, floe growth in winter and ice advection (Bateson et al., 2020, 2022).

3.3 FSD definition

The FSD is usually defined as the floe areal FSD, $f(r)$, or floe number FSD, $n(r)$ (Rothrock and Thorndike, 1984; Toyota et al., 2006; Perovich and Jones, 2014; Horvat and Tziperman, 2015; Zhang et al., 2015; Hwang et al., 2017b; Bateson et al., 2020). By integrating $f(r)$ over floe radius between r and $r+dr$, $f(r)dr$ (dimensionless) is obtained, corresponding to the area of floes per unit ocean surface area with radius between r and $r+dr$. Rothrock and Thorndike (1984) first proposed the FSD theory as a fractional area distribution F in the region Ω with area a,

$$F(r_0,\Omega) = \int_{r_0}^{\infty} f(r)dr = \frac{1}{A}\iint_A H[r(x,y)-r_0]dx\,dy, (x,y) \in \Omega, \quad (1)$$

where r (no less than r_0) is floe radius at the location (x,y), and Ω (with area A) is a fixed geographic region of interest covered by floes. For the Heaviside function H, $H(q)=1$ if $q \geq 0$ and $H(q)=0$ if $q<0$. As r_0, the minimum of r, approaches zero, $F(0^+,A)$ is the ice concentration. To avoid edge effects, if a floe overlaps the boundary of Ω, its area within Ω is counted only. Here, the double integrals represent area integrals over A.

The cumulative floe number distribution (CFND, $N(r,\Omega)$) is also used (e.g., Toyota et al., 2006), which is defined as the number of floes per unit area in a region Ω with size larger than or equal r_0,

$$N(r_0,\Omega) = \int_{r_0}^{\infty} n(r)dr. \quad (2)$$

3.4 Evaluation metrics - perimeter density

In this study, we use the perimeter density per unit ice area P_i (units: m^{-1}) to evaluate the model performance, because it reduces the impacts of partially captured floes at the edge of the image for the FSD retrieval (Perovich, 2002; Perovich and Jones, 2014). There are different ways to calculate P_i. In the following, we describe how the FSD models calculate P_i, as well as how P_i can be calculated from the observational FSD data. Details on the calculation of P_i is provided in the supporting information Sect. S1.

As outlined in Roach et al. (2018a) and Bateson et al. (2022), 12 Gaussian spaced floe size categories are applied in FSDv2-WAVE and CPOM-FSD simulations. In these two prognostic FSD models, P_i is calculated from areal FSD f_i distributed into floe size categories i as follows:

$$P_{i\_prog} = 2\sum_{i=1}^{12} \frac{f_i(r_{i_{max}} - r_{i_{min}})}{r_i c_{ice}}, \quad (3)$$

where r_i, $r_{i_{max}}$ and $r_{i_{min}}$ are the midpoint, upper and lower limit for each floe size category i. Here c_{ice} represents the area-weighted SIC in the selected region.

P_i for WIPoFSD can be calculated from

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$$P_{i\_wipofsd} = \frac{\int_{r_{min}}^{r_{var}} 2\gamma r n(r) dr}{c_{ice}} = \frac{2(3-\alpha)(r_{var}{}^{2-\alpha} - r_{min}{}^{2-\alpha})}{(2-\alpha)(r_{var}{}^{3-\alpha} - r_{min}{}^{3-\alpha})}. \quad (4)$$

In this study, we used daily outputs from the FSD models to calculate P_i. To obtain P_i from the daily model outputs, we calculated an area-weighted mean, on the same date as the observations, over the grid cells within the study areas of the Chukchi Sea and the Fram Strait (Fig. 1). In supporting information, we note that the P_i varies depending on the choice of binning and calculation methods (see Sec. S2 and Fig. S1 in the supporting information). To ensure matching with the model outputs, the FSD observation data were binned into the same 12 Gaussian spacing floe size categories used by the FSD models and estimated from areal FSD,

$$P_{i\_obs} = \sum_{i=1}^{12} \frac{2A_{floe_i}}{r_i A_{ice}}. \quad (5)$$

A_{ice} is the total area of sea ice within the image.

4 Results

4.1 Model evaluation: perimeter density

The comparison of P_i between observations and models is shown in Fig. 2. Observations show a substantial difference in P_i between the two regions (t-test, t (47) = 6.43, p < 0.001) (Fig. 2a). It shows a significantly higher P_i of 20.77 ± 6.54 km^{-1} in the Chukchi Sea site than the P_i of 12.16 ± 3.79 km^{-1} in the Fram Strait site (Fig. 2a). Higher P_i in the Chukchi Sea indicates a larger fraction of small floes in that region. It should be noted that the P_i values in the Fram Strait are comparable with the reported values from previous observational studies, which range between 5.26 km^{-1} and 13.68 km^{-1} from May to July in the Beaufort Sea and the Chukchi Sea (Perovich, 2002; Perovich and Jones, 2014; Arntsen et al., 2015).

FSDv2-WAVE P_i values spread out over a wide range and show the opposite regional difference to the observations (a higher P_i 151.85 ± 76.01 km^{-1} in the Fram Strait region than the value 119.51 ± 61.59 km^{-1} in the Chukchi Sea region) (Fig. 2c). WIPoFSD (Chukchi Sea: 105.53 ± 1.45 km^{-1}, Fram Strait: 118.34 ± 11.05 km^{-1}) and CPOM-FSD (Chukchi Sea: 51.97 ± 16.69 km^{-1}, Fram Strait: 52.09 ± 24.65 km^{-1}) show a general overestimation of P_i to the observations and the regional difference is much less evident in these two models (Figs. 2c and 2d).

Figs. 2e–2k show the comparison of normalized P_i per floe size category. The observation results show a declining P_i with increasing floe radius *r*. The FSDv2-WAVE results show the same relationship but with a steeper slope than the observation, showing much larger proportion of P_i for small floes (r < 10–30 m) whilst showing much smaller proportion of P_i for large floes (30–50 m < r < 400–800) than the observations (Figs. 2e–2k). This pattern is consistent in different months and regions. The CPOM-FSD results also show a similar pattern, yet the model P_i values are in a much better agreement with the observations for large floes (r > tens of meters), especially during July and August in the Fram Strait region (Figs. 2g and 2h). This better match for larger floes has proved to be due to the effects of in-plane brittle fracture (Bateson et al., 2022). The results from the two prognostic models (FSDv2-WAVE and CPOM-FSD) consistently show an 'uptick' (a steepening

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upward slope in the largest floe size categories) in P_i (Figs. 2e–2k). This type of 'uptick' in the prognostic models has been reported by Bateson et al. (2022) and Roach et al. (2018a). The WIPoFSD results also show a steeper slope than the observation, but a better agreement with the observations than the two other model results. Similar to the two other models, the WIPoFSD model also shows an overestimation of P_i in small floes (r < 10–30 m) (Figs. 2e–2k).

Now we examine the relationship between SIC and P_i. The observation results show a negative relationship between SIC and P_i (correlation coefficient r_{cor} = −0.47, p < 0.01), which means higher P_i in a lower SIC (i.e., the presence of smaller floes in a lower SIC). A similar relationship was found by Perovich (2002) and Perovich and Jones (2014) in July to September. The WIPoFSD model shows the same negative relationship between SIC and P_i (r_{cor} = −0.75, p < 0.01), but the correlation is stronger and overall P_i values are much larger than the observations (Fig. 3). In the Chukchi region, the P_i values are mostly located within the 'pack ice' region (SIC > 80%) for both observations and WIPoFSD model outputs (Fig. 3a). In Fram Strait, however, the WIPoFSD P_i values become shifted toward a lower SIC than the observations (Fig. 3b).

The two prognostic models show an opposite correlation to the observations and WIPoFSD results. Both FSDv2-WAVE and CPOM-FSD data show positive relationships between SIC and P_i (r_{cor} = 0.38–0.39, p < 0.01) (Fig. 3). In the pack ice region (SIC > 80%), the two prognostic models simulate much higher P_i than the observations, in particular the P_i values from FSDv2-WAVE are almost 7–16 times higher than the observations in both study regions (Fig. 3). This indicates a much higher floe fragmentation in the model simulations than the observations in a pack ice condition. In a low ice concentration, the difference becomes smaller, especially for CPOM-FSD (Fig. 3).

4.2 Effects of image resolution on the FSD retrieval

In Sect. 4.1, the three models all show larger proportion of P_i for small floes (r < 10–30 m) than the observations (Figs. 3e–k). This large proportion of model P_i for small floes may be attributed to the limited image resolution in retrieving small floes. To test this, we investigate P_i derived from MEDEA (δ = 1 m) images and from WV (δ = 0.5 m) images (Fig. 4). The results show that the P_i values from the images are in a good agreement for the floes with r > ~15 m (Figs. 4e and 4f). This confirms the compatibility of the FSD retrieval from the images with different resolutions. Importantly, however, for the floes with the floe radius r smaller than ~15 m, P_i derived from the WV image becomes significantly higher than the MEDEA-derived P_i values (Figs. 4e and 4f). The difference in normalized P_i for the two smallest bins (r < 14.29 m) between the WV and MEDEA images reaches 1.12 km^{-1} (Fig. 4e) in the cases in Figs. 4a and 4b and 3.48 km^{-1} (Fig. 4f) in the cases in Figs. 4c and 4d.

4.3 Model evaluation: sea ice concentration

As an important floe growth process in the emergent FSD, floe welding rate is set to be proportional to the square of SIC in the two prognostic models, FSDv2-WAVE and CPOM-FSD (Roach et al., 2018a, b; Bateson et al., 2022). In this section, we present the model-observation comparison results for SIC to validate floe welding for the prognostic models. In the Chukchi

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Sea, CPOM-FSD shows a good agreement in SIC with the observations (correlation coefficient r_{cor} > 0.98, RMS error < 7%) (Table 2). FSDv2-WAVE, however, shows a considerable bias, underestimating SIC by 16–17% compared to the observations (Fig. 5a). In the Fram Strait, FSDv2-WAVE better agrees with the observations (r_{cor} > 0.90, RMS error < 7%, Table 2) than CPOM-FSD (Fig. 5b). For example, the RMS errors for CPOM-FSD are more than two times larger than FSDv2-WAVE (Table 2). FSDv2-WAVE slightly underestimates SIC by 2–4% compared to the observations in the MIZ (SIC<80%). CPOM-FSD strongly underestimate the SIC by 13%–15% in the MIZ compared to the observations.

This difference can be attributed to different atmospheric forcing that is used in the models (Schröder et al., 2019). FSDv2-WAVE uses JRA55b reanalysis data for the atmospheric forcing, whilst CPOM-FSD and WIPoFSD use 6-hourly NCEP-2 reanalysis data (Table 1). The underestimated SIC from the two prognostic models may be closely related to the underpredicted floe welding rate during spring and early summer. A negative bias in spring SIC shown in the prognostic models may partially explain the overestimation of P_i especially for small floes (Fig. 2).

For WIPoFSD model, the evolution of P_i is constrained by the floe size parameter r_{var} (Eq. 4), which is also impacted by a simple floe growth restoration scheme including floe welding, lateral growth and new ice formation (Bateson et al., 2020). However, this floe growth restoration scheme is not closely related to SIC. In contrast to the other schemes, changes in r_{var} are linked to SIC in the WIPoFSD model via lateral melt, which acts to reduce both (Bateson et al., 2020; Bateson et al., 2022). For WIPoFSD, SIC decreases 40% in the Chukchi Sea from May to July, similar to the observed decrease (39%) from NSIDC SIC and ASI SIC. In contrast, the SIC for WIPoFSD decreased about 20% in the Fram Strait, 2 times more than the observations (9%). Bateson et al. (2020) conducted a sensitivity study to test the role of lateral melting in affecting FSD by removing the lateral melt feedback on floe size. The results demonstrate that lateral melt is less important in changing the FSD in WIPoFSD. This could explain a smaller discrepancy P_i between the WIPoFSD model and the observations than the other two models (Fig. 2).

4.4 Processes controlling Floe size distribution evolution

In the prognostic models, FSD evolution is constrained by the parameterized processes. In the period of May–August, the dominant FSD evolution processes are lateral melt and wave-induced breakup, as lateral growth, new ice formation and floes welding are negligible during this season. To test the effects of lateral melt and wave breakup, we constructed two data sets: monthly changes of P_i arising from lateral melt and FSD changes arising from wave breakup. The constructed FSD changes are shown in Fig. 6.

The results show that FSDv2-WAVE produces large, positive changes in P_i from wave fracture (Figs. 6b and 6d) in summer, while CPOM-FSD produces negative changes in P_i from wave fracture (Figs. 6f and 6h). This indicates that the wave-induced fracture process is much more significant for the floe fragmentation in FSDv2-WAVE than CPOM-FSD. The more significant wave breakup in FSDv2-WAVE may be attributed to the fact that FSDv2-WAVE uses a coupled ocean wave scheme rather than internal wave scheme used in CPOM-FSD model, and that the SIC in the Chukchi Sea is significantly

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lower in FSDv2-WAVE, which is forced with the JRA55a reanalysis, while CPOM-FSD are forced with the NCEP-2 reanalysis.

CPOM-FSD shows a stronger reduction in P_i arising from lateral melt (Figs. 6e and 6g) in summer than FSDv2-WAVE. This indicates that the lateral melt process is much more dominant in CPOM-FSD than FSDv2-WAVE. The difference in lateral melt is likely to be related to the difference in sea surface temperature in the models. CPOM-FSD uses a prognostic mixed-layer ocean model and form drag scheme to simulate ocean mixed-layer properties and the topography of sea ice on sea ice-ocean-atmosphere heat exchange (Bateson et al., 2022). On the other hand, FSDv2-WAVE uses a single ocean layer and ocean heat content diagnosed from a run of Community Climate System Model version 4 (Roach et al., 2019). This difference in ocean components can produce different oceanic heat fluxes in determining the strength of lateral melt between FSDv2-WAVE and CPOM-FSD.

Our FSD observations lie in the southern part (red box in Fig. 6a) of the Chukchi Sea region, where both models show large changes in P_i due to wave fracture and lateral melt compared with the northern Chukchi Sea region (blue box in Fig. 6a). For the Fram Strait region, the observation site is located in the northern region where sea ice floes experience weaker lateral melt and wave fracture (blue box in Fig. 6c). To test the sensitivity of model P_i between the northern (weak wave fracture and lateral melt) and southern (strong wave fracture and lateral melt), we calculated P_i from both models between the southern and northern regions of the Chukchi Sea and the Fram Strait.

As expected, the results show a considerable difference in P_i between the two regions (Fig. 7). The P_i values from the northern regions are considerably smaller than the values from the southern regions for the two models (Fig. 7). In the Chukchi Sea region, the SIC values from the northern region are clustered between 90% and 100%, and the P_i values for both models are comparable to the observation values (Fig. 7a and Table 3). In the Fram Strait, the SIC values from the northern region spread over a wider range of 50–100% (Fig. 7b). Interestingly, CPOM-FSD results from the northern Fram Strait region become very comparable to the observations in terms of the P_i values and the range of SIC (Fig. 7a), while the P_i values from FSDv2-WAVE still show much larger values (Fig. 7b and Table 3). Note that the observation site in the Fram Strait is located within the northern region. In a direct comparison encompassing a larger model region (Fig. 3), the P_i values from CPOM-FSD were larger than the observation values (and a positive correlation with SIC). The close match between CPOM-FSD and the observations for the northern Fram Strait region suggest no significant wave fracture and lateral melt has occurred in the observation site. This can be supported by the fact that most of the satellite observations in the Fram Strait represent regions where the sea ice has experienced less thermodynamic and dynamic impacts (e.g., Fig. 1c), so the effects of lateral melt and wave fracture were likely small. It should be noted that CPOM-FSD implements in-plane brittle fracture into the model. Recent studies suggest that brittle fracture can determine the initial FSD in spring before wave fracture and lateral melt (Gherardi and Lagomarsino, 2015). Therefore, the close agreement between CPOM-FSD and the observations may represent the initial state of FSD before any significant wave fracture and lateral melt occur. In case of FSDv2-WAVE, the P_i values from the northern Fram Strait region still show much larger numbers. It is difficult to pinpoint the exact causes of this overestimation as the effects of wave fracture would be quite small in the northern region (Fig. 6d).

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5 Discussion and conclusion

In this study, we evaluate three state-of-art FSD models (FSDv2-WAVE, CPOM-FSD and WIPoFSD) against new observation data derived from 1-m resolution MEDEA imagery. The observation results show clear regional differences between the two study regions, i.e., much larger perimeter density P_i (smaller floes) in the Chukchi Sea region than in the Fram Strait region. Model outputs, however, fail to show such a regional difference.

The direct comparison between the observations and daily model outputs reveals that the models consistently show (i) overall overestimation of P_i, (ii) much larger proportion of the normalized P_i for small floes (r < 10–30 m) and (iii) much smaller proportion of the normalized P_i for the larger floes (30–50 m < r < 400–800 m). Among the three FSD models, WIPoFSD and CPOM-FSD show a much smaller difference to the observations than FSDv2-WAVE. The observations and WIPoFSD model both show a positive correlation between SIC and P_i (i.e., smaller floes in a lower SIC), while the two prognostic models show the opposite (negative) correction. The causes of such differences include (i) the limitations within the observations such as image resolution, (ii) underestimation of SIC and the associated effects on floe wielding parameterisation, and (iii) overactive wave fragmentation scheme in the models.

The effects of the limited image resolution are examined by comparing (1-m resolution) MEDEA-derived P_i with (~0.5-m resolution) WV-derived P_i. It shows that WV-derived P_i is almost 1.12 to 3.48 km^{-1} larger than MEDEA-derived P_i. However, this difference is still far too small to explain the difference between the observations and model outputs, varying between 17.42 km^{-1} and 186.44 km^{-1} in Figs 2e–2k (See Table S1). This suggests that the image resolution could be one of the contributors to the overestimation of modelled P_i for small floes, but it is still inconclusive whether the limited image resolution is the main contributor or other factors such as model parameterisations contribute to the difference. It requires much higher resolution images (e.g., aerial photographs) to properly investigate the effects of the image resolution.

Regarding underestimation of SIC and the associated effects on floe wielding, the strength of floe welding is strongly related to the SIC in the prognostic models evaluated in this study (Roach et al., 2018a, b; Bateson, 2021; Bateson et al., 2022). Previous studies have identified the dominant role of floe welding in the formation processes of large floes (Toyota et al., 2011; Roach et al., 2018a, b). In particular, Bateson (2021) has assessed the effects of floes welding on the FSD in the CPOM-FSD model, suggesting that floe welding occurring in spring can influence the FSD in summer. A low ice concentration reduces the floe wielding during spring and consequently results in an initial over-fragmented state in early summer. Therefore, a negative bias in spring SIC shown in the prognostic models can partially explain the large proportion of normalized P_i for small floes and the small proportion of normalized P_i for larger floes in the two prognostic models (Fig. 2).

For WIPoFSD, the bias in the P_i is not related to the underestimation of SIC and the consequent floe wielding parameterisation. Instead, the bias in P_i is likely due to the fixed power-law exponent of $\alpha = 2.56$ for non-cumulative distribution used in the model. This value is larger than the exponent from our dataset (i.e., in the Chukchi Sea $\alpha = 2.34$, in the Fram Strait $\alpha = 2.07$). Previous studies have found the exponent ranges vary seasonally and regionally (Stern et al.,

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2018a, b). The typical exponent value ranges from about 1.8 to 3.6 for non-cumulative distribution in the Chukchi Sea and the Beaufort Sea during May–August (Holt and Martin, 2001; Wang et al., 2016; Hwang et al., 2017b; Stern et al., 2018a, b) and from 2.0 to 2.8 (non-cumulative distribution) in the Fram Strait in June (Kergomard, 1989). Thus, we suggest that employing a seasonally and spatially variable exponent in the model may improve the model performance.

In terms of overactive wave fracture in the prognostic models, the wave fracture model applied by Horvat and Tziperman (2015) and Horvat and Roach (2022) has been implicated as producing unrealistically fragmented FSDs in the Chukchi Sea. As wave events episodically propagate hundreds of kilometres into the sea ice, the impact of this oversensitivity may be to produce unrealistically high perimeter densities in our study regions. To investigate this, we examined the P_i in the northern regions where wave-induced breakup is negligible. In these regions, most modelled P_i match our observations better. However, we found that the P_i from FSDv2-WAVE still show positive bias in the Fram Strait region. These biases may be attributed to the initially over-fragmented ice conditions in early spring set in the models.

In conclusion, the new FSD dataset was found to be valuable in evaluating the FSD models, which shows considerable differences from the observations in terms of P_i and the relationship between P_i and SIC. The summer P_i change in the models depends strongly on initial floe size distribution before melting starts, which is affected by floe formation and growth processes (e.g., the welding of meter-scale floes) in the models. Our findings also indicate positive biases of P_i are closely linked to overactive wave fracture in the models. This suggests accurate parameterisation of wave-induced sea ice breakup is essential for simulating the summer FSD correctly. Limited resolution of satellite images that we used can underestimate the small-size floes, yet this study provides an encouraging possibility for the model evaluation and improvement, so achieving a more accurate Arctic climate prediction.

Data availability

MEDEA images are openly available at the Global Fiducials Library website (http://gfl.usgs.gov/). WorldView images cannot be shared due to the license. However, the images can be ordered from LAND INFO Satellite Imagery Search Portal (https://search.landinfo.com/) or other satellite imagery providers. FSD imagery data retrieved from satellite imagery in this study can be accessible from UK Polar Data Centre soon (DOI will be generated before the publication of this paper). The model outputs used for analysing the monthly change of FSD in the study are available from https://doi.org/10.5281/zenodo.3463580 for FSDv2-WAVE and from http://dx.doi.org/10.17864/1947.300 for CPOM-FSD and WIPoFSD. The daily model outputs used in this study for model-observation comparison will be available before the publication of this paper.

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Author contribution

YW conceived the study under the supervision of BH, YA and CH. YW prepared the FSD observations with the support from BH. AB completed simulations of CPOM-FSD and WIPoFSD and shared model outputs from Bateson et al. [2022]. YW performed the data analysis and completed the comparison of the FSD observations to model output, with support from BH, AB, YA and CH. YW prepared the manuscript with guidance and contributions from all authors.

Competing interests

Yevgeny Aksenov is a member of the editorial board of The Cryosphere. The peer-review process was guided by an independent editor, and the authors have also no other competing interests to declare.

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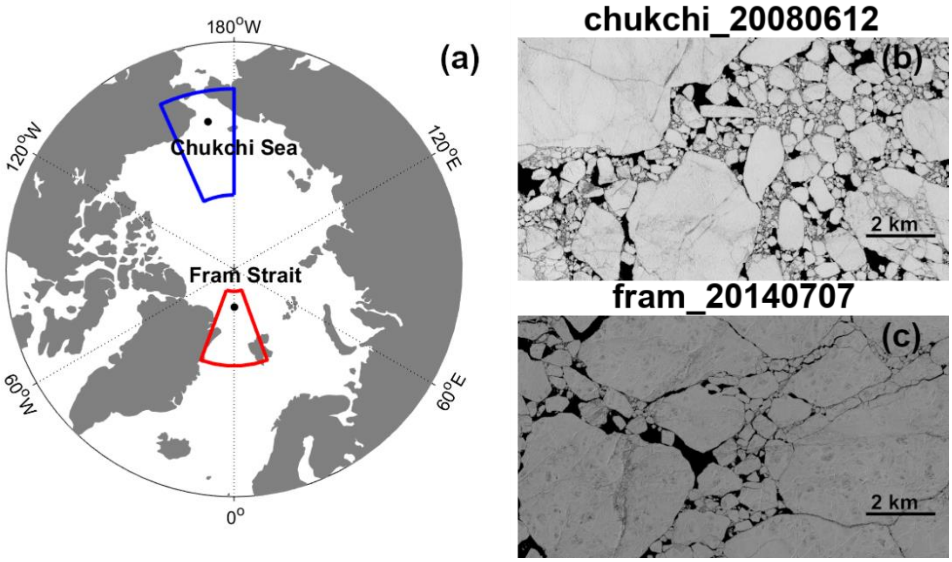

580 **Figure 1: (a) Map of the study regions. Satellite images acquired on (b) 6 June 2008 in the Chukchi Sea and (c) 7 July 2014 in the Fram Strait. The blue and red boxes are the boundary of the Chukchi Sea region and the Fram Strait region respectively. The black dots within the study regions mark the locations where satellite imagery data were acquired (70°N and 170°W in the Chukchi Sea and 84.9°N and 0.5°E in the Fram Strait).**

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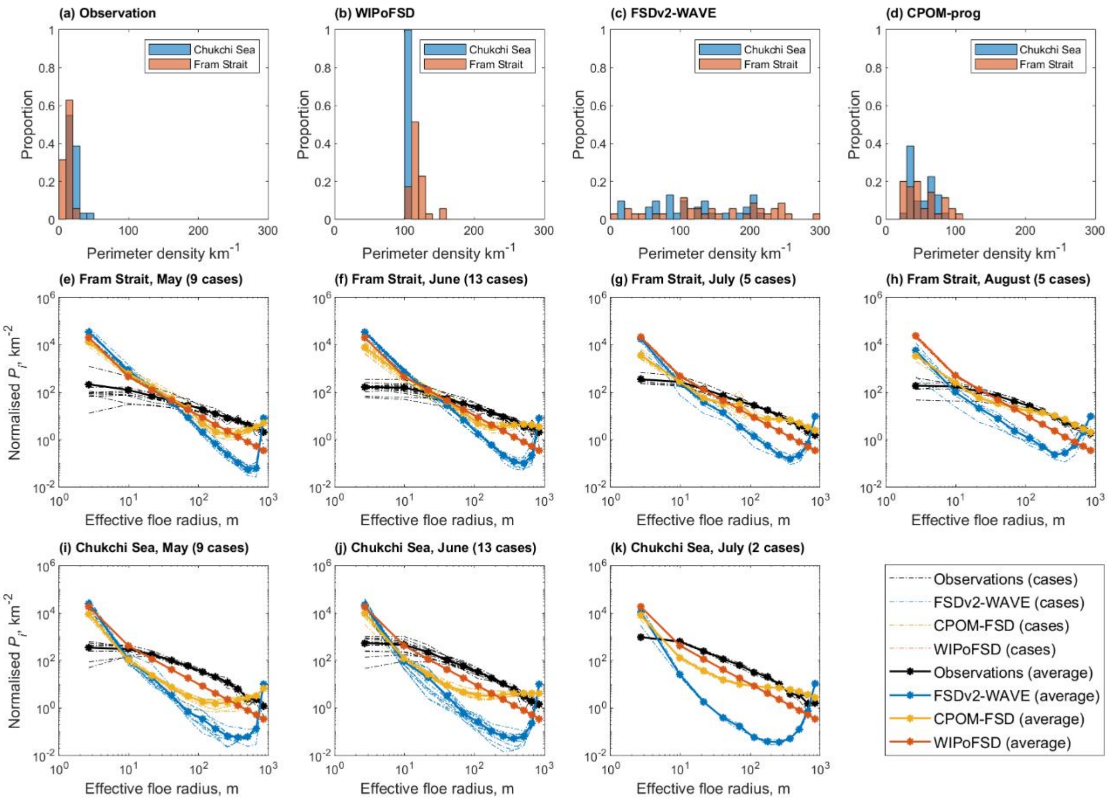

Figure 2: Frequency histograms of floe P_i from (a) observation, (b) WIPoFSD, (c) FSDv2-WAVE and (d) CPOM-FSD. In (a)–(d), blue colour indicates the frequency distribution of P_i for the Chukchi Sea and red colour for the Fram Strait. Normalized P_i are shown for (e) May, (f) June, (g) July and (h) August in Fram Strait, as well as for (i) May, (j) June and (k) July in the Chukchi Sea. In (e)–(k), the observations are shown in black line and three models in different colours (FSDv2-WAVE—blue, CPOM-FSD—yellow, WIPoFSD—red). The normalized perimeter density distributions were obtained by dividing the width of every floe size category into P_i at each region. In (e)–(k), the normalized P_i of all cases in each month are shown with dashed lines with the mean value shown with solid lines.

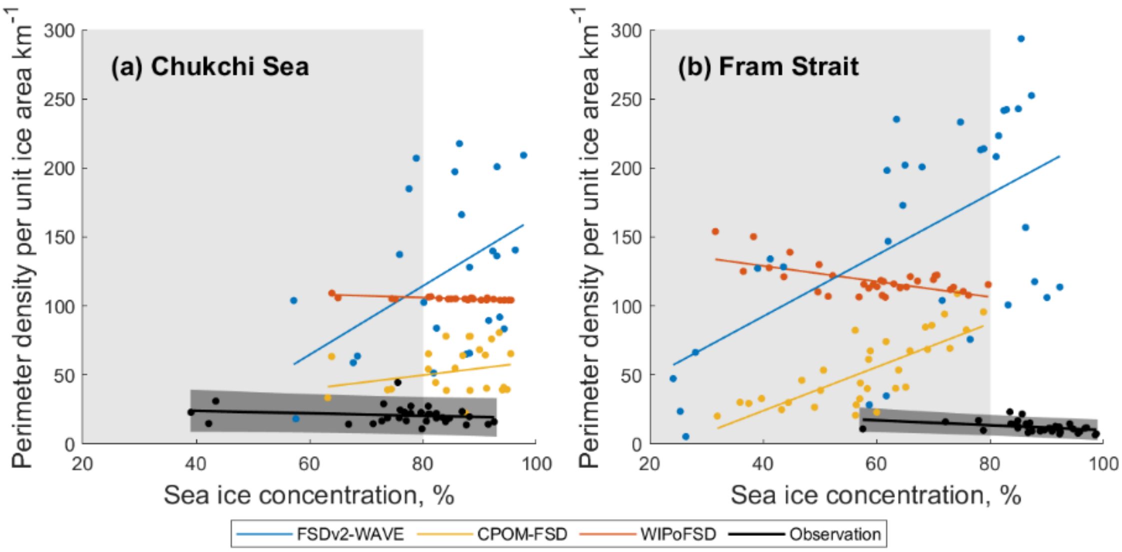

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Figure 3: Perimeter density P_i according to SIC for (a) the Chukchi Sea region and (b) the Fram Strait region. Dark grey shades along the regression lines of the observations mark a 95% confidence interval. The light grey shade marks the MIZ, defined as SIC between 15% and 80%.

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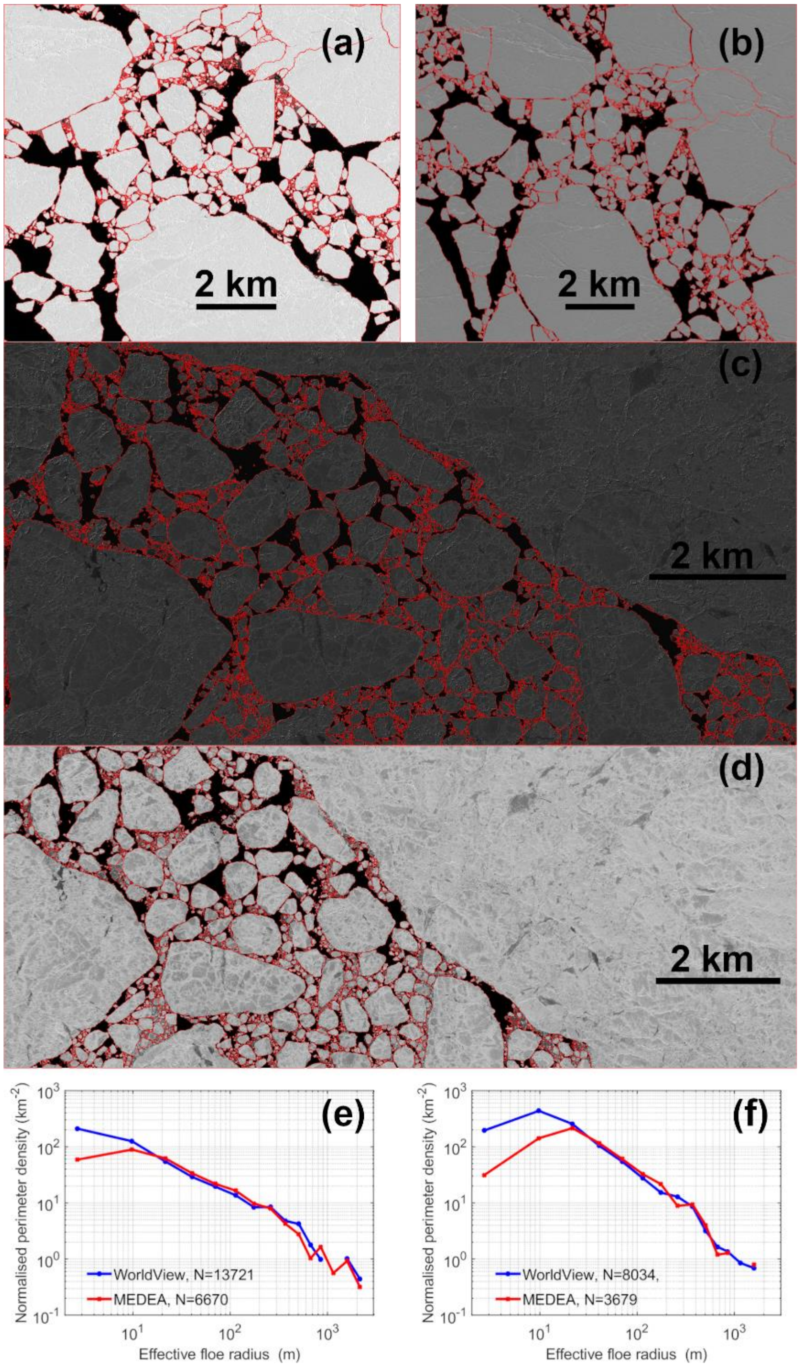

Figure 4: Comparison of normalized perimeter density between (a) WV© image (δ = 0.5 m) and (b) MEDEA image (δ = 1 m) on 5 June 2013 at 84.9°N, 0.1°E (Fram Strait) is shown in (e) and between (c) WV image (δ = 0.5 m) on 1 June 2013 and (d) MEDEA image (δ = 1 m) on 31 May 2013 at 70°N, 170°W (Chukchi Sea) is shown in (f). The image size of the co-located scenes shown in (a), (b), (c) and (d) cover an area of 106 km^2, 82 km^2, 66 km^2 and 64 km^2 respectively. In panels (e)–(f), *N* is the number of floes derived from satellite images.

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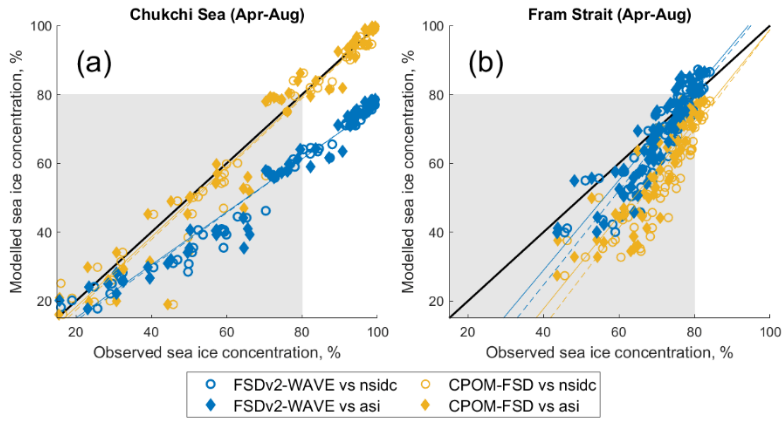

Figure 5: A comparison of SIC between observations and prognostic models in the Chukchi Sea (a) and (b) the Fram Strait.
610 **Monthly SIC data from April to August for the period 2000–2014 were used for the comparison. In (a)–(b), the comparison between the observations and two prognostic models are shown in different colours (FSDv2WAVE: blue, CPOM-FSD: yellow). The comparison between NSIDC and models are marked with circles and their linear fits are shown as dashed line. Diamonds and solid lines indicate the comparison between ASI and models.**

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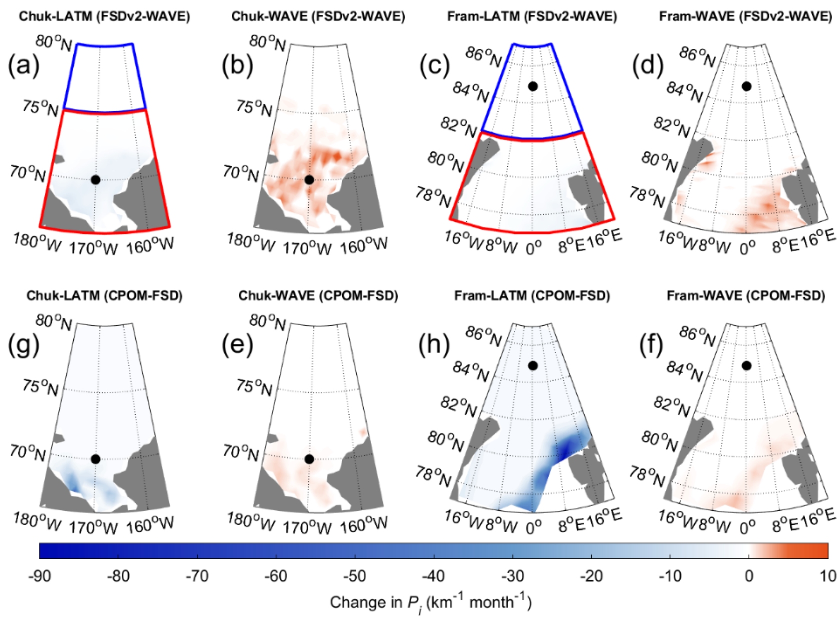

Figure 6: Monthly changes of P_i simulated by the two prognostic models over the period May to July during 2000–2014. (a) Change of FSD arising from lateral melt for FSDv2-WAVE in the Chukchi Sea. (b) is same as (a) but for wave induced FSD change. (c) and (d) are same as (a)and (b) but in the Fram Strait. (e)–(h) is same as (a)–(d) but for CPOM-FSD. The blue and red box in (a) and (c) show the northern and southern region of the two study regions. Black dots indicate the location of observations in the study regions.

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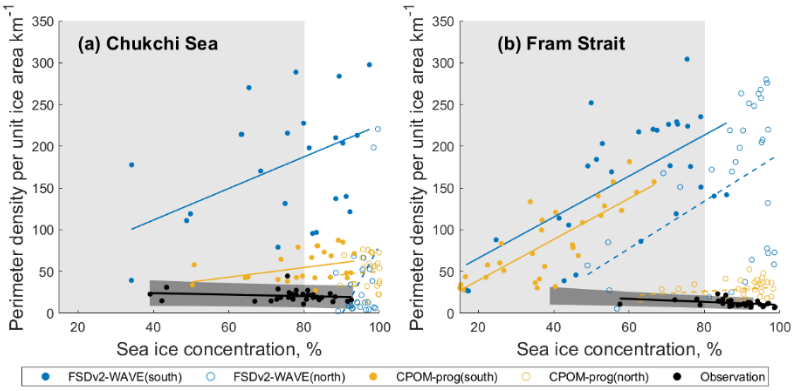

625 **Figure 7: Similar to Figure 3 but show the comparison between observations (black) and two prognostic models (FSDv2-WAVE—blue, CPOM-FSD—yellow) in southern regions (solid circle) and northern regions (hollow circle) of the study region in the Chukchi Sea (a) and the Fram Strait (b).**

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Table 1. Summary of model simulations used in this study.

<table>
<tr><th>Simulation</th><th>Sea ice model</th><th>Ocean coupling</th><th>Atmosphere forcing</th><th>Wave forcing</th><th>Grid</th><th>Run period</th></tr>
<tr><td>FSDv2-WAVE</td><td>CICE v5.1</td><td>To SOM[a]</td><td>6-hourly Atmospheric reanalysis JRA55[c]</td><td>Coupled Wavewatch III v5.16[e]</td><td>Displaced pole 1° (320 x 384)</td><td>2000–2014</td></tr>
<tr><td>CPOM-FSD</td><td rowspan="2">CICE v5.1.2</td><td rowspan="2">To mixed layer ocean model[b]</td><td rowspan="2">6-hourly NCEP-2 reanalysis[d]</td><td rowspan="2">3-hourly ERA-Interim reanalysis[f]</td><td rowspan="2">Tripolar 1° (129 × 104)</td><td rowspan="2">1980–2016</td></tr>
<tr><td>WIPoFSD</td></tr>
</table>

[a] Slab Ocean Model (SOM) (Bitz et al., 2012)

[b] Petty et al. (2014)

[c] Japan Meteorological Agency (2013).

[d] Kanamitsu et al. (2002).

[e] WAVEWATCH III Development Group (2016).

[f] Dee et al. (2011)

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Table 2. Statistical summary for the three FSD models against the NSIDC SIC and ASI SIC. NSIDC and ASI SIC data used for
640 **the comparison are between April and August for the analysis period of 2000–2014.**

	Correlation coefficient				**RMS error**			
	NSIDC		**ASI**		**NSIDC**		**ASI**	
	CS	**FS**	**CS**	**FS**	**CS**	**FS**	**CS**	**FS**
FSDv2-WAVE	0.99	0.91	0.98	0.90	18%	7%	18%	7%
CPOM-FSD	0.98	0.86	0.98	0.86	6%	16%	7%	14%

[a] Chukchi Sea.

[b] Fram Strait.

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645 **Table 3. The mean P_i (km^{-1}) and standard deviation simulated by FSDv2-WAVE and WIPoFSD in the southern regions and northern regions of the Chukchi Sea (CS) region and the Fram Strait (FS) region.**

	Southern CS	**Northern CS**	**Southern FS**	**Northern FS**
FSDv2-WAVE	172.35±74.87	38.50±59.33	160.50±70.94	152.60±89.13
CPOM-FSD	53.58±17.55	48.73±19.61	84.23±43.71	28.70±10.41