Sea ice fragmentation and its role in the evolution of the Arctic sea ice cover

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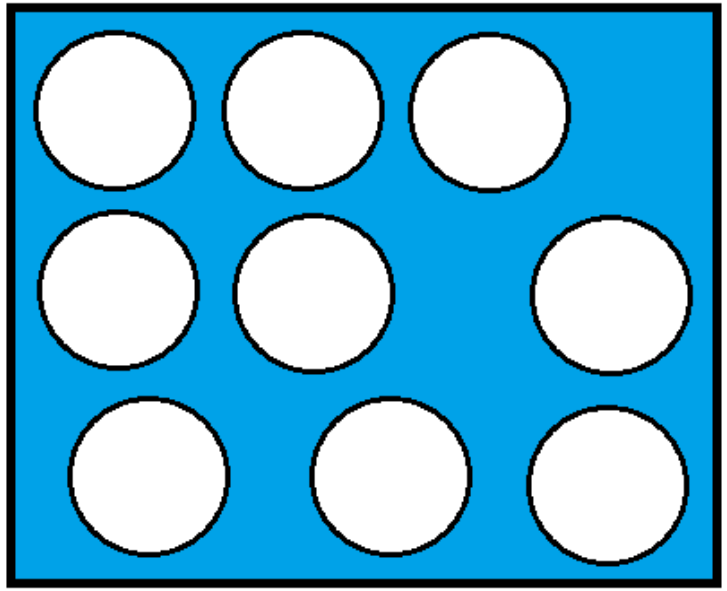
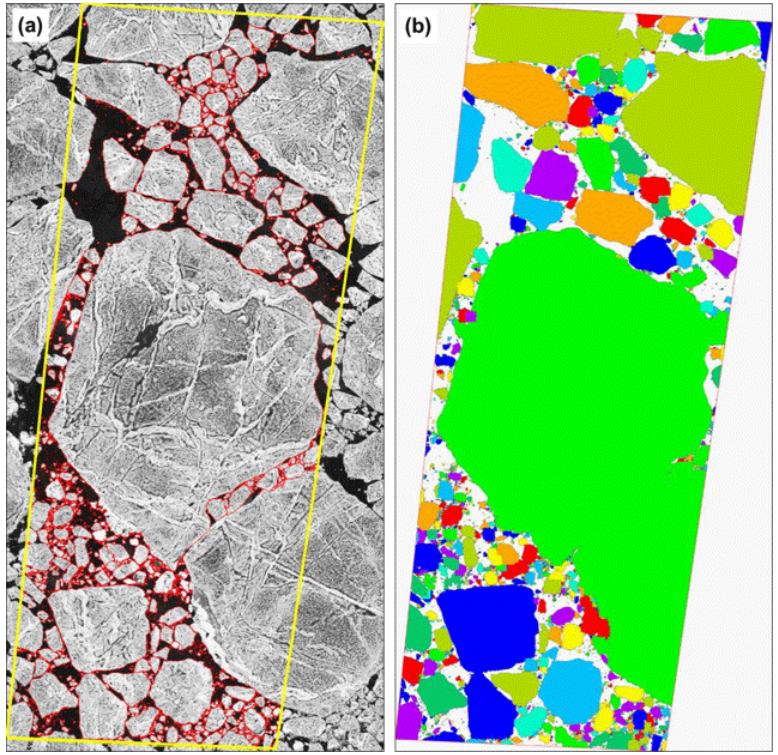
Sea ice is composed of discrete units called floes

sea ice floes in models



observations of sea ice floes



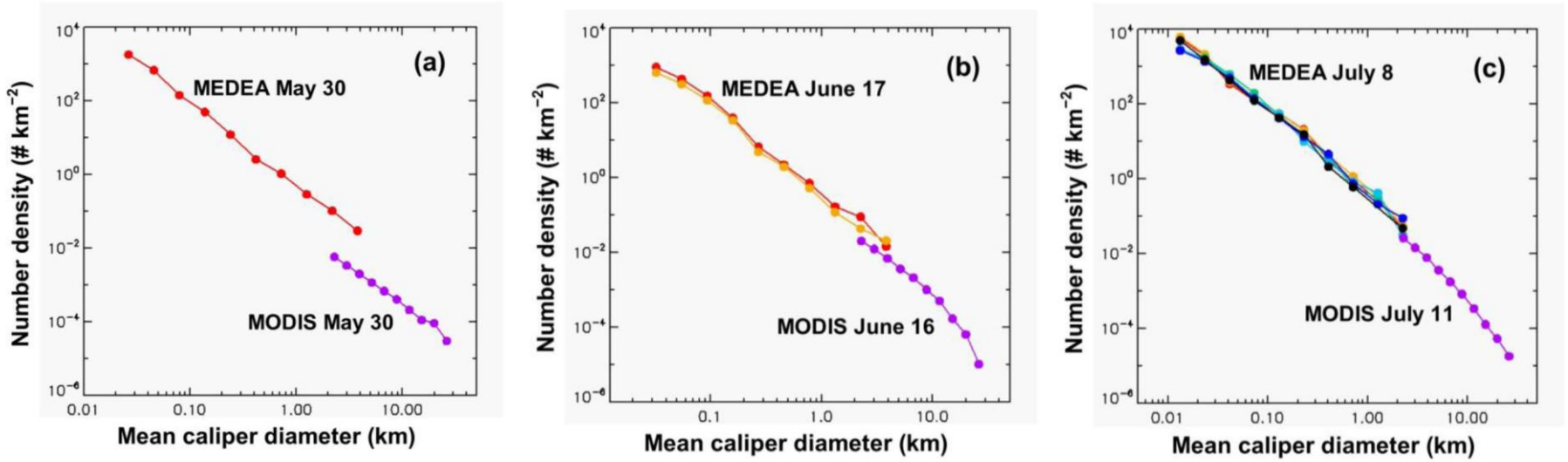
Plot on right obtained from: Stern, Harry L., Axel J. Schweiger, Margaret Stark, Jinlun Zhang, Michael Steele, and Byongjun Hwang. "Seasonal evolution of the sea-ice floe size distribution in the Beaufort and Chukchi seas." Elem Sci Anth 6, no. 1 (2018). Plot reproduced under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

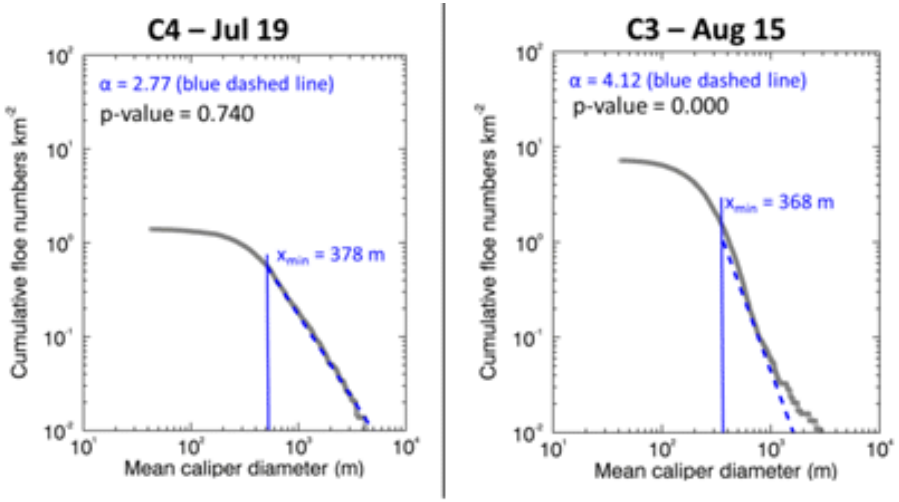
Currently sea ice models mostly assume a constant floe size.

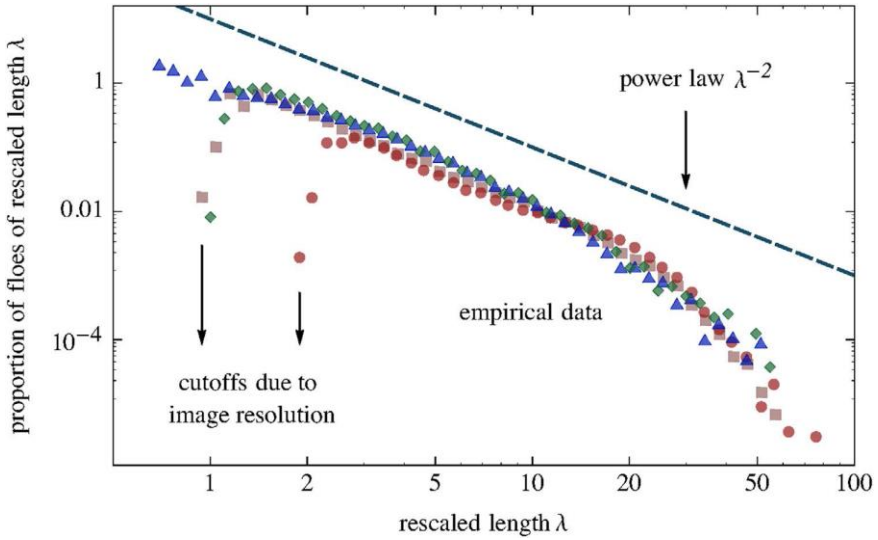
Floe size is important for several processes:

- Lateral melt volume
- Ice rheology
- Momentum transfer between the sea ice, atmosphere and ocean

Observations of the sea ice floe size distribution (FSD) are often fitted to a power law







Plots obtained or adapted from (clockwise from top left):

Stern, Harry L., Axel J. Schweiger, Margaret Stark, Jinlun Zhang, Michael Steele, and Byongjun Hwang. "Seasonal evolution of the sea-ice floe size distribution in the Beaufort and Chukchi seas." Elem Sci Anth 6, no. 1 (2018).

Gherardi, Marco, and Marco Cosentino Lagomarsino. "Characterizing the size and shape of sea ice floes." Scientific reports 5 (2015): 10226.

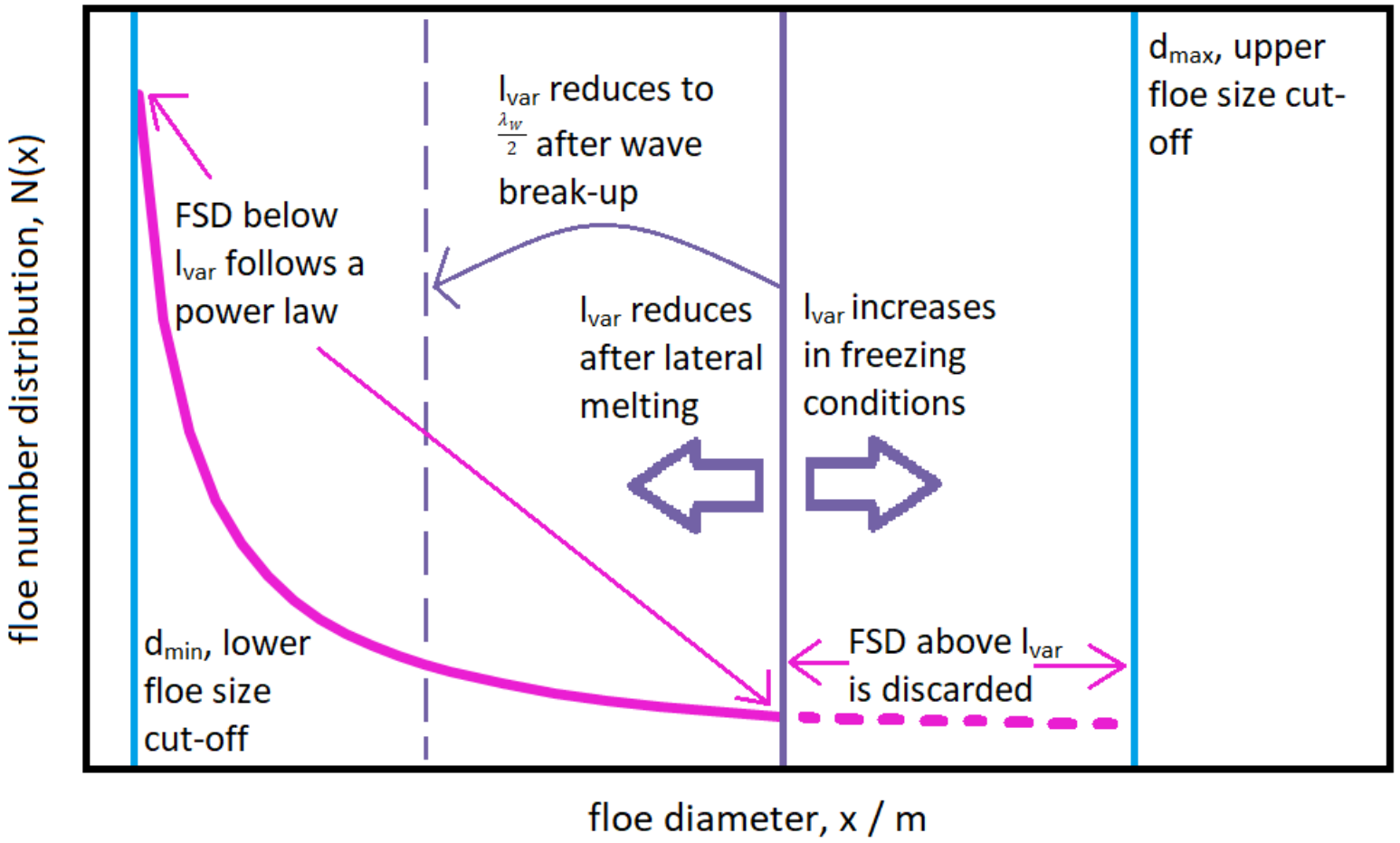
Hwang, Byongjun, Jeremy Wilkinson, Edward Maksym, Hans C. Graber, Axel Schweiger, Christopher Horvat, Donald K. Perovich et al. "Winter-to-summer transition of Arctic sea ice breakup and floe size distribution in the Beaufort Sea." Elementa Science of the Anthropocene 5 (2017).

Overview of presentation

- There have been several recent efforts to model the floe size distribution (FSD) in sea ice models such as the Los Alamos sea ice model, or CICE.
- Here we will consider and compare two different FSD models: the WIPoFSD model of Bateson et al. (2020), which assumes a power law, and the prognostic FSD model of Roach et al. (2018, 2019), which allows the shape of the FSD to emerge at process level.
- We compare the output of both FSD models to observations of mid-sized floes, and demonstrate that prognostic model performance is improved by the inclusion of brittle fracture.
- We then compare the impacts of including the two FSD models in CICE on sea ice concentration, volume, and extent metrics.
- Finally, we consider the advantages and disadvantages of the two FSD models and discuss the requirements of a full brittle fracture parameterisation.

Methods

The WIPoFSD (fitted power law) model imposes a power law onto the FSD with a fixed exponent (Bateson et al. 2020)



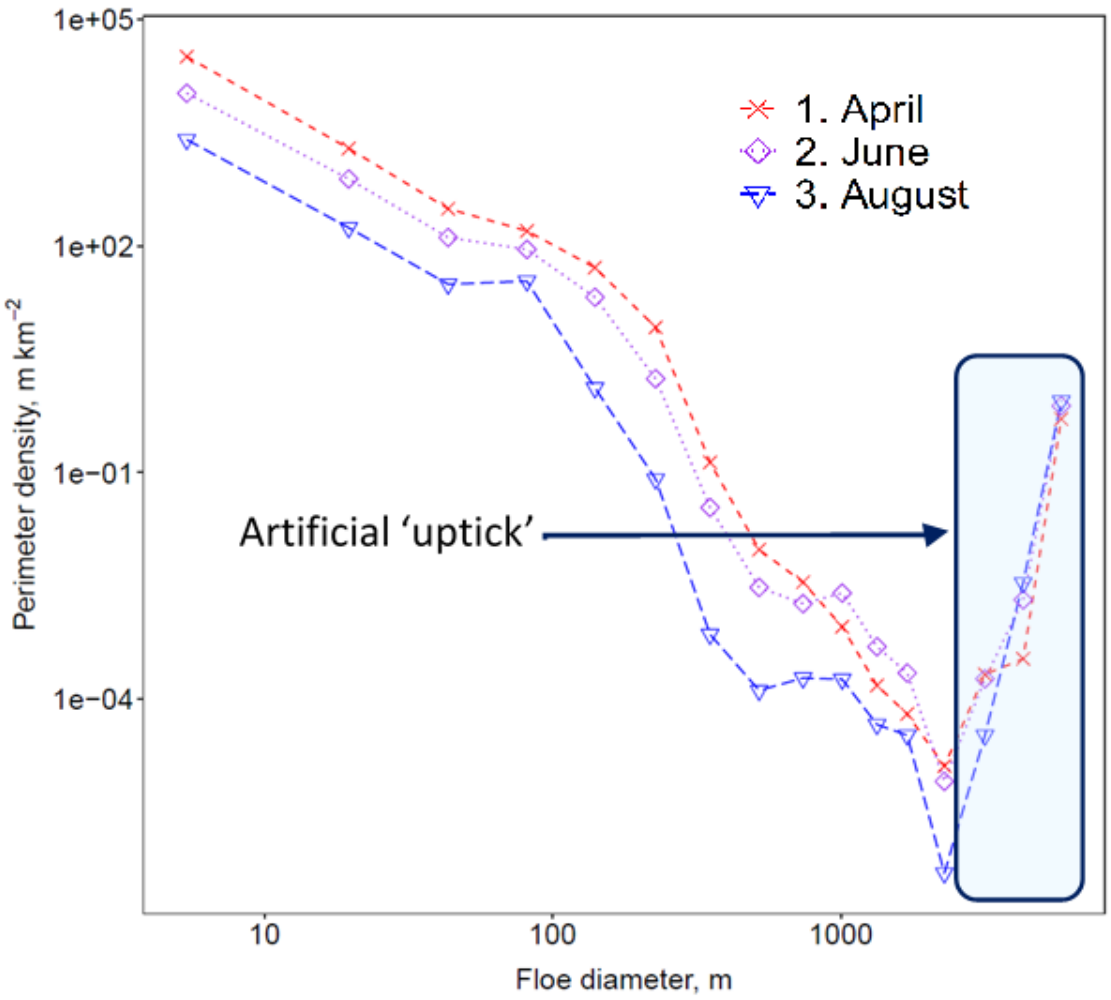
$$N(\, x \mid d_{min} \leq x \leq l_{var}\,) = Cx^{\alpha}$$

The FSD model is adapted from an implementation developed at the National Oceanography Centre of the UK (NOC). The model includes a wave attenuation and floe breakup model adapted from waves-ice model of the Nansen Environmental and Remote Sensing Centre (NERSC) Norway, details are given by Williams et al. (2013a, 2013b).

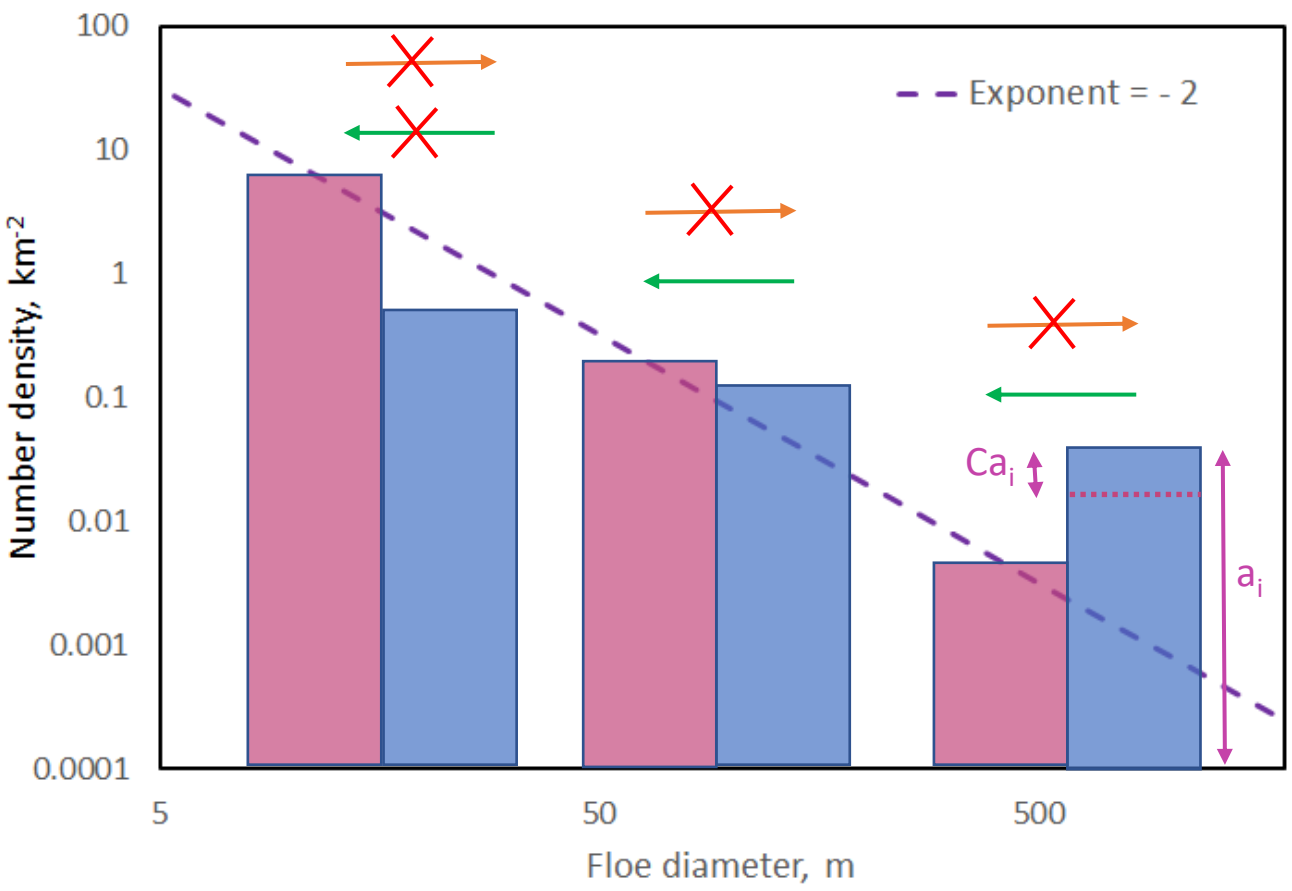
The prognostic model (Roach et al., 2018, 2019) uses an FSD that does not make assumptions about the shape of the distribution

- Model assigns sea ice area to specific floe size-thickness categories.

- Several processes are parameterised:
  - Lateral melt and growth.
  - Advection.
  - Welding together of floes.
  - Wave break-up of floes.
  - Wave dependent floe formation.
  - Brittle fracture (new).



We have introduced a new quasi-restoring brittle fracture scheme to the prognostic model

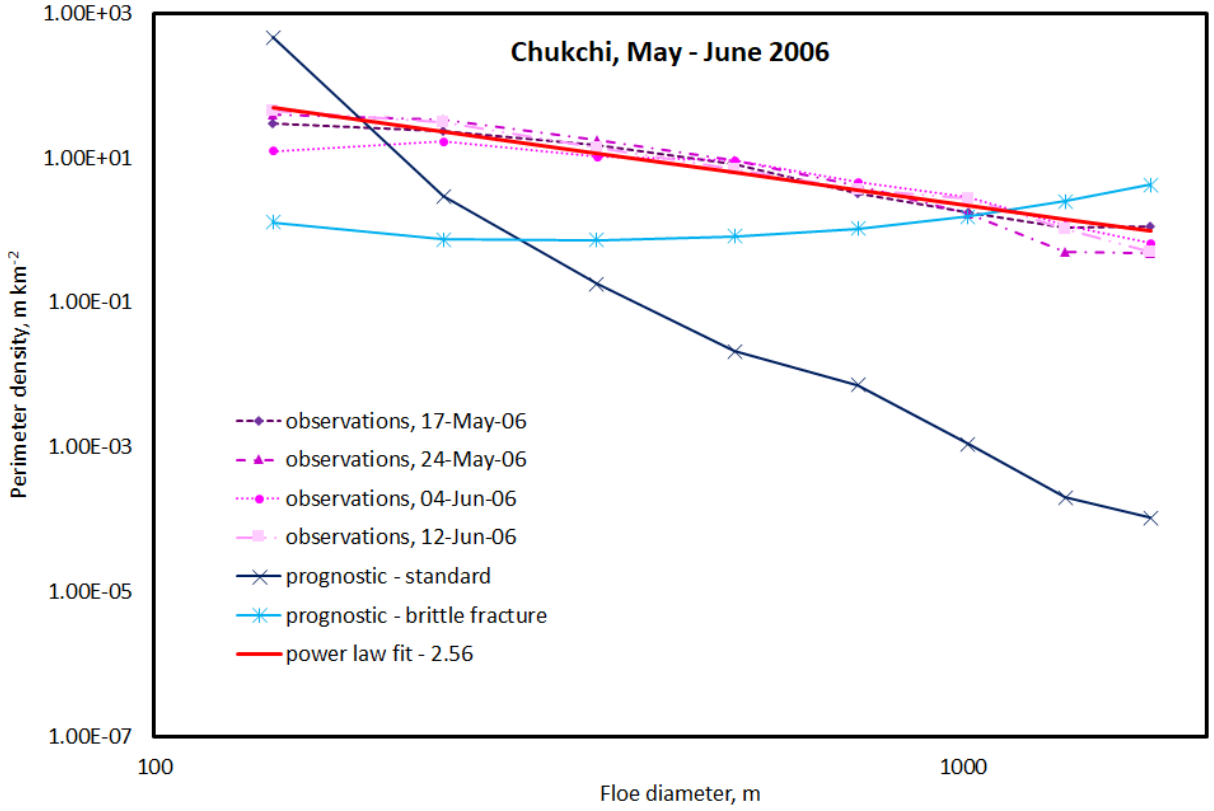


Three key components:

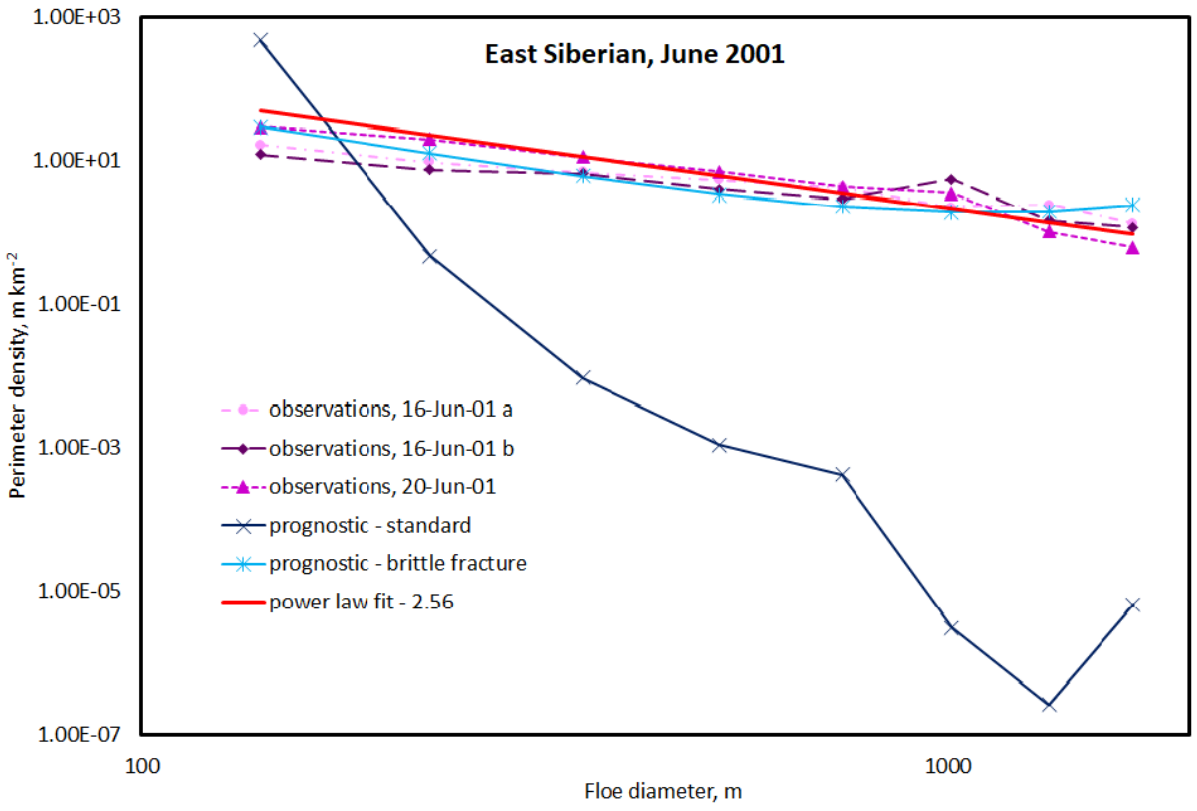
- Sea ice area fraction is only redistributed from larger categories to adjacent smaller categories.
- Sea ice area fraction is only moved between adjacent categories where the number density gradient exceeds the exponent limit of -2.
- The sea ice area distributed is Ca_i where a_i is the total sea ice area fraction in the larger category and C is the restoring constant.

The inclusion of the new breakup scheme in the prognostic model significantly improves model output compared to observations

Chukchi Sea (70 N, 170 W), May – June 2006



East Siberian Sea (82 N, 150 E), June 2001



The floe size observations used in these figures was produced by Phil Hwang (University of Huddersfield) using the methodology of Hwang et al. (2017). The exponent of the power law fit was calculated by Yanan Wang (UoH) using the methodology of Virkar and Clauset (2014).

Model setup for comparison

- CPOM CICE-ML-FSD is a version of CPOM CICE with:
  - prognostic Mixed Layer (ML) [Petty et al., 2013]
  - form drag [Tsamados et al., 2014]
  - *either* **WIPoFSD (power law) model** [Bateson et al., 2020]
    $d_{min} = 5.38\ \mathrm{m}$, $d_{max} = 30000\ \mathrm{m}$, $\alpha = -2.56$ (α value determined from observations)
  - *or* **prognostic FSD model** [Roach et al., 2018, 2019]
  - **reference** run uses a fixed floe size of 300 m

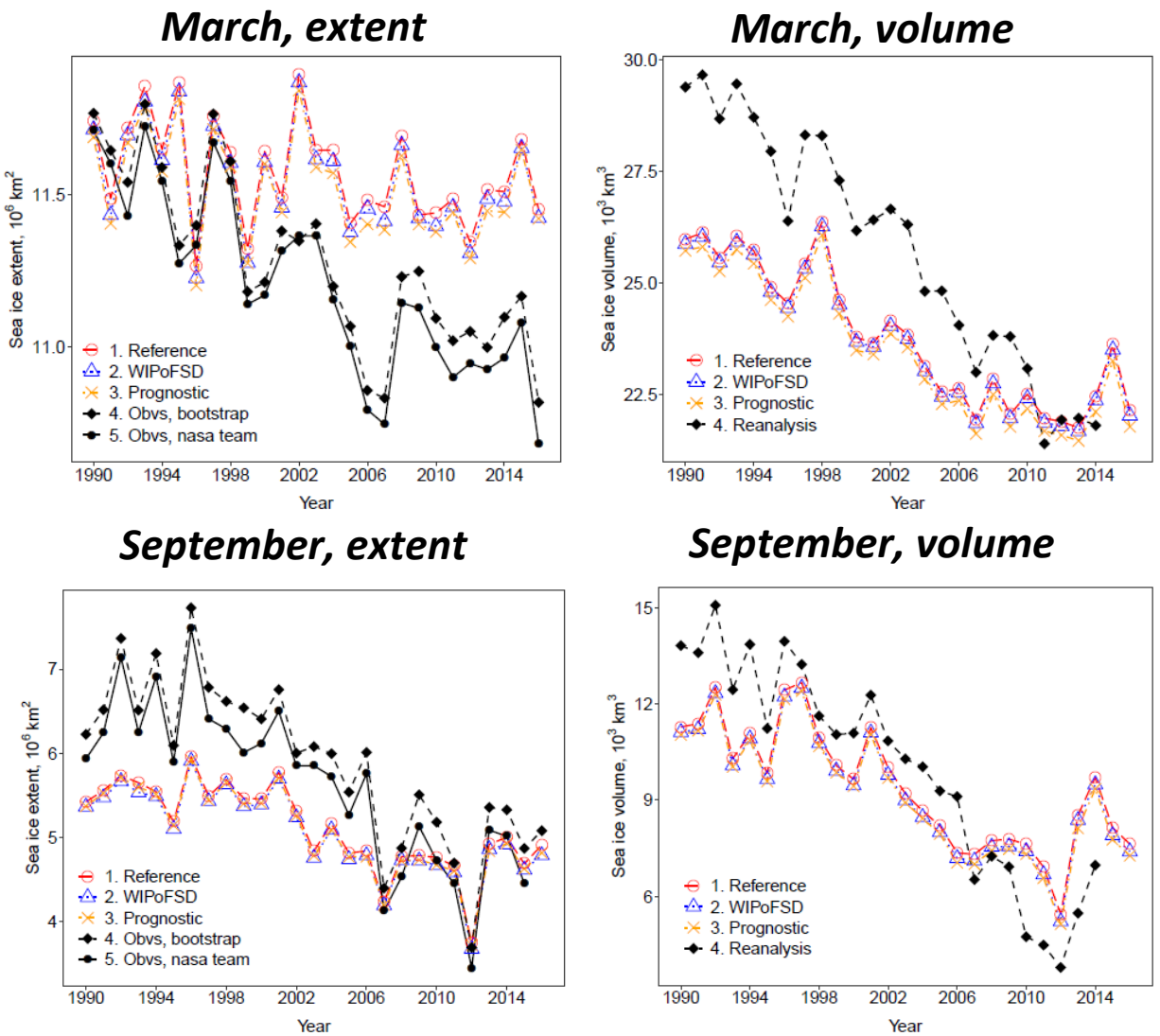
- Stand-alone, atmosphere-forced runs over Arctic Ocean.

- Spin up from 1980-1999, **analysis from 2000-2016**

Results

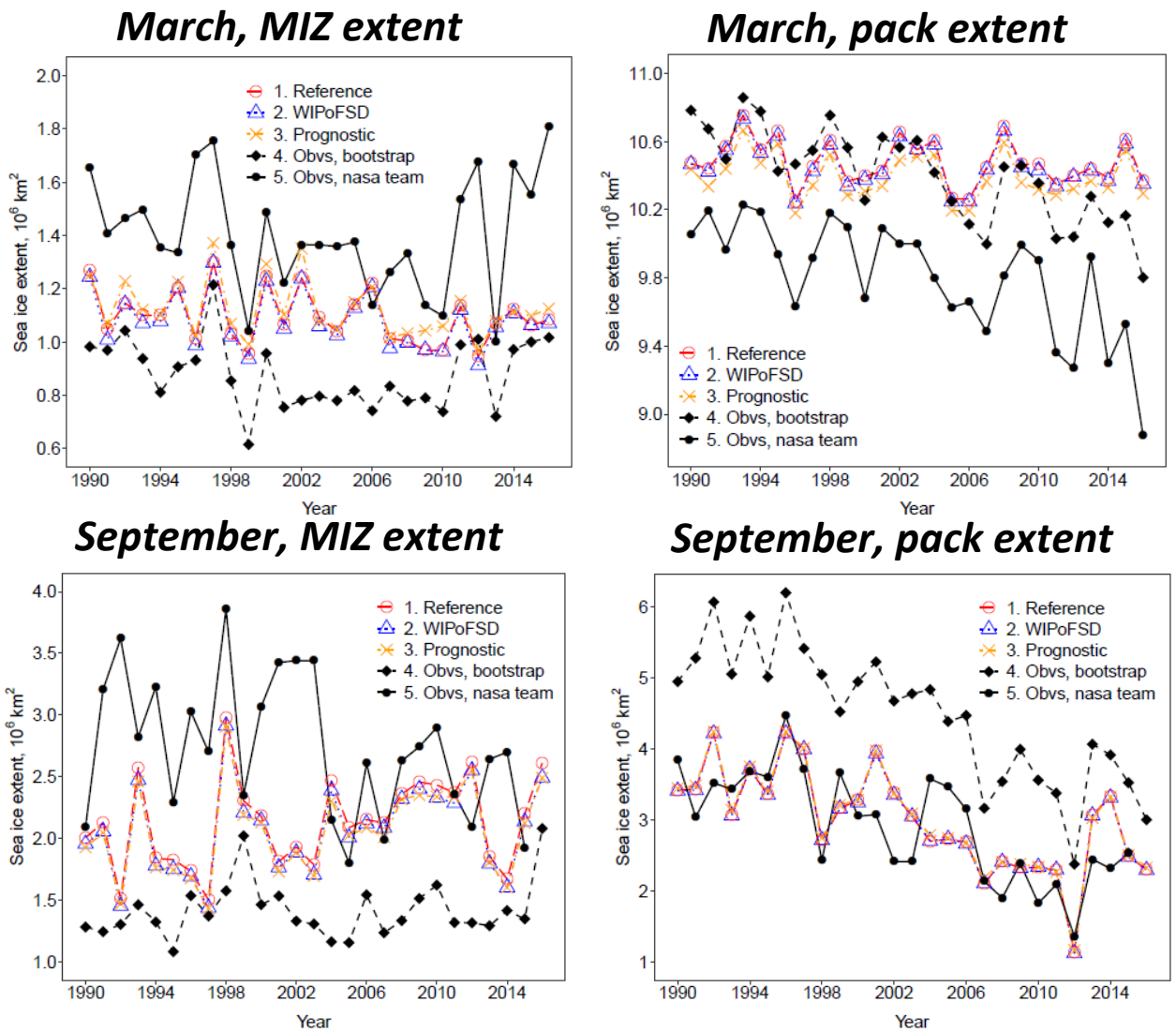
The inclusion of either FSD model does not have a large impact on the interannual variability of the sea ice extent or volume

- Comparison of total sea ice extent and volume in March and September (to represent min. and max. sea ice extent).
- Sea ice concentration data: Bootstrap algorithm v3 (Comiso, 1999) and NASA Team algorithm v1 (Cavalieri et al., 1996). Sea ice volume reanalysis: PIOMAS (Zhang and Rothrock, 2003).
- The inclusion of either FSD model in CICE does not demonstrate a clear improvement in capturing observations.

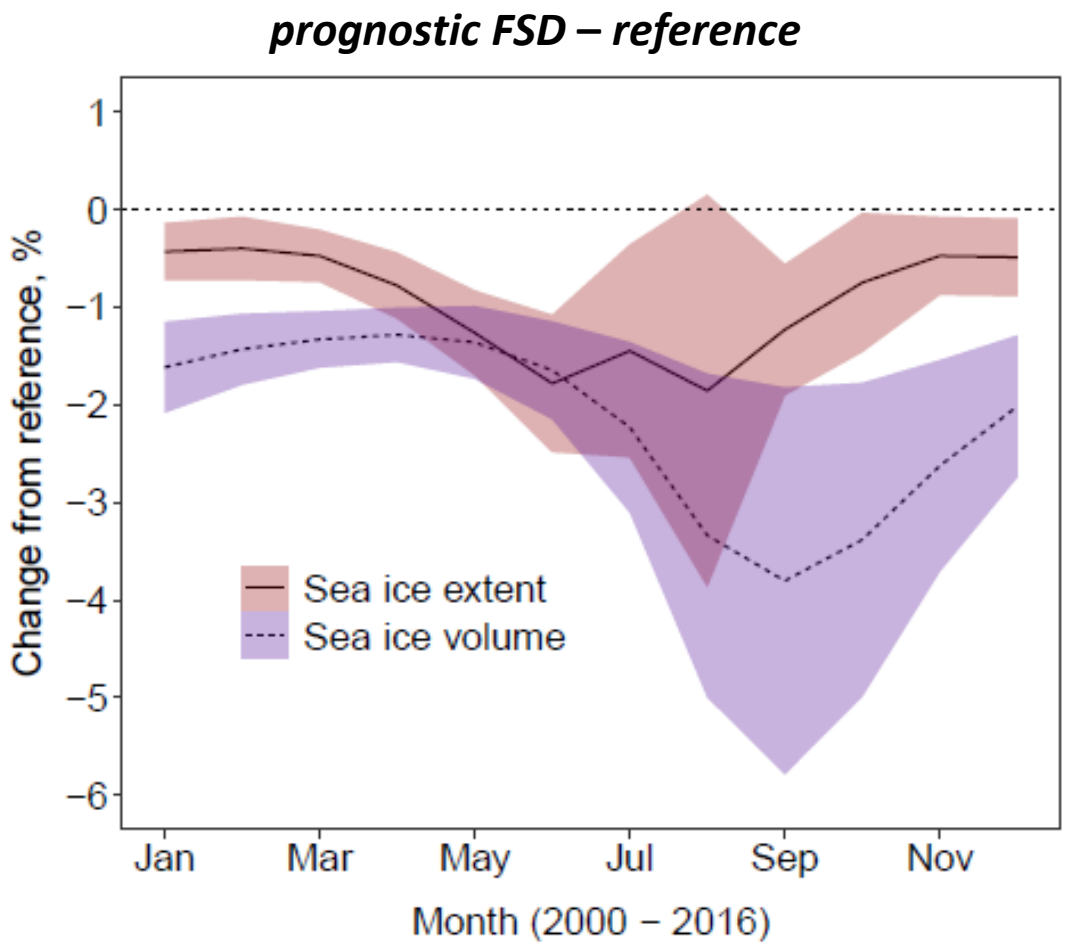


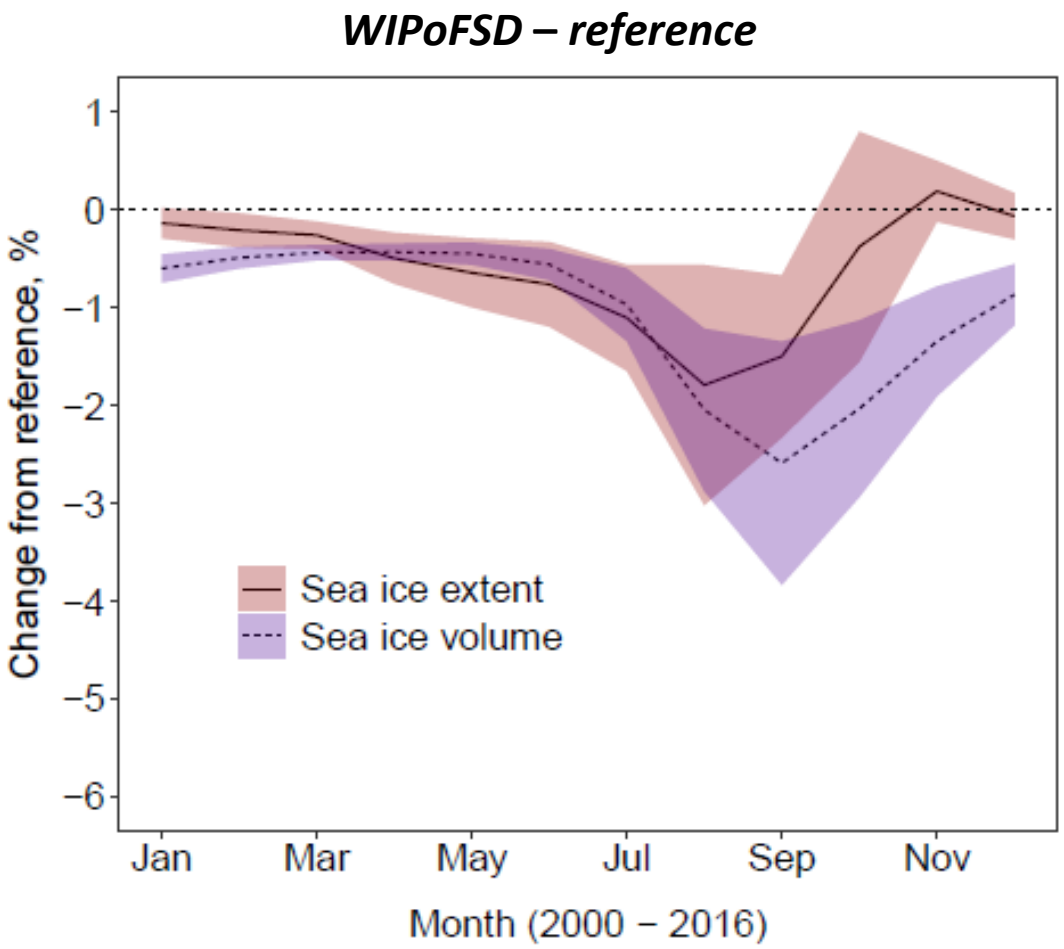
It is challenging to assess regional impacts of the FSD model (e.g. within the MIZ) due to high observational uncertainty

- Comparison of MIZ and pack sea ice extent in March and September (to represent minimum and maximum sea ice extent).
- Inclusion of FSD processes in CICE results in changes to extent metrics of order 0.1 x 10^6 km^2.
- All three simulations simulate pack and MIZ extent within large uncertainty of observations.



The prognostic model has a larger impact on the total sea ice mass balance compared to the WIPoFSD model

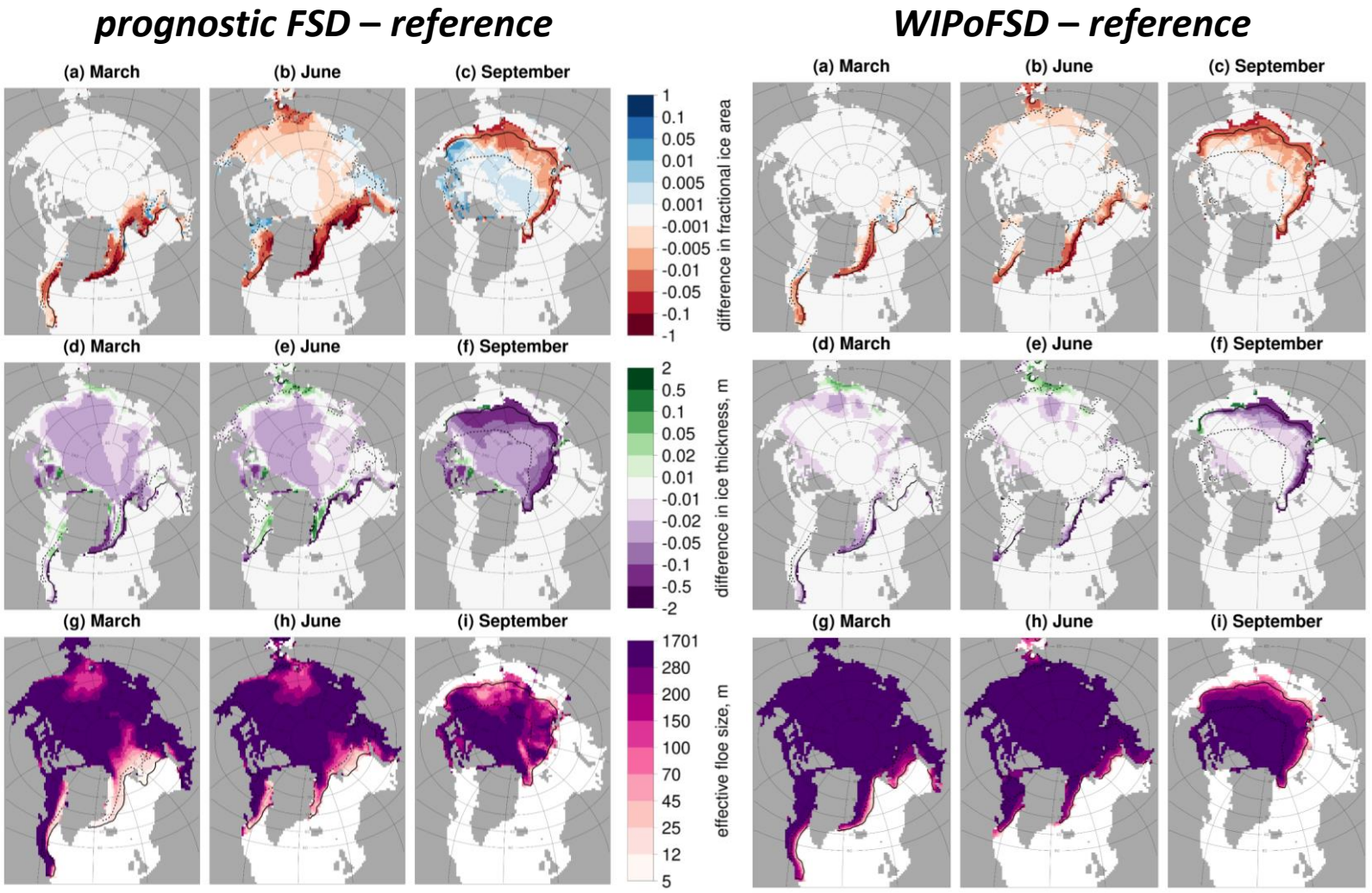




Plots show the difference in the sea ice extent and volume for simulations with an FSD model compared to simulations without.

The prognostic model has a less homogeneous impact on the sea ice extent and thickness compared to the WIPoFSD model

- Effective floe size (l_{eff}) = single floe size with the same perimeter density as the FSD.
- Both FSD models produce significant reductions in the MIZ sea ice thickness, particularly in September.
- The prognostic FSD model shows a higher differentiation between the MIZ and pack ice impacts.
- The different spatial impacts of the FSD models can be linked to the larger spatial variability in effective floe size for the prognostic model.



Discussion and Conclusions

Requirements for a future parameterisation of brittle fracture

- Quasi-restoring approach used here significantly improves prognostic model output compared to observations and is based on idealised models of brittle fracture.
- However, the scheme effectively represents two mechanisms: fracture events in winter, and melting and fragmentation of floes along existing cracks and weakness during the melting season.
- These two mechanisms will occur over different timescales and scale with different processes.
- The winter fracture mechanism is fast and expected to depend on sea ice strength and stress.
- The summer breakup mechanism is slower and expected to depend on several factors including melt rate, melt pond formation, and the distribution of surface cracks from winter fracture events.
- Direct observations of these processes are required to enable a better characterisation of the timescales and dependencies for each.

Advantages and disadvantages of the power law and prognostic FSD models

Power law FSD model

Simple model – easier to constrain mechanisms that cause the impacts.

Can be easily tuned to observations.

Computationally efficient.

Power law not valid across all floe sizes (Horvat et al., 2019).

Observations suggest that exponent is not fixed but varies over both spatial and temporal scales (Stern et al., 2018).

Prognostic FSD model

The impact of processes on the FSD can be represented in a physically realistic manner.

Able to capture more variability in FSD processes across the sea ice cover.

Can only produce a physically realistic distribution if all relevant processes are included in the model; this is not true for current FSD models.

Model is computationally expensive – standard setup uses 60 new floe size-thickness categories.

Conclusions

- The observations considered here suggest that the assumption of a power law with a fixed exponent is a reasonable assumption for mid-sized floes.
- The inclusion of a simple brittle fracture scheme significantly improves prognostic model performance, motivating the need for a full parameterisation of brittle fracture.
- Neither FSD model produces a significant impact compared to observations over a pan-Arctic scale, but larger and distinct impacts can be seen over more regional scales.
- The effective floe size is a useful way to characterise the FSD and understand how differences between FSD models emerge.
- There are clear advantages and disadvantages to each modelling approach and the preferred FSD model will depend on the application.

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