Modelling the Arctic wave-affected marginal ice zone, comparison with ICESat-2 observations

Guillaume Boutin[1], Timothy Williams[1], Christopher Horvat[2], Laurent Brodeau[3]

And also the NERSC SIM group and all the people at LOPS I have worked with on wave—sea ice modelling

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2. Brown University, Providence
3. CNRS, Institut de Géophysique de l'Environnement, Grenoble, France

NERSC

SASIP

SCHMIDT FUTURES

Outline

Introduction

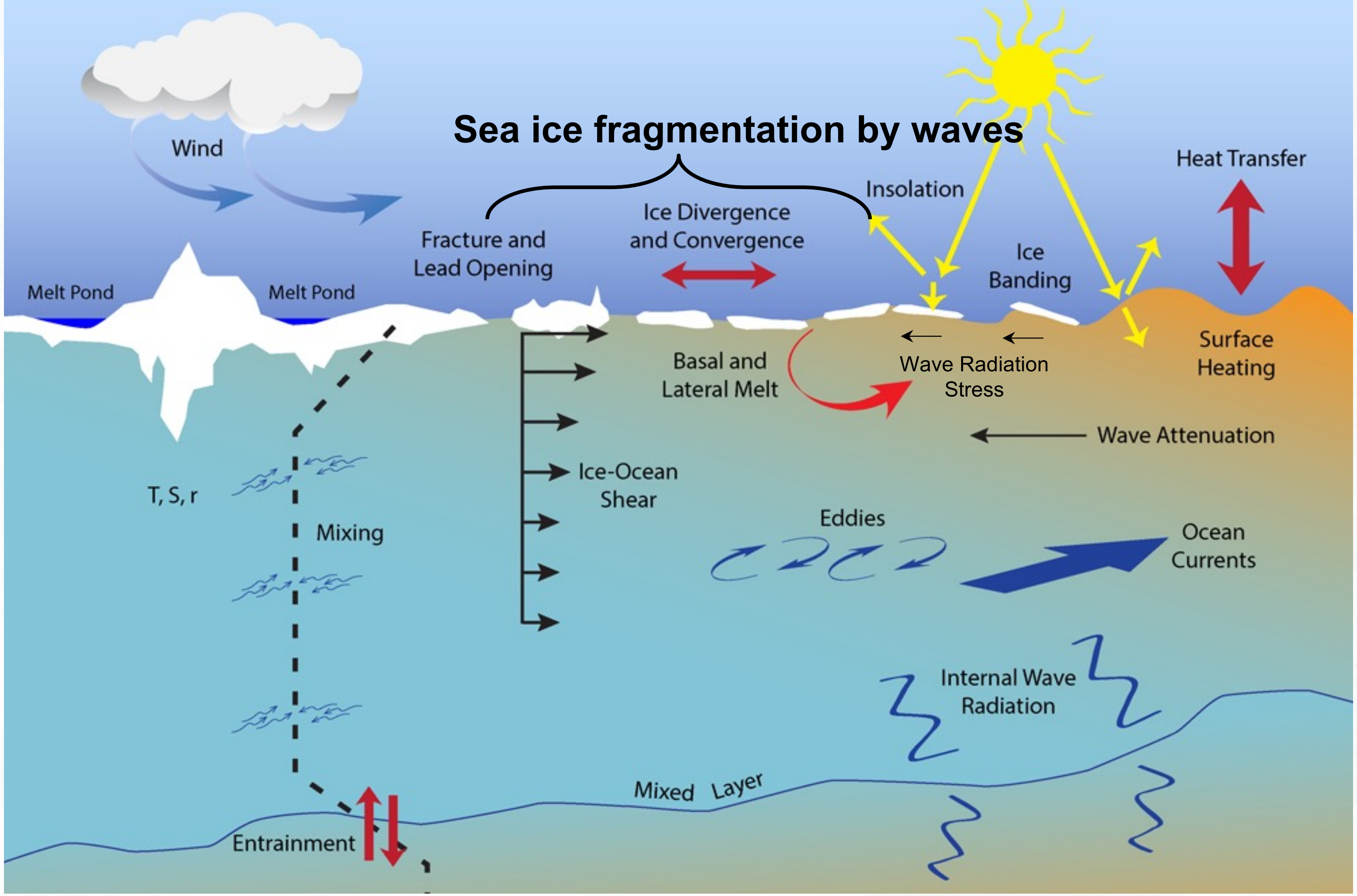
I) Investigating wave impact on sea ice in a coupled wave—sea-ice model

- Introduction to the coupled neXtSIM-WW3 model
- Case study in the Barents Sea

II) Evaluation of the wMIZ extent using ICESat-2

- Introduction to the ICESat-2 Dataset
- Comparison Model/Obs
- Discussion

Introduction



Credits : APL, Univ. of Washington

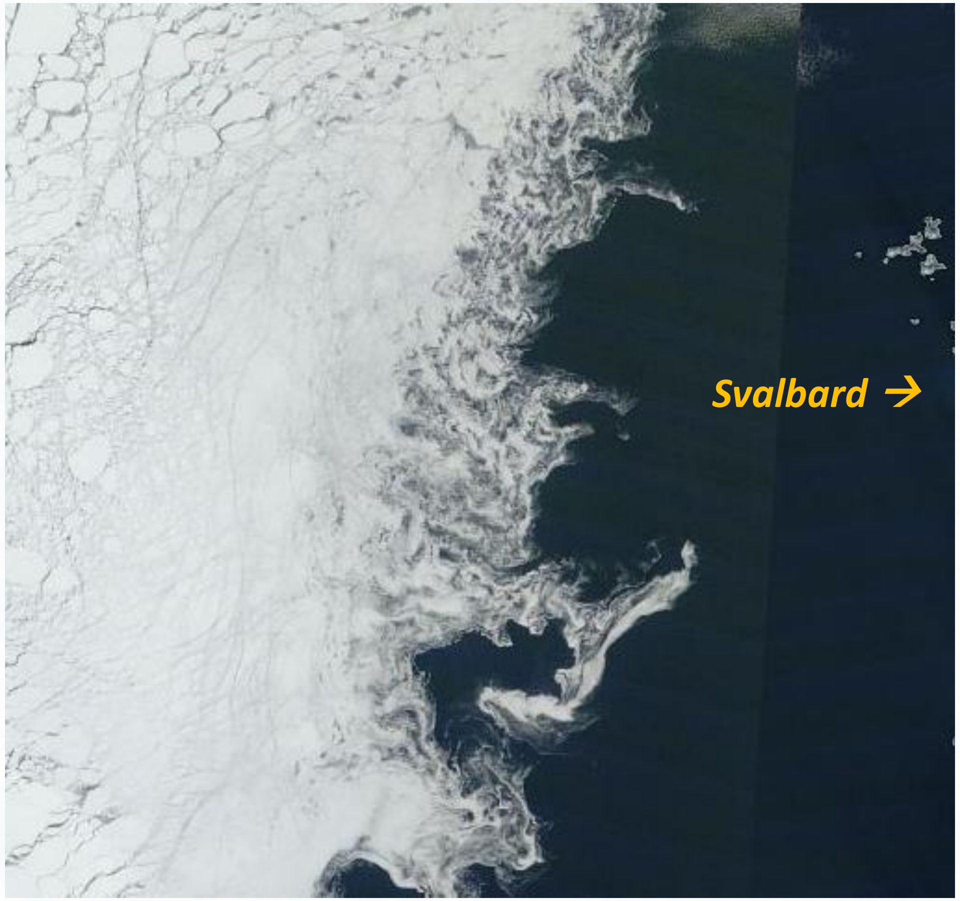
Waves are attenuated by sea ice

Waves break the ice cover into floes : O(10)→O(100) metres

With the decrease in sea ice extent, **impact of waves on sea ice is expected to grow in the XXI^th century**

Introduction

Example of a potential impact:



Aqua/MODIS corrected reflectance images. 15/09/2015, North of Svalbard (worldview.earthdata.nasa.gov)

Manucharyan and Thompson (2017):

Eddies → export sea ice to the open ocean
IF the eddy-induced stress **>** ice resistance to deformation

Sea ice resistance to deformation is low for:

- Low-concentration → in models
- Fragmented sea ice → not in models

Why:

- Very few data
- No wave-sea ice coupled models (until 2019/2020)

Can we estimate the impact of waves on sea ice dynamics in the MIZ, using a wave—ice coupled model ?

Wave impact on sea ice in coupled wave—sea-ice model

A bit of context: previous wave—sea ice work at NERSC (2020—2021)

The Cryosphere

Wave–sea-ice interactions in a brittle rheological framework

Guillaume Boutin[1], Timothy Williams[1], Pierre Rampal[2,1], Einar Olason[1], and Camille Lique[3]

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European Geosciences Union

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Sea ice model: neXtSIM

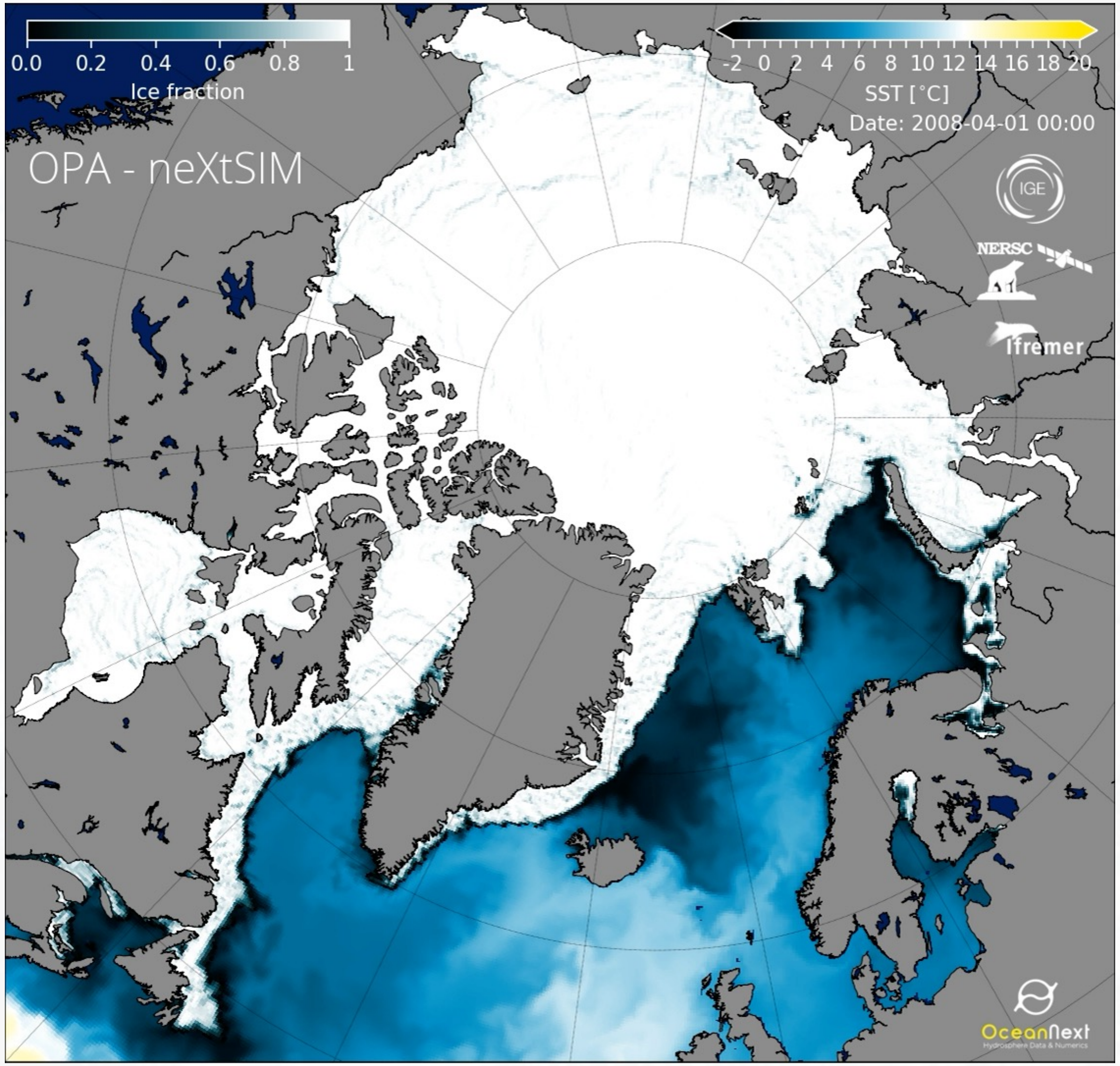
Introducing with an example:

- 2008 simulation using neXtSIM (Jan→Jul)

- 12km resolution in the Arctic

- Lots of leads! (uncommon in sea ice models at these resolutions)

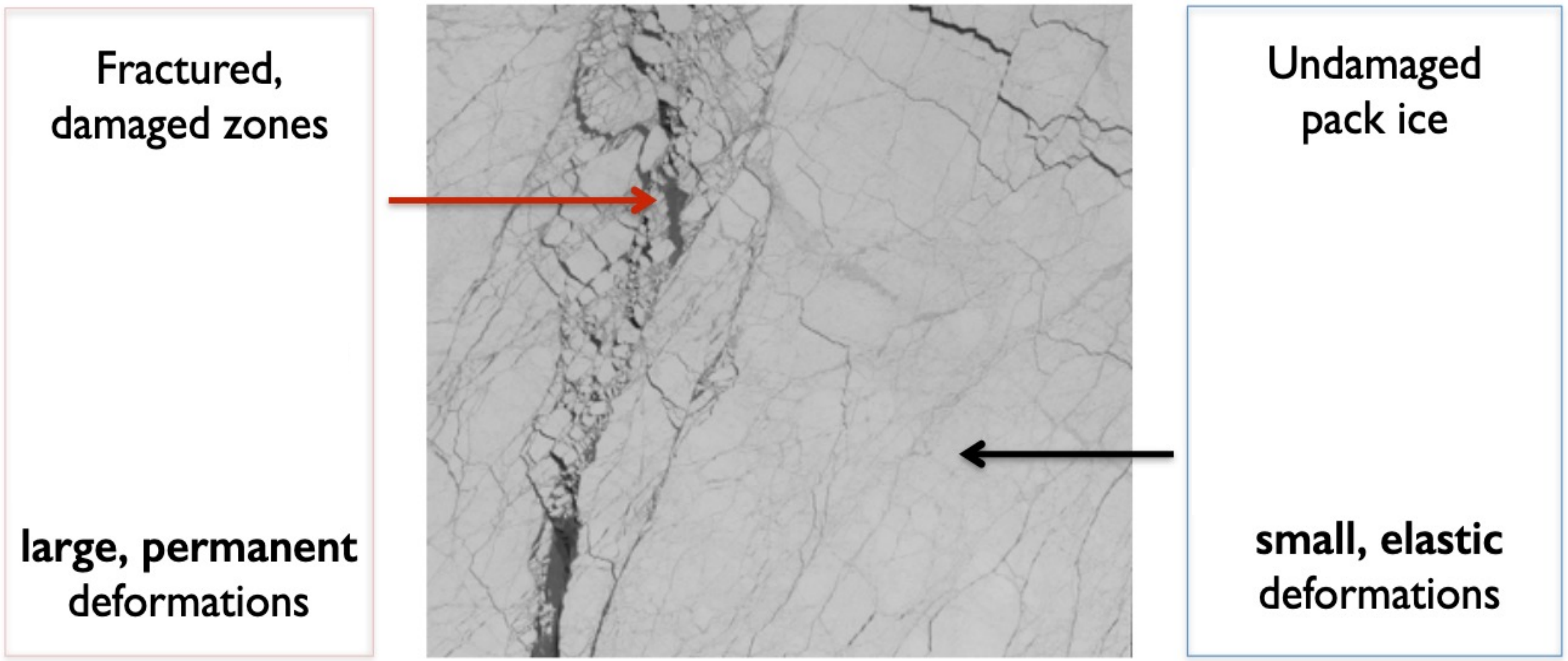
How do we get leads at 12km resolution?



Plotting tools: L. Brodeau

Sea ice model: neXtSIM

neXtSIM uses a brittle rheology = includes damage quantity

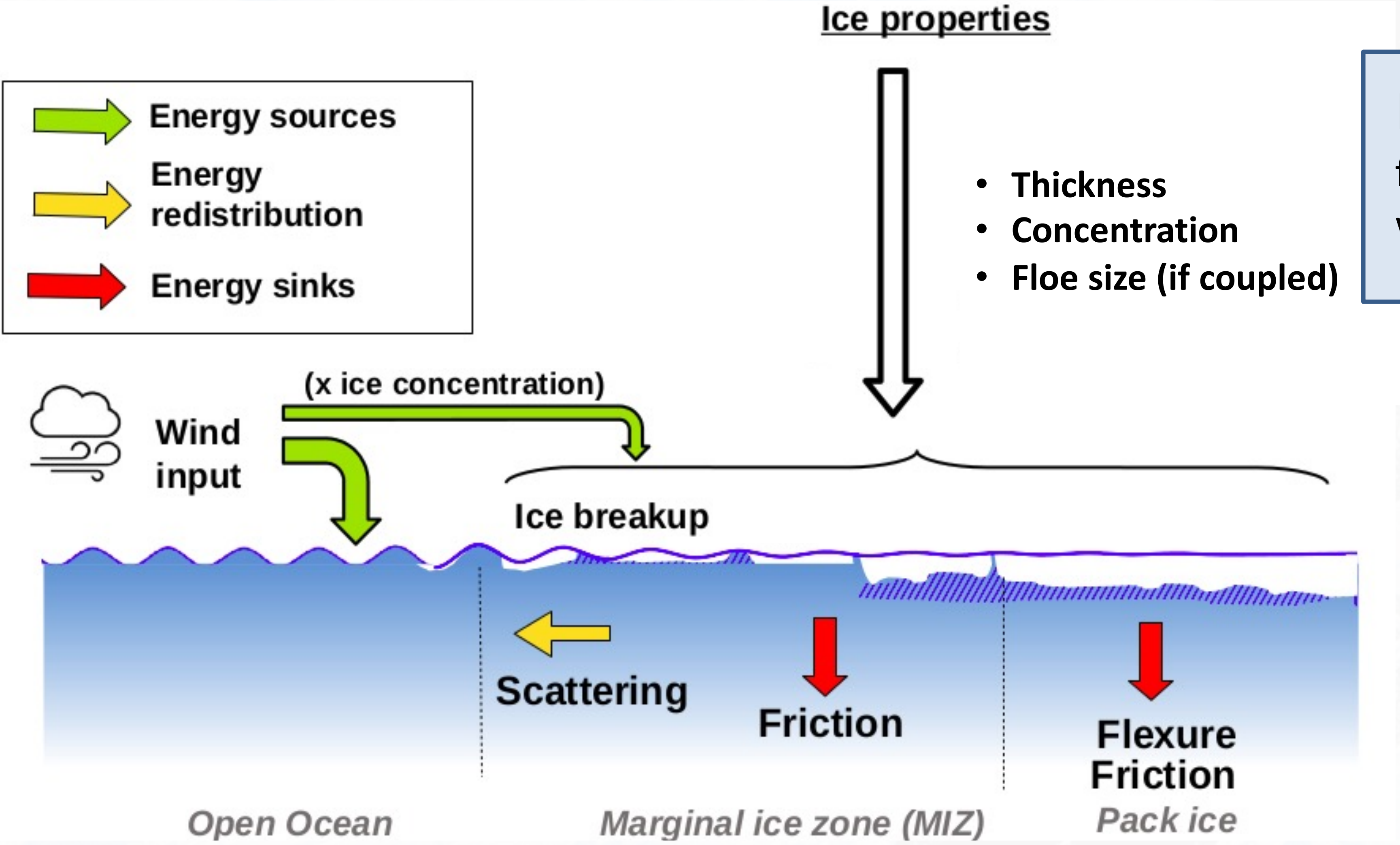


Ice damage is a quantity defined between 0 (undamaged ice) and 1 (damaged)

When damage is maximum, internal stress → 0

Figure taken from Dansereau (2016)

Wave model: WAVEWATCH III

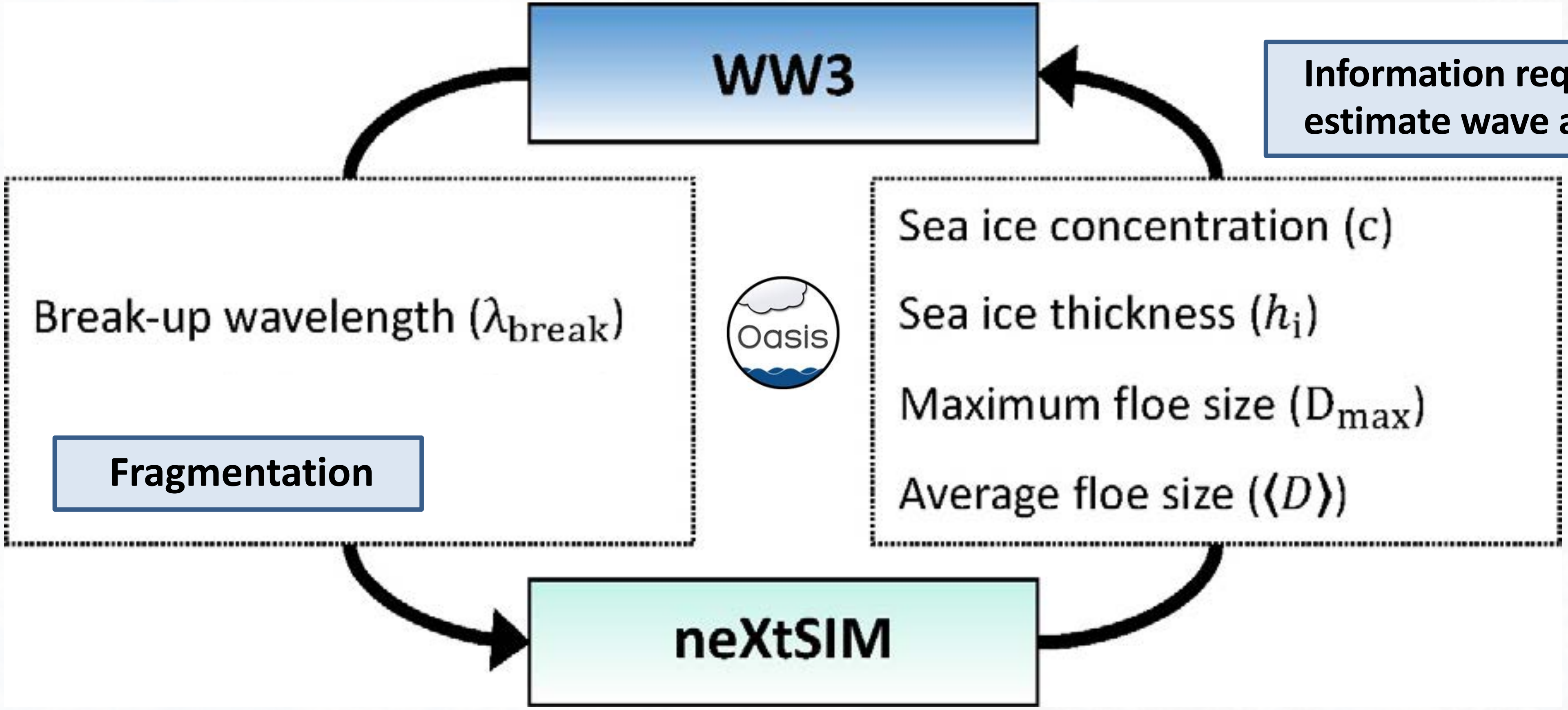


Main features:

feedbacks between floe size and wave attenuation → λ_{break}

Boutin et al. (JGR, 2018)

The coupled framework

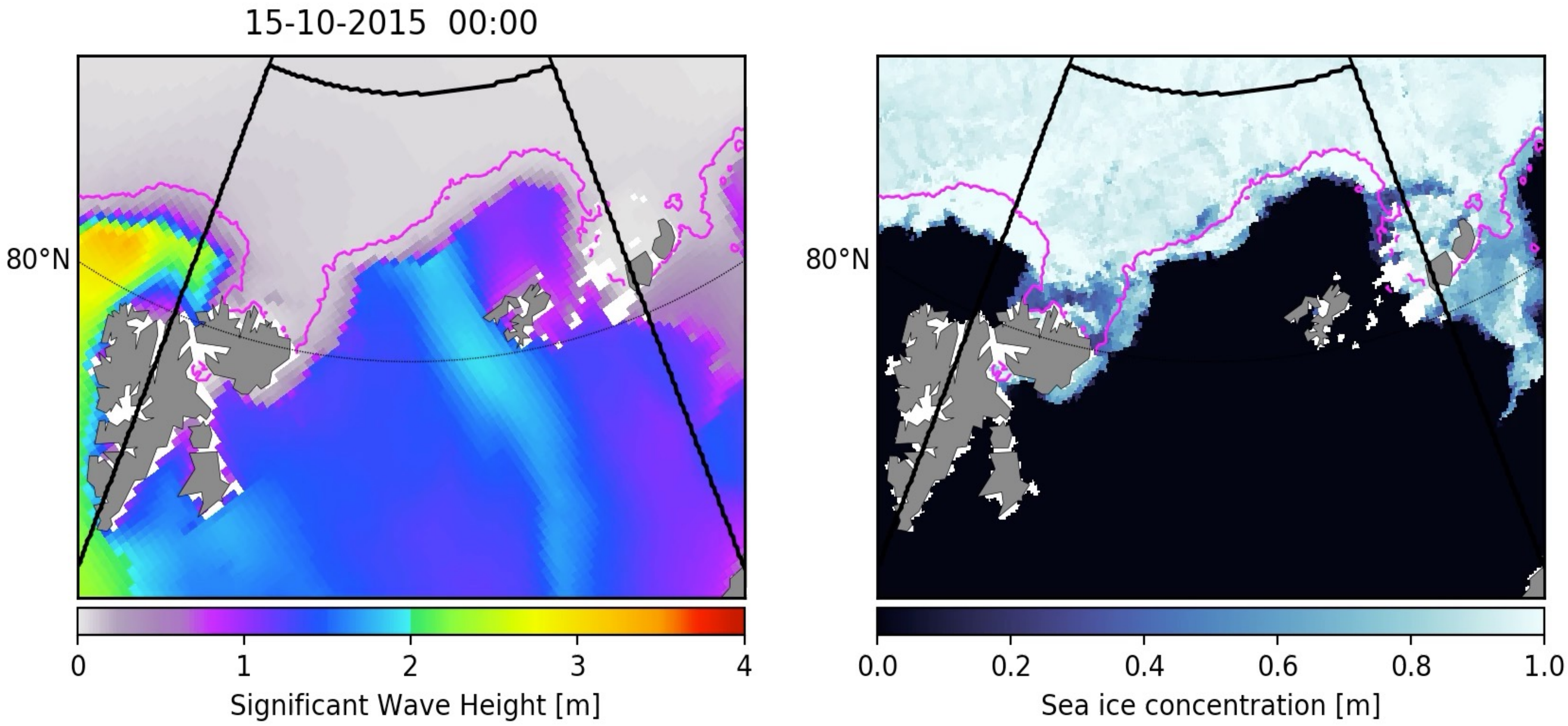


Information required to estimate wave attenuation

Update of floe size +
impact on sea ice momentum equation:
if ice is broken, damage increases

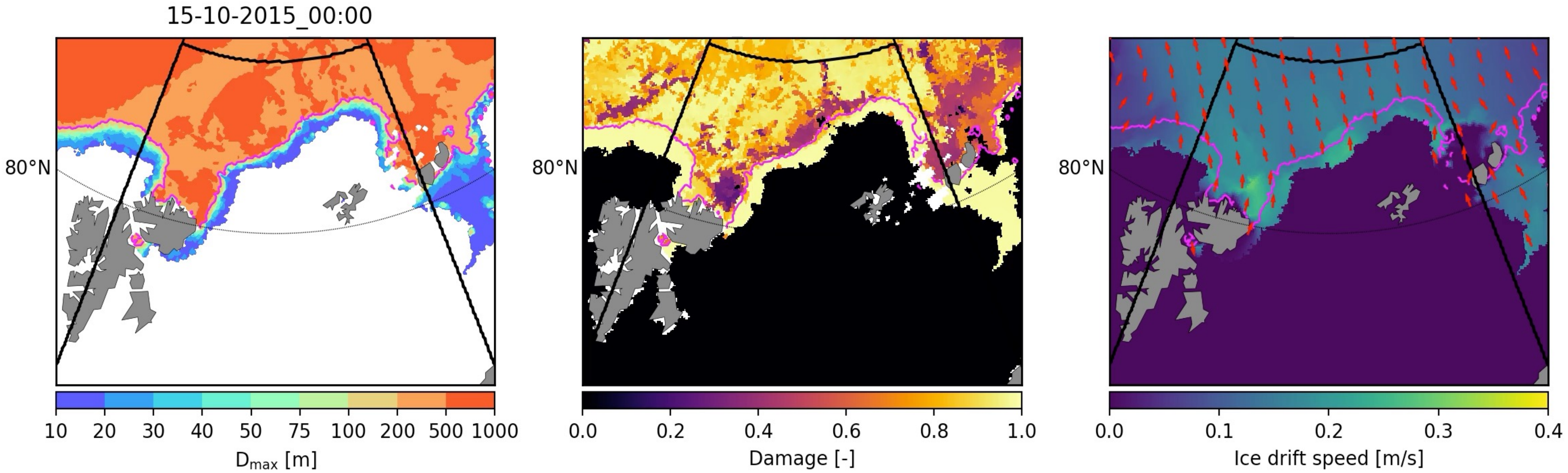
Barents Sea case study

A storm in October 2015



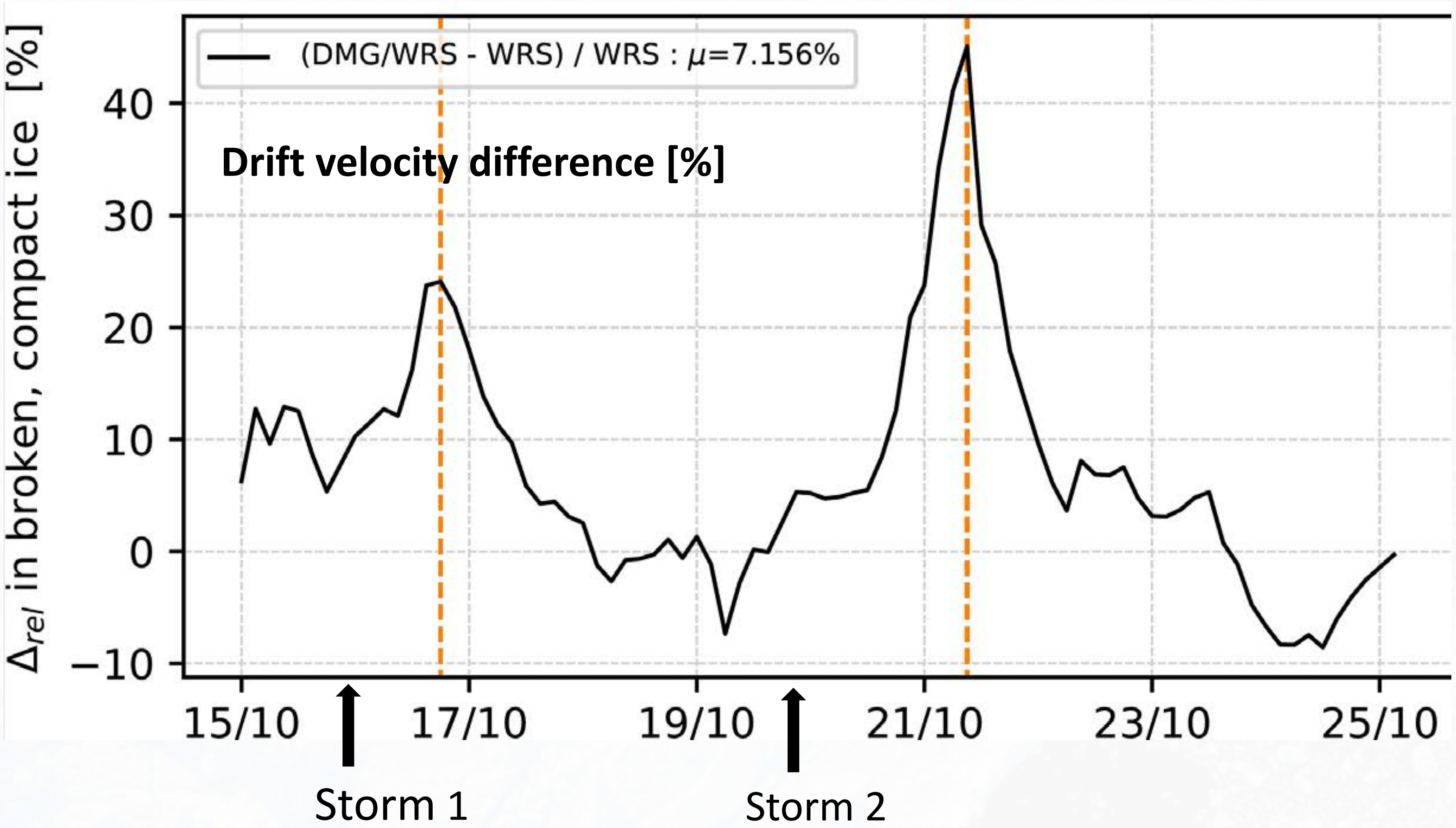
Barents Sea case study

Evolution of the MIZ during this storm



Barents Sea study case

Impact on sea ice dynamics: 2 simulations



DMG: coupled simulation with damage/fragmentation link

WRS : coupled simulation, no link damage/fragmentation

Fragmentation increases the mobility of compact and broken sea ice after extreme events

Conclusion Part I

- Assuming fragmentation reduces sea ice resistance to deformation, we estimated the impact of waves on sea ice dynamics in the MIZ.

- We find that **waves can significantly increase the mobility of thick/compact sea ice, particularly in the wake of a storm.**

Waves make the impact of storms on sea ice drift last longer, over a larger area. This area depends on how far waves can propagate into the ice cover.

Part II: Evaluating the extent of the wMIZ

- The magnitude of wave impact on sea ice mostly depends on how far they travel into the ice cover **→ the wMIZ***

- A good wave-in-ice model investigating this impact should therefore ensure the wMIZ extent is right, but **observations** mostly come from *in-situ* campaigns:

Observations of the wMIZ are rare, localized in time and space

***wMIZ = MIZ definition based on how far waves travel in ice**

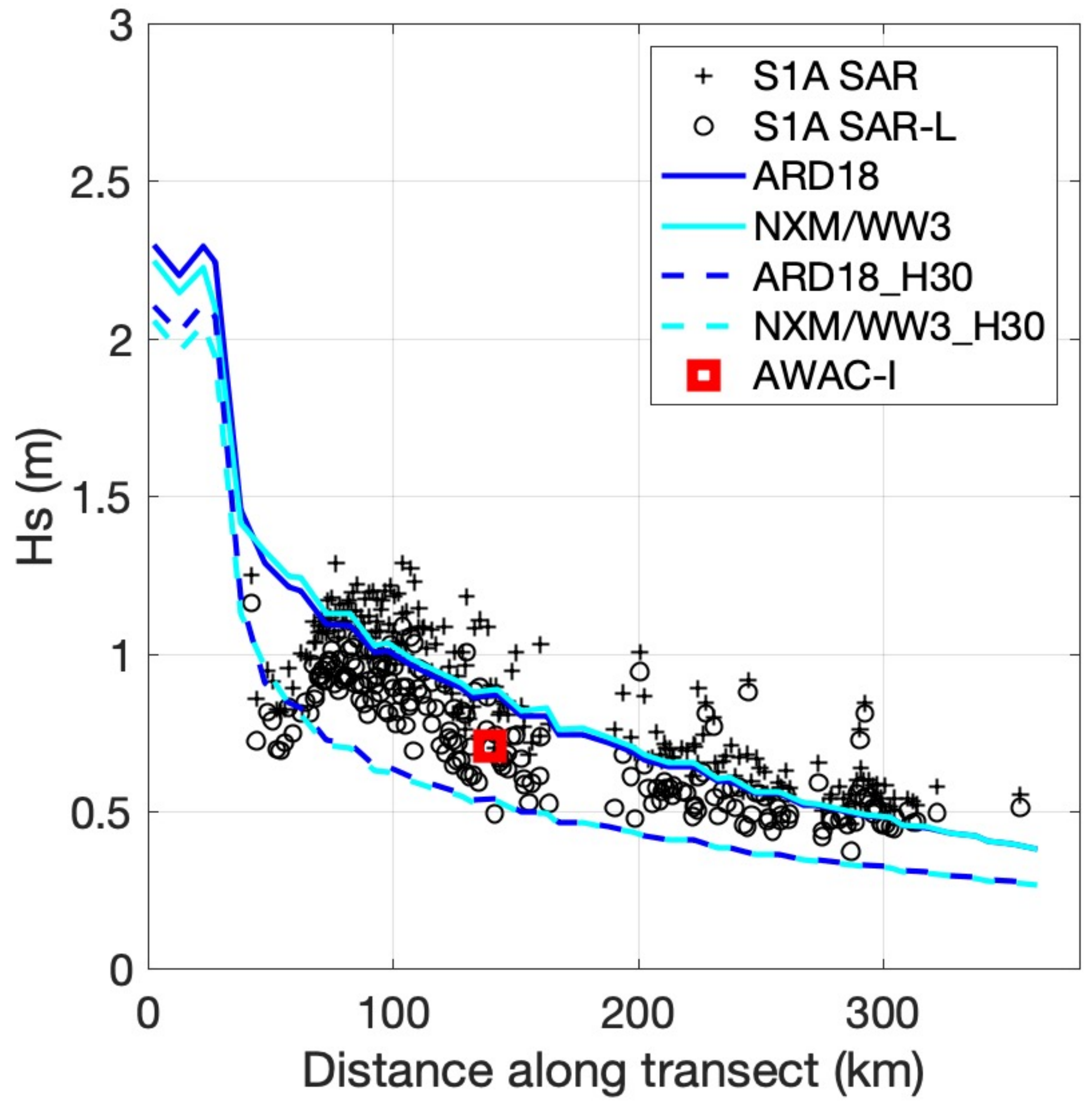
Part II: Evaluating the extent of the wMIZ

- **Our model, evaluated in the Beaufort sea***

- Good agreement for **broken sea ice extent** with SAR
- Good agreement for **Hs with all buoys + SAR**
- What about other regions, other seasons?

Ideally, we would use remote sensing to evaluate the wMIZ.

*Following Ardhuin et al., 2018, JGR Oceans



Part II: Evaluating the wMIZ extent

NERSC

Here comes ICESat-2

Horvat et al., 2020

Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL087629

Special Section:
The Ice, Cloud and land Elevation Satellite-2 (ICESat-2) on-orbit performance, data discoveries and early science

Observing Waves in Sea Ice With ICESat-2

C. Horvat[1], Ed Blanchard-Wrigglesworth[2], and A. Petty[3,4]

[1]Institute at Brown for Environment and Society, Brown University, Providence, RI, USA, [2]Department of Atmospheric Science, University of Washington, Seattle, WA, USA, [3]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA, [4]NASA Goddard Space Flight Center, Greenbelt, MD, USA

Step 1: They divide a track (in-ice) into segments

Step 2: Is it "wave-affected"? (yes/no)

Step 3: Results are binned monthly on a 100km polar stereographic grid, compute the ratio of wave-affected segments to total number of segments

Part II: Evaluating the wMIZ extent

Here comes ICESat-2

Horvat et al., 2020

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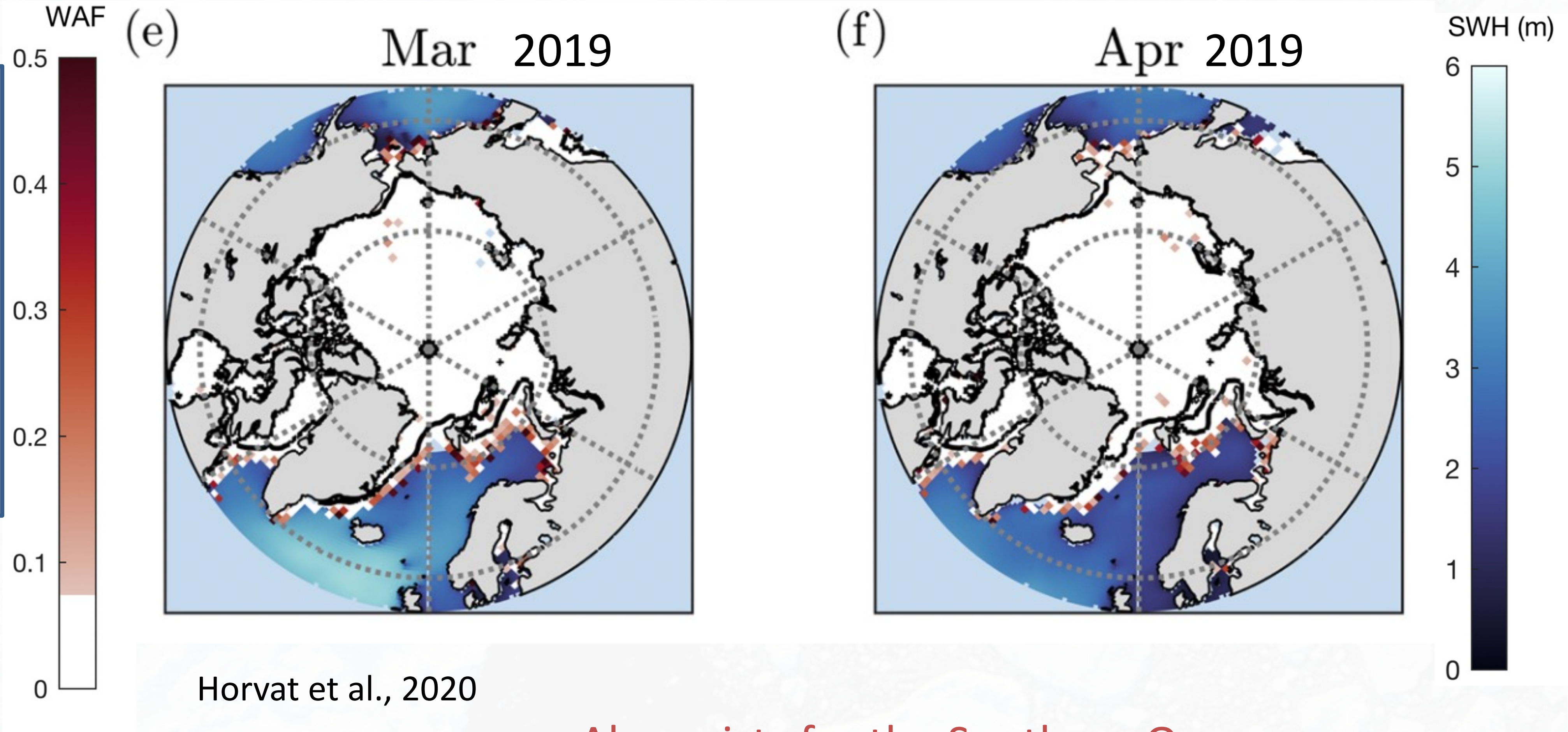
The wave-affected fraction (WAF) can be used to define the wMIZ extent

Part II: Evaluating the wMIZ extent

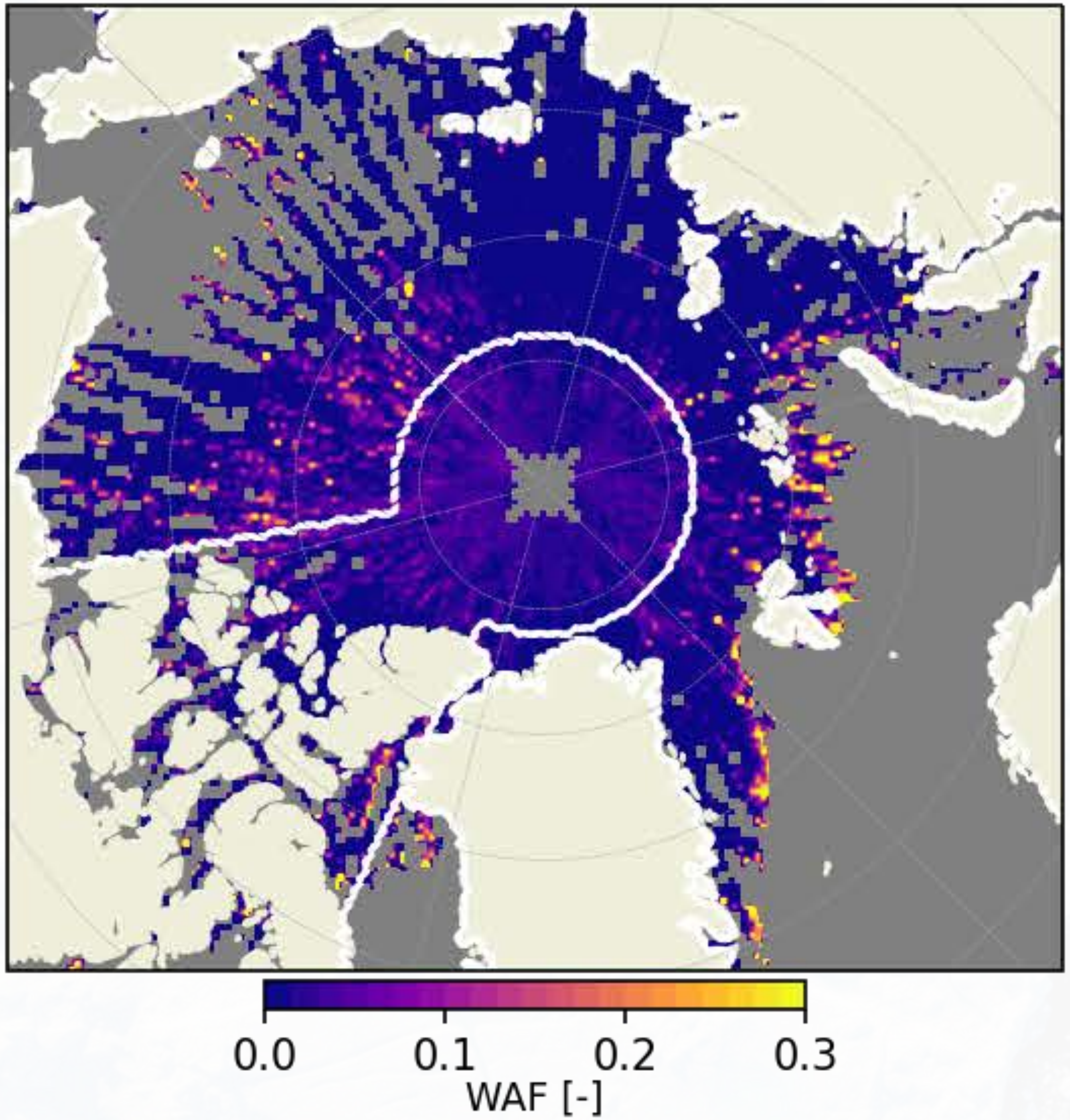
If (WAF > 7.5%), then the cell is wave-affected
→
Definition of a wMIZ extent



Horvat et al., 2020

Also exists for the Southern Ocean.

Methods

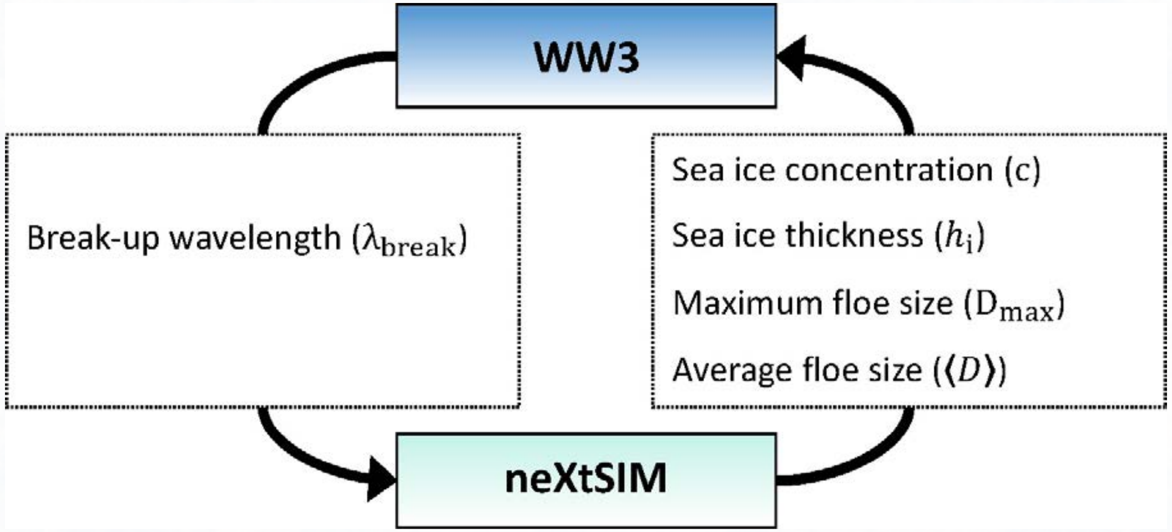


100km is too coarse to evaluate a model.
(wMIZ would be 1 grid cell)

We use a version of the dataset binned on 25km grid

- It is noisier than 100km (use of 10% threshold instead of 7.5%)
- More uncertain (less segments per cell)
- More missing values (less than 1000 segments per cell)

Methods



Update of floe size, that's all

We run the model on this same 25km grid

neXtSIM-WW3, no link between fragmentation and damage in REF run.

- Length: October 2018 → May 2020
- ERA5 reanalysis → atmosphere forcings
- GLORYS12 → Ocean forcing (neXtSIM only)

Model/Obs wMIZ Comparison

How to define the wMIZ in the model in way consistent with the WAF from ICESat-2?

- The satellite detects waves when wave amplitude is higher than 0.54m → Hs > ~0.75m

- Data are binned monthly

Model/Obs wMIZ Comparison

How to define the wMIZ in the model in way consistent with the WAF from ICESat-2?

- The satellite detects waves when wave amplitude is higher than 0.54m → Hs > ~0.75m

- Data are binned monthly

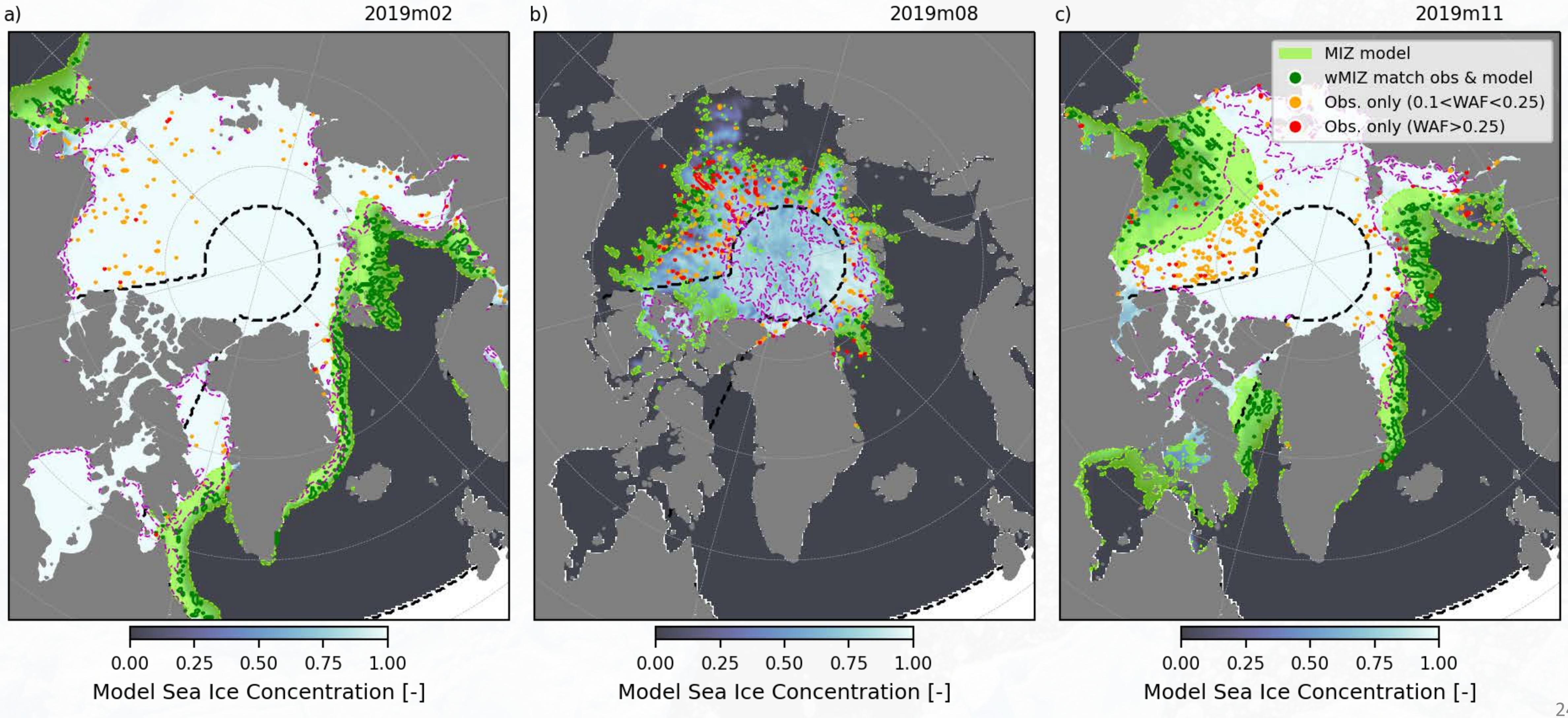
We define the modelled wMIZ extent as: **max*(Hs) > 0.75m (in-ice**)**

*Maximum is taken monthly

**We only consider "in-ice" cells, if ice concentration in the model exceeds 0.15

Model/Obs wMIZ Comparison

Using this definition:



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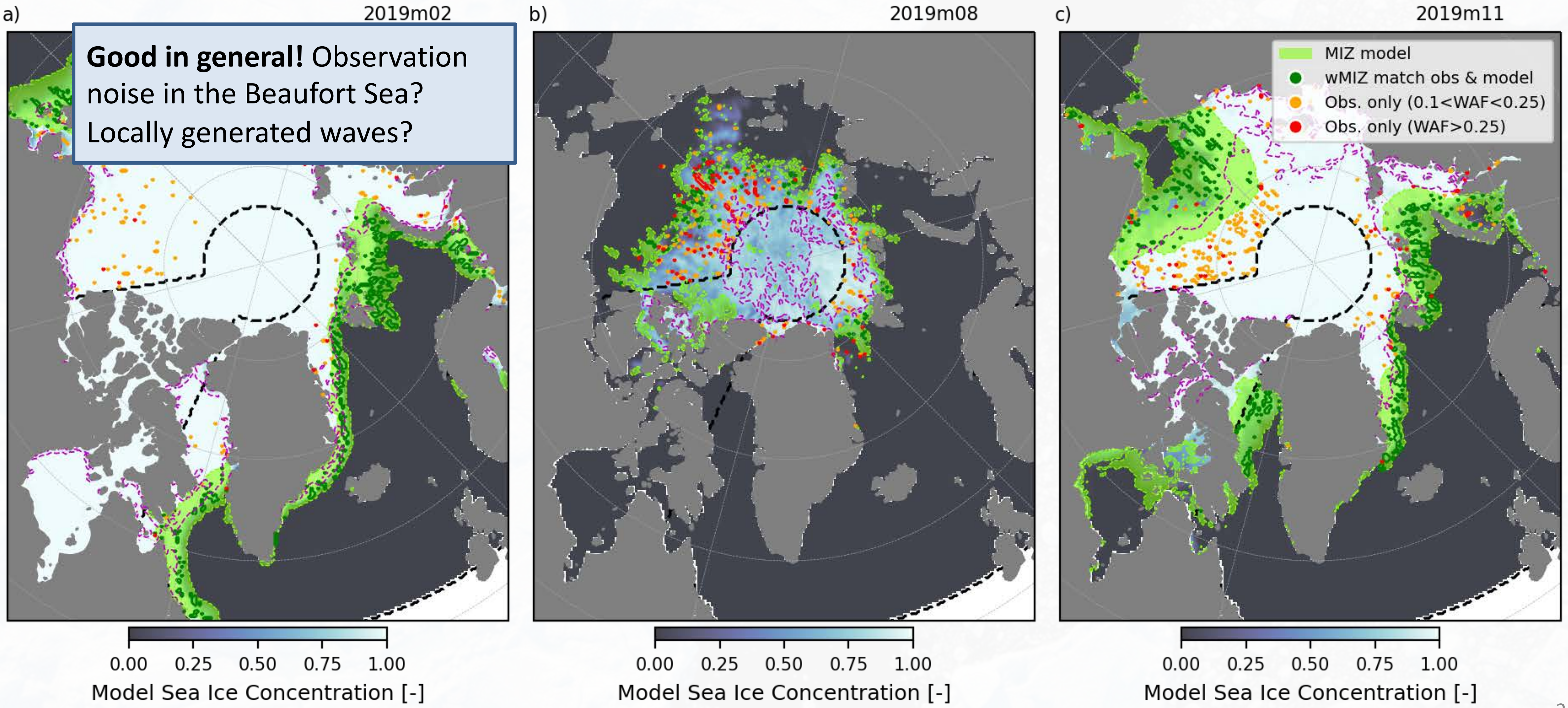

Good in general! Observation noise in the Beaufort Sea? Locally generated waves?

Model/Obs wMIZ Comparison

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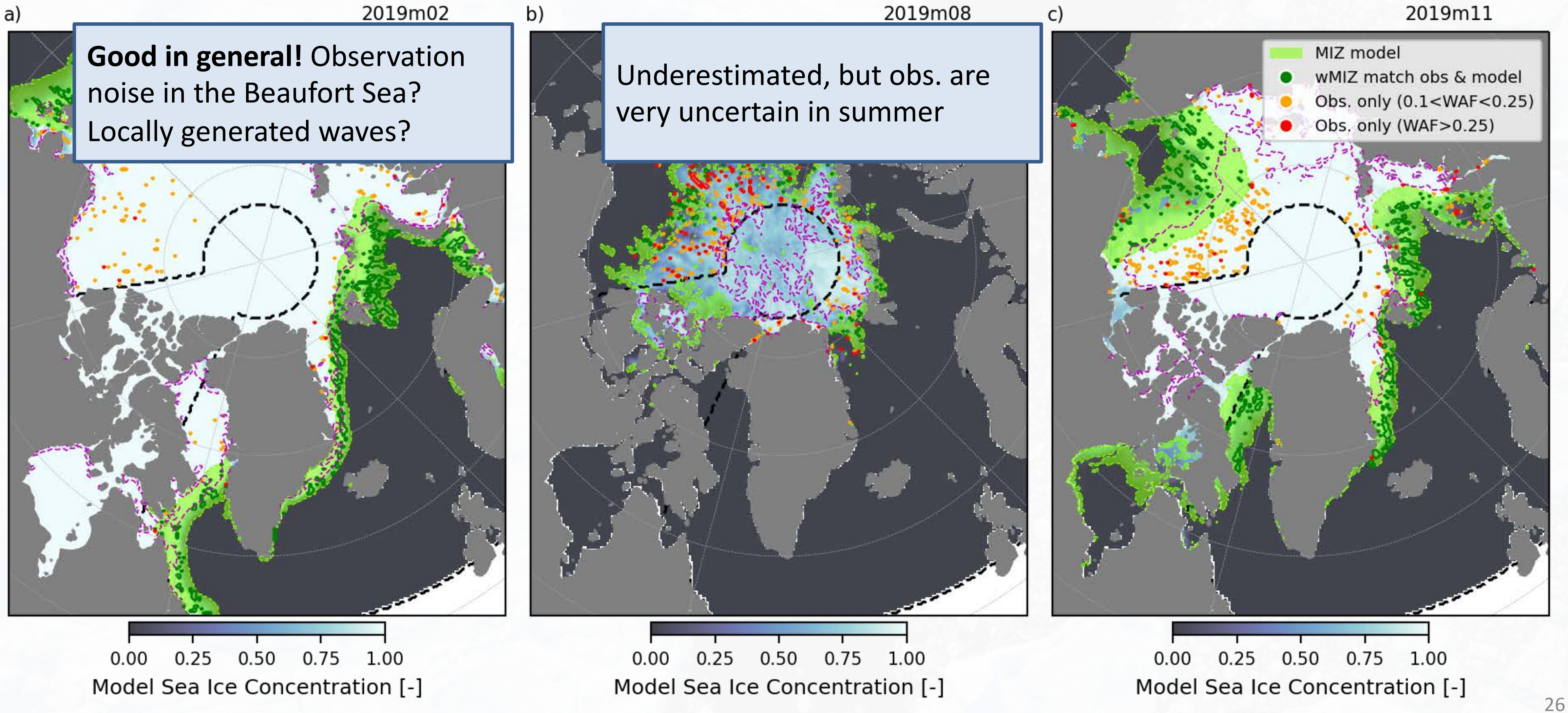


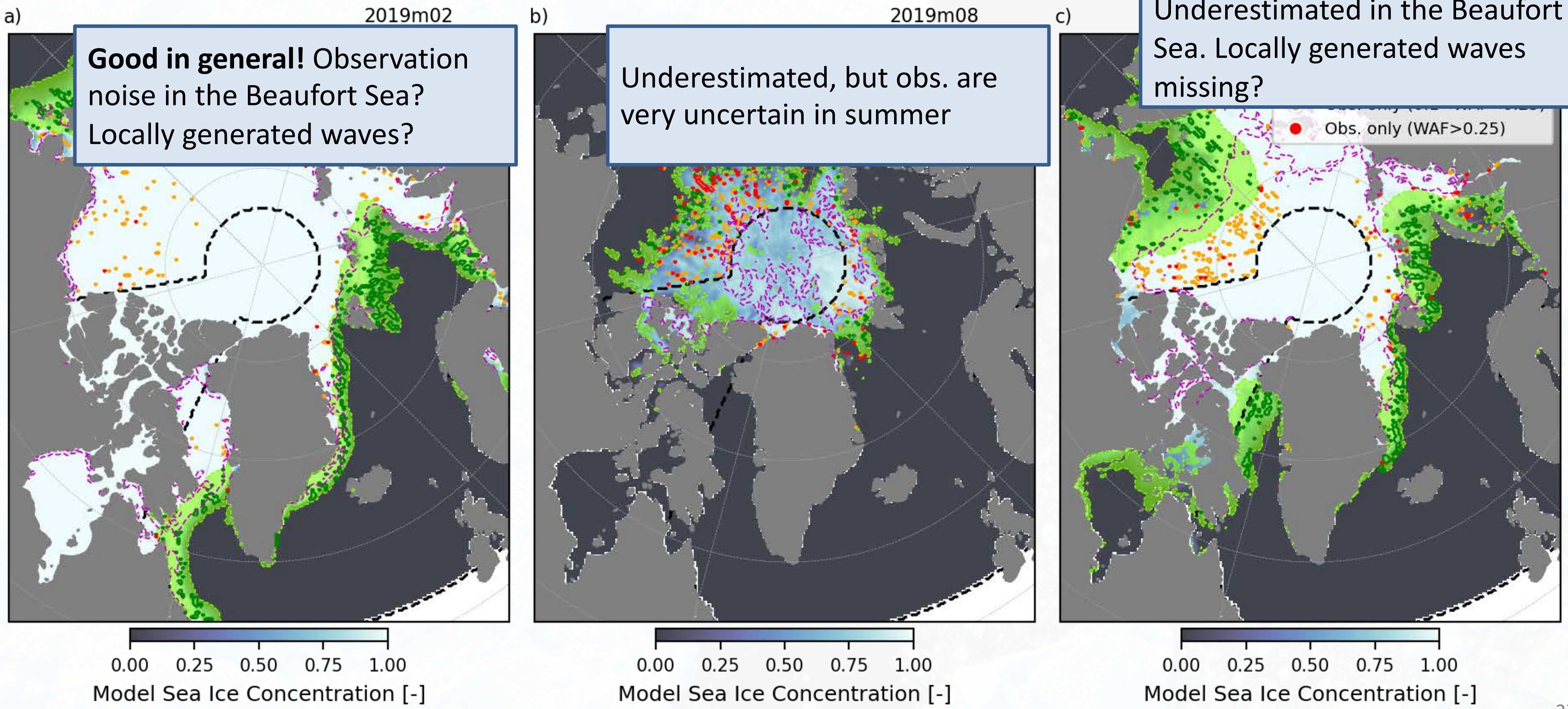
Model/Obs wMIZ Comparison

Using this definition:

Good in general! Observation noise in the Beaufort Sea? Locally generated waves?

Underestimated, but obs. are very uncertain in summer

Atlantic sector seems good. Underestimated in the Beaufort Sea. Locally generated waves missing?



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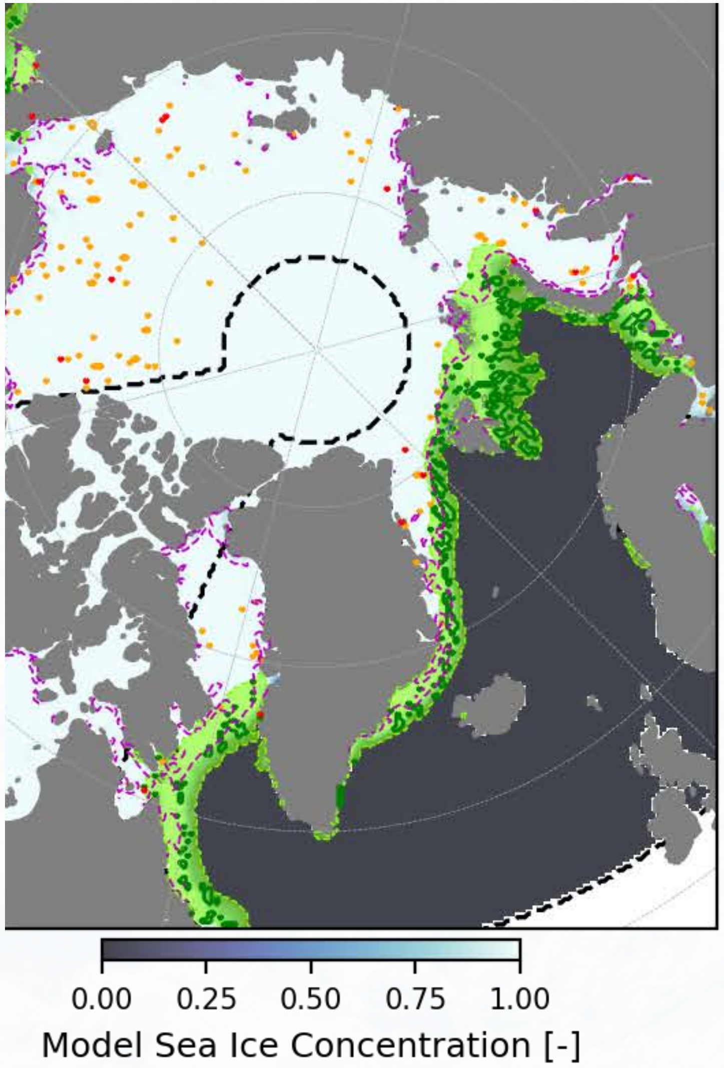
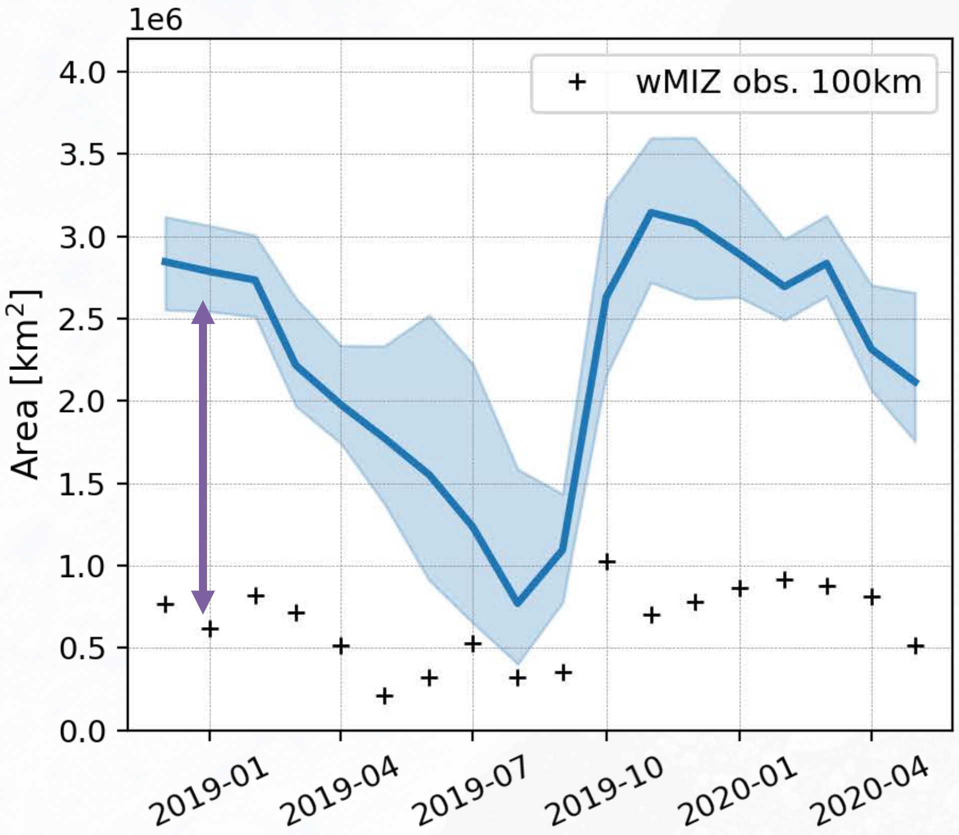


Shaded area: sensitivity to Hs threshold +/- 30cm



Not unexpected as:

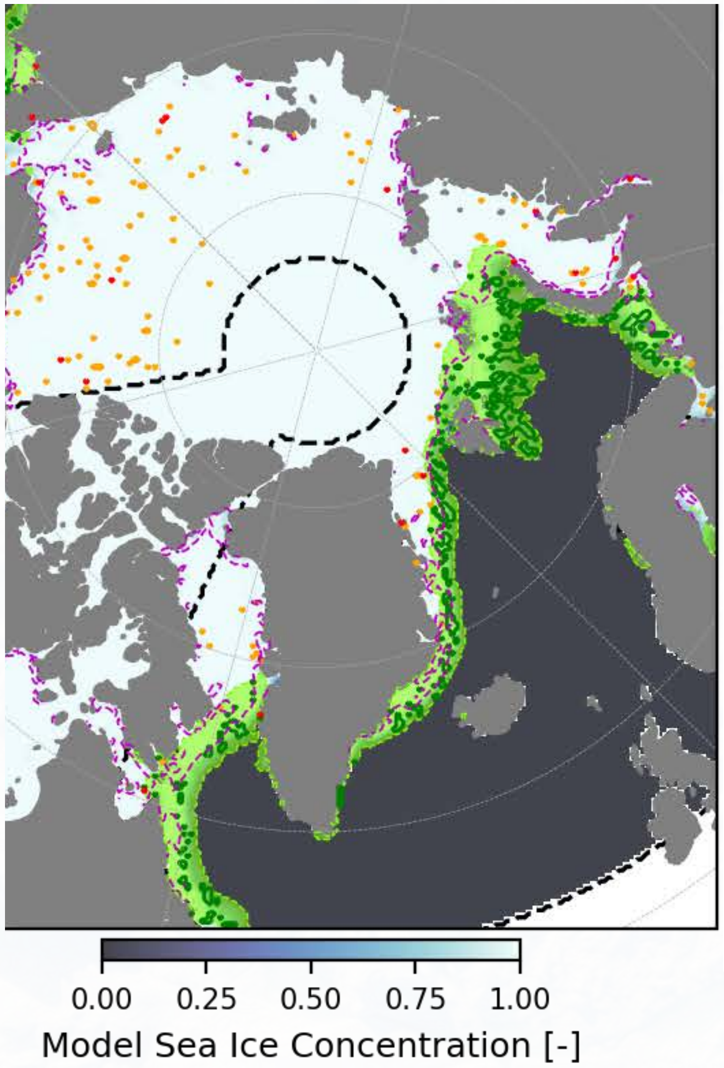
- ICESat-2 data is very sparse

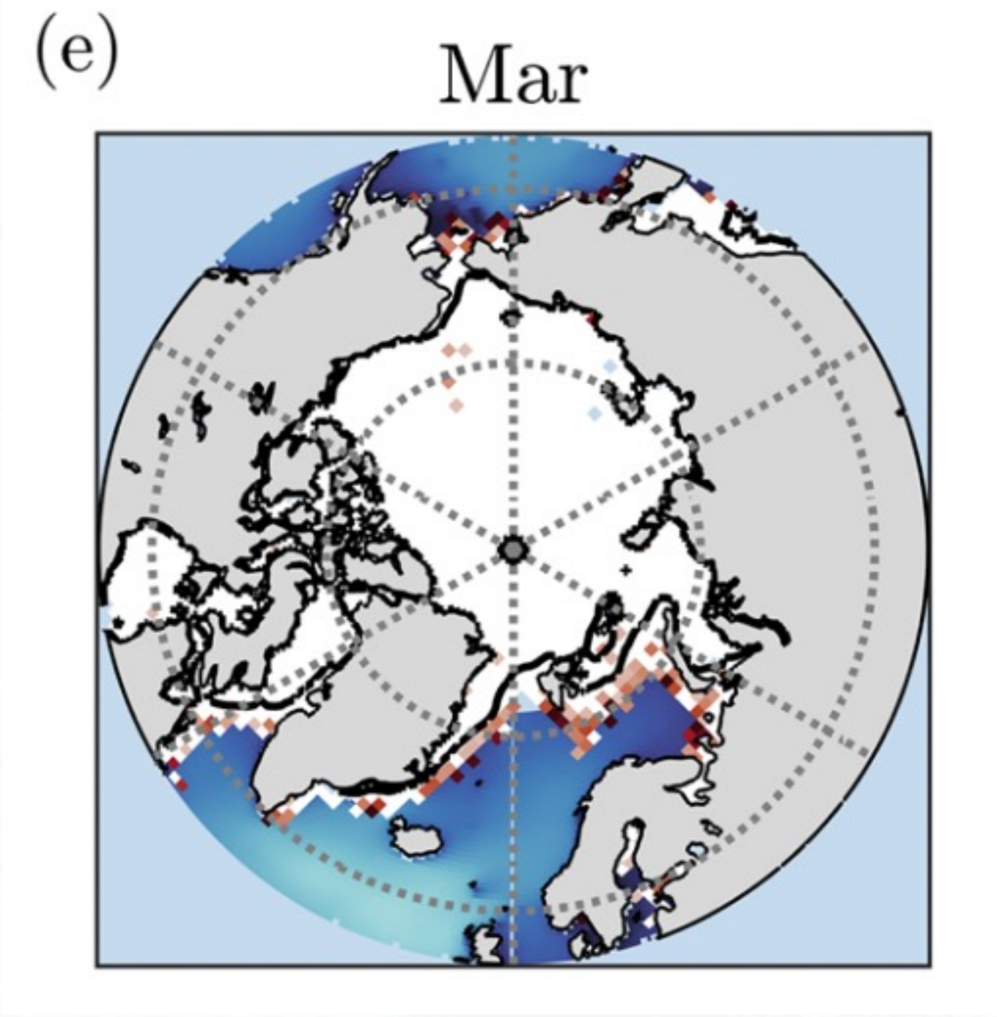
- Observations of waves are relatively certain, but still noise

- **Observations of "no-waves" are very uncertain**

Quantitative evaluation is not straightforward

Model/Obs wMIZ Comparison





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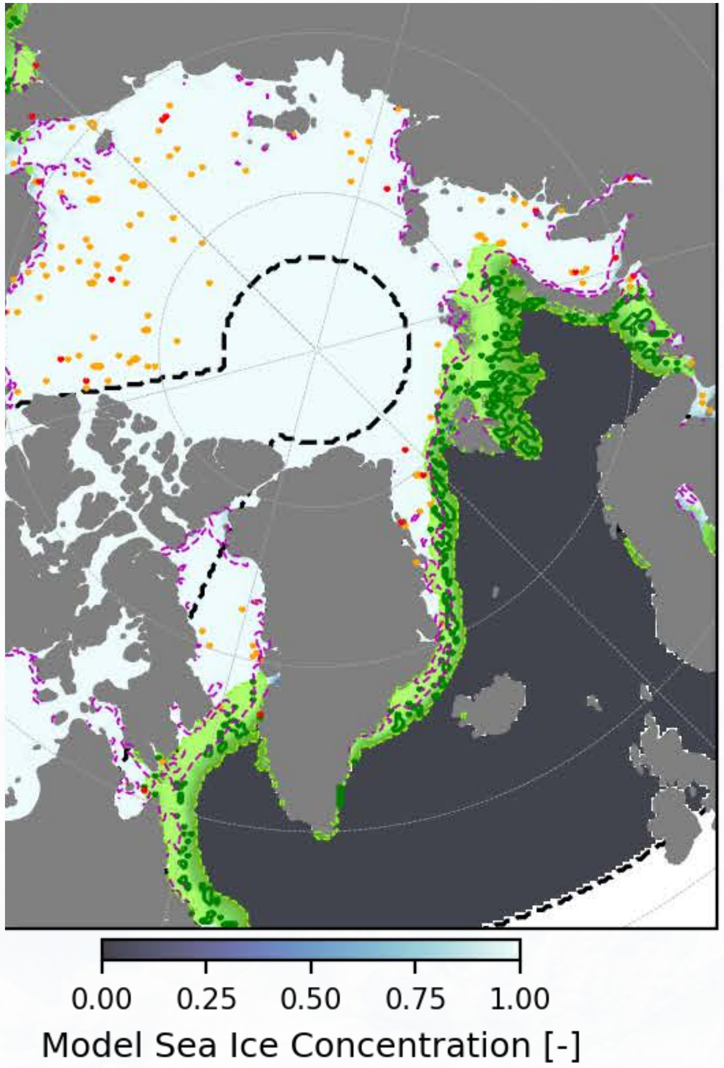

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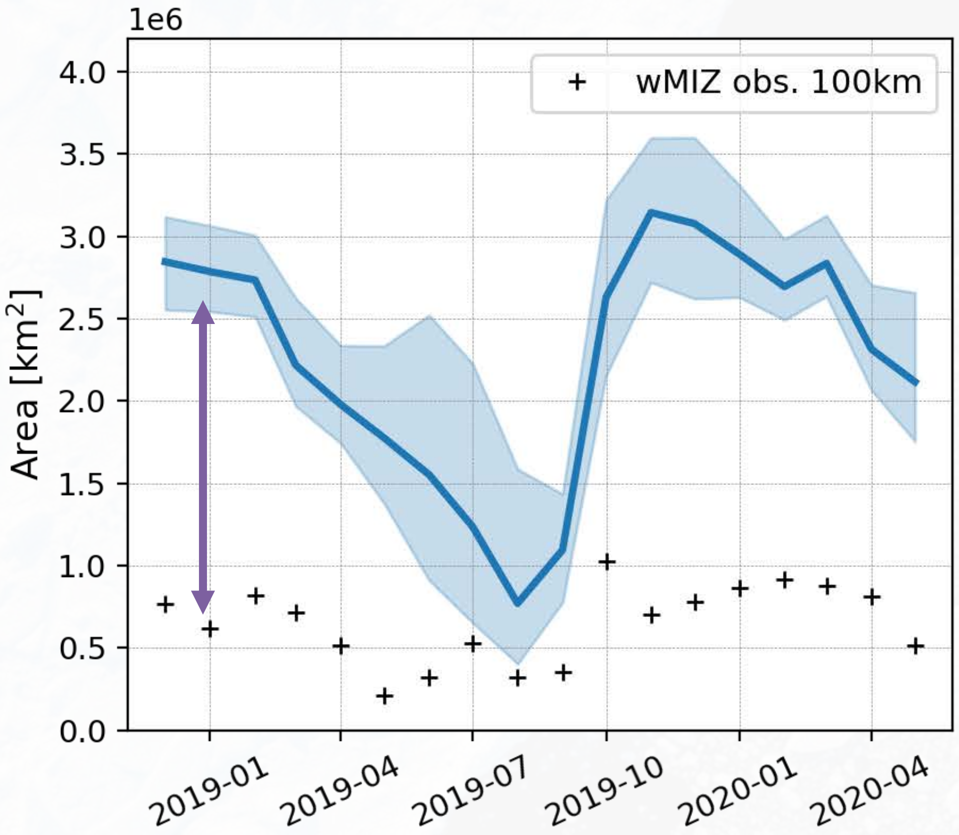

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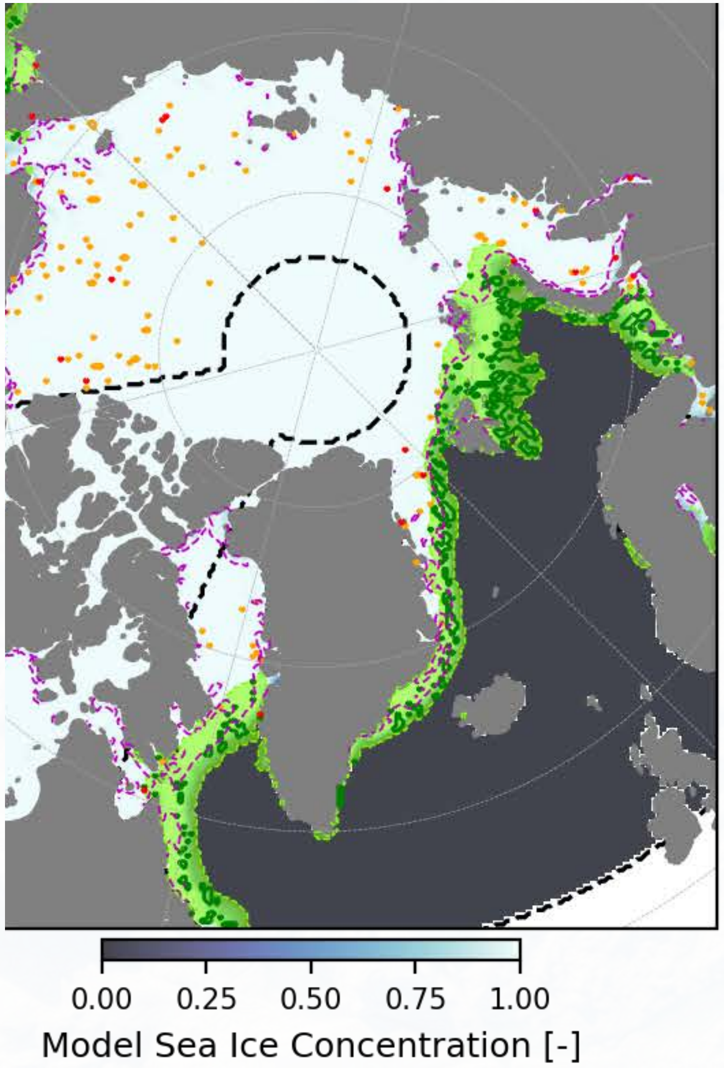
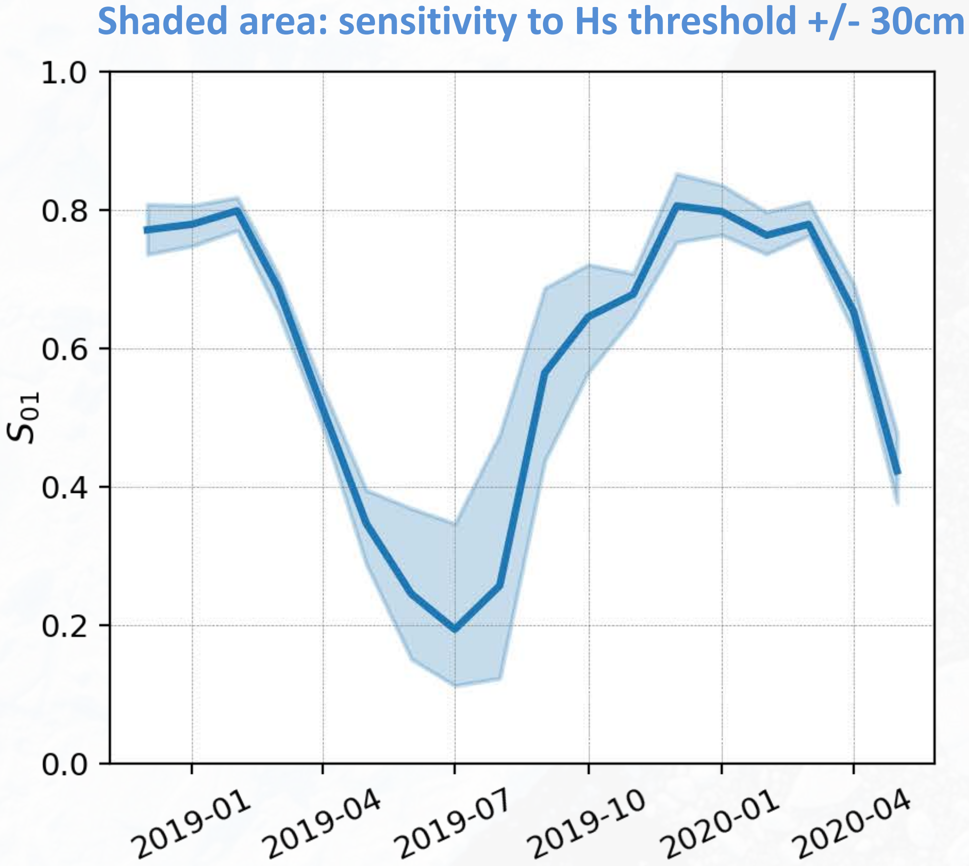


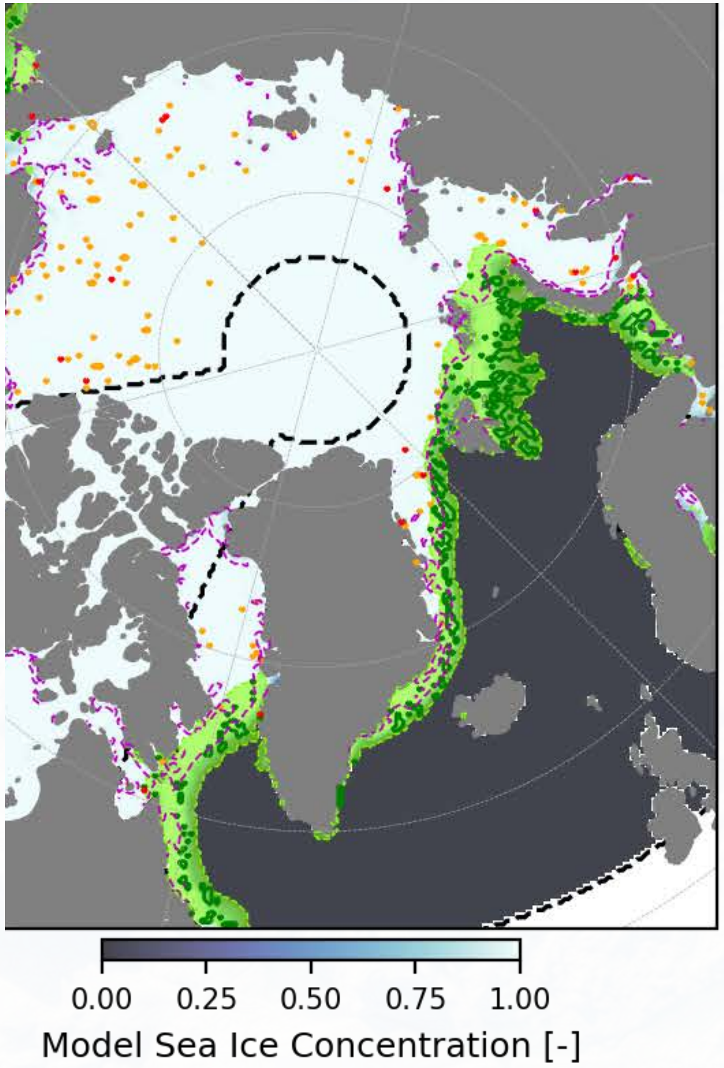


Metric 1: Percentage of wave observations within the model wMIZ (recall)

- Only account for observations of waves

Informs about whether the model **underestimates the wMIZ** extent or not

Model/Obs wMIZ Comparison



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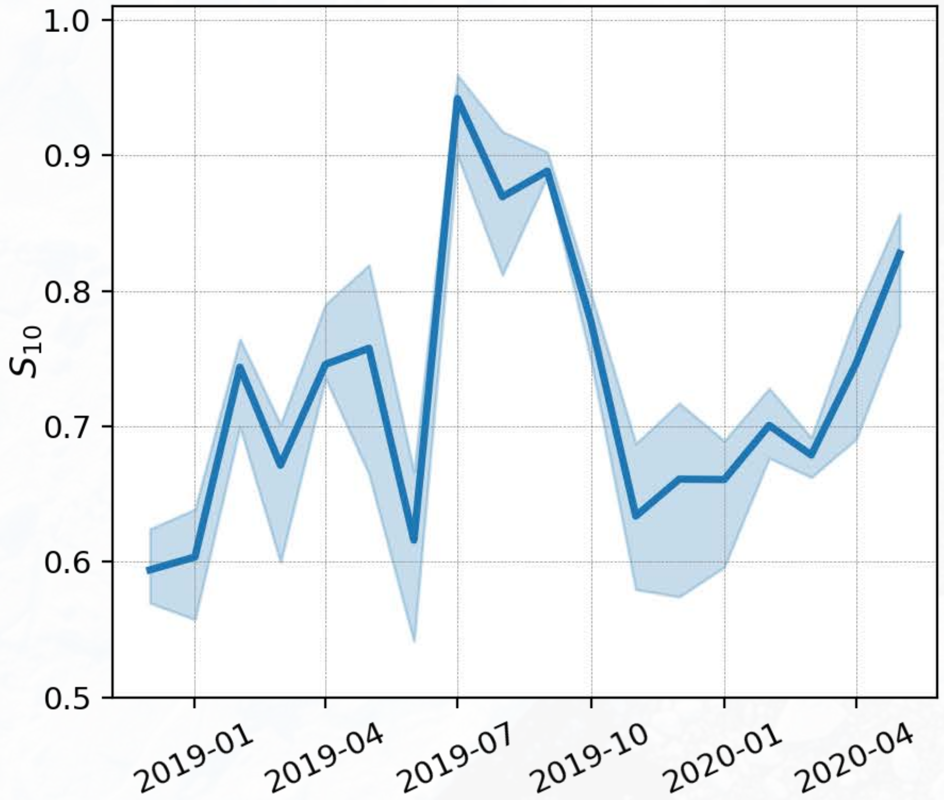

Metric 2: Percentage of the model wMIZ where waves are indeed observed (precision)

- Need to increase the certainty of "no-wave" observation.
- Only account for cells > 30k segments (compromise coverage/ certainty)

Informs about whether the model **overestimates** the wMIZ extent or not

Model/Obs wMIZ Comparison

The values we get for each metrics depend on hypothesis we made for:

- The definition of the modelled wMIZ
- The threshold for the WAF value (ICESat-2)
- The minimum number of ICESat-2 segments per month

A qualitative assessment (maps) is needed in combination with these metrics.
But that is what we did here!

Using our methodology, we can explore the sensitivity of our results to physical parameters, for different seasons and large areas

Comparing model scores

S01: Percentage of wave observations within the model wMIZ (recall)
S10: Percentage of the model wMIZ where waves are indeed observed (precision)

	Dec-Mar		Apr-May		Jun-Aug		Sep-Nov	
Simu.	S_{01}	S_{10}	S_{01}	S_{10}	S_{01}	S_{10}	S_{01}	S_{10}
REF	0.77	0.66	0.48	0.77	0.23	0.81	0.63	0.77

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DMG	0.77	0.66	0.48	0.77	0.22	0.80	0.61	0.77

Adding the relationship between damage and fragmentation changes almost nothing
(Expected, because it is not directly related to wave attenuation)

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DMG	0.77	0.66	0.48	0.77	0.22	0.80	0.61	0.77
HBMX	0.78	0.64	0.50	0.75	0.26	0.77	0.64	0.75

HBMX = Higher waves off-ice. (increasing β_{max} by 12.5%)

“Boosting” wave generation (off-ice) does not improve the results in the summer/autumn

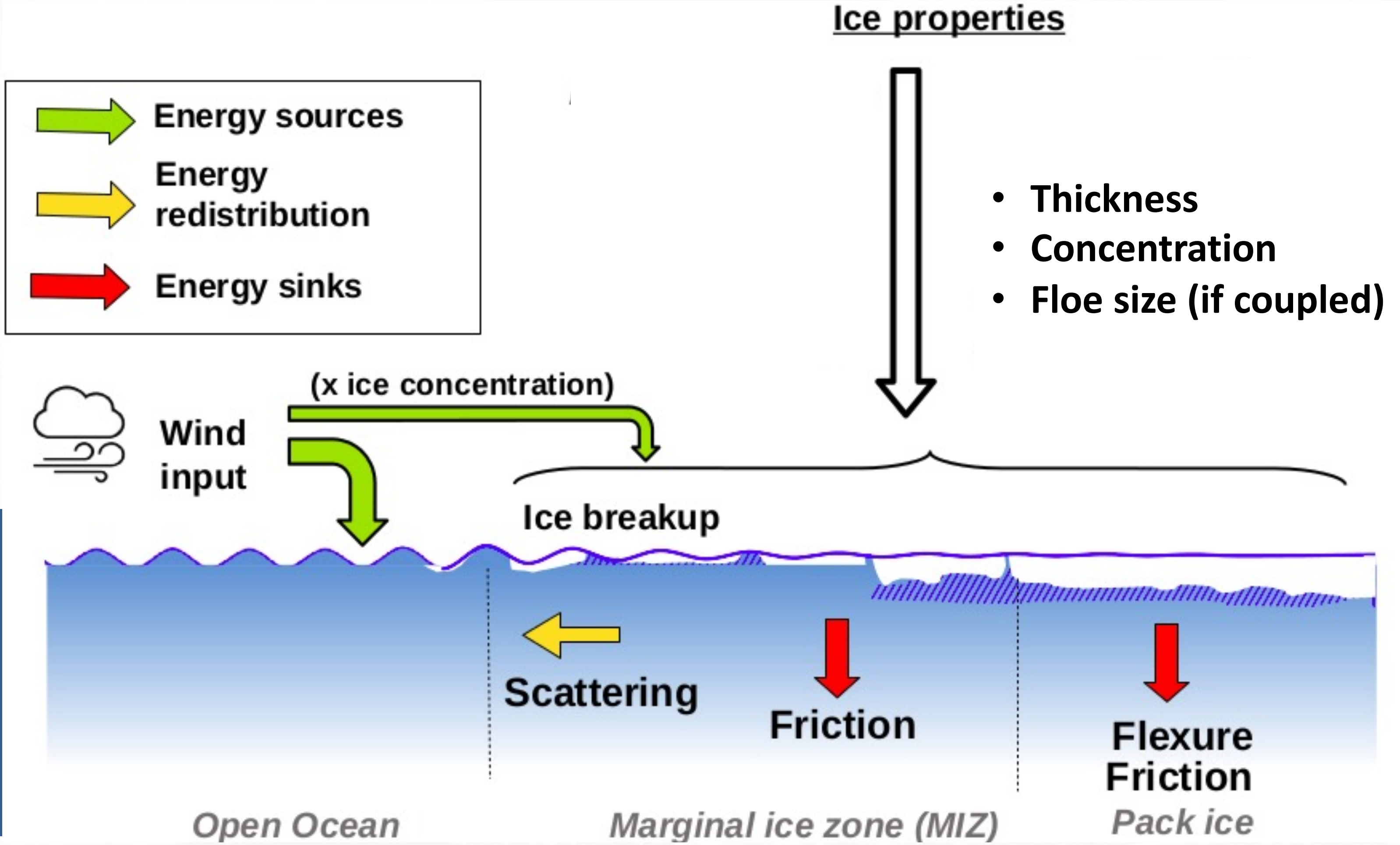
Analysing Results

Underestimation of wMIZ in summer/autumn:

- Not the wind (HBMX)
- Not ice extent (checked)
- Not ice thickness (underestimated)

Could still be:

- **Wave attenuation**
- **Wave generation in ice-covered regions**



Boutin et al. (JGR, 2018)

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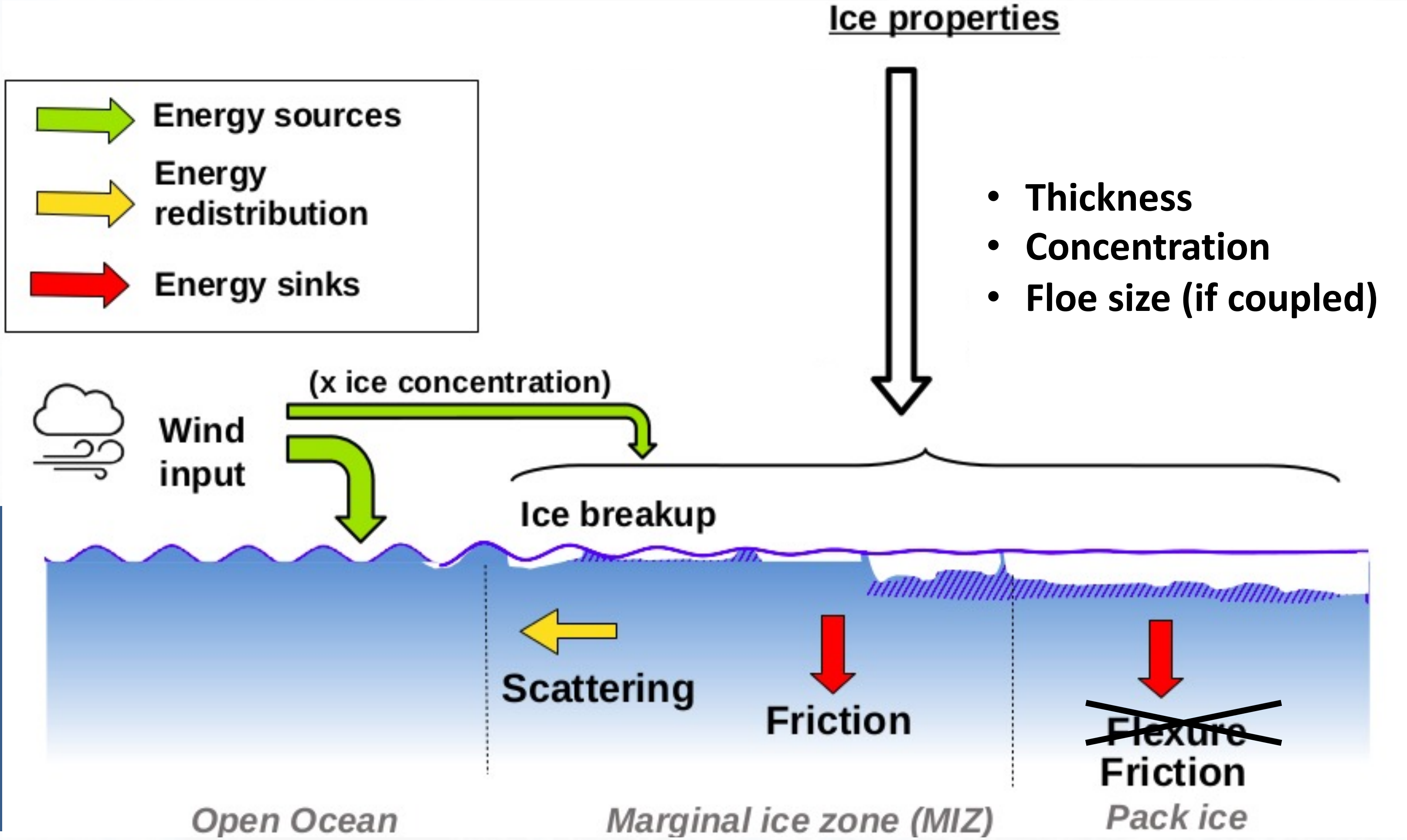

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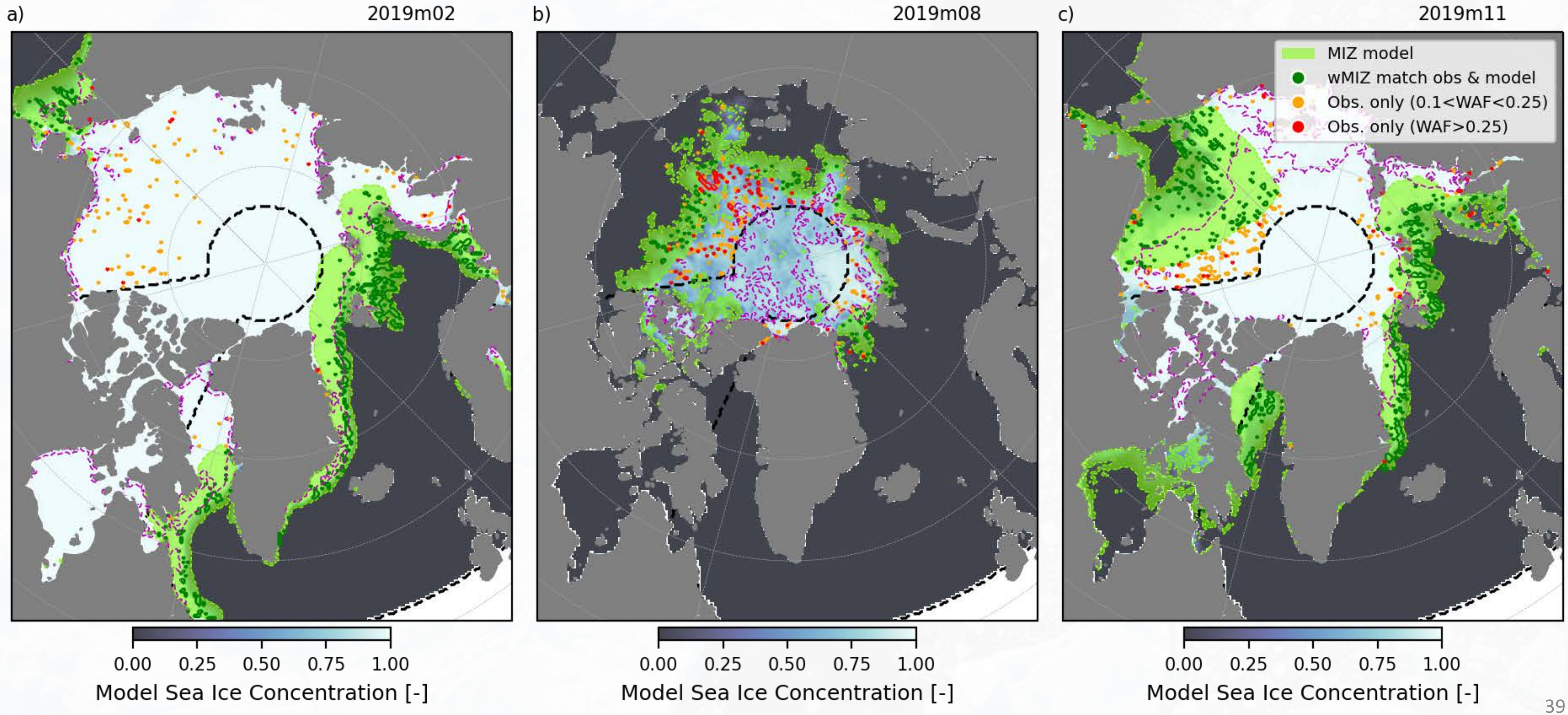
Analysing Results

NIDIS NIDIS = No Inelastic dissipation



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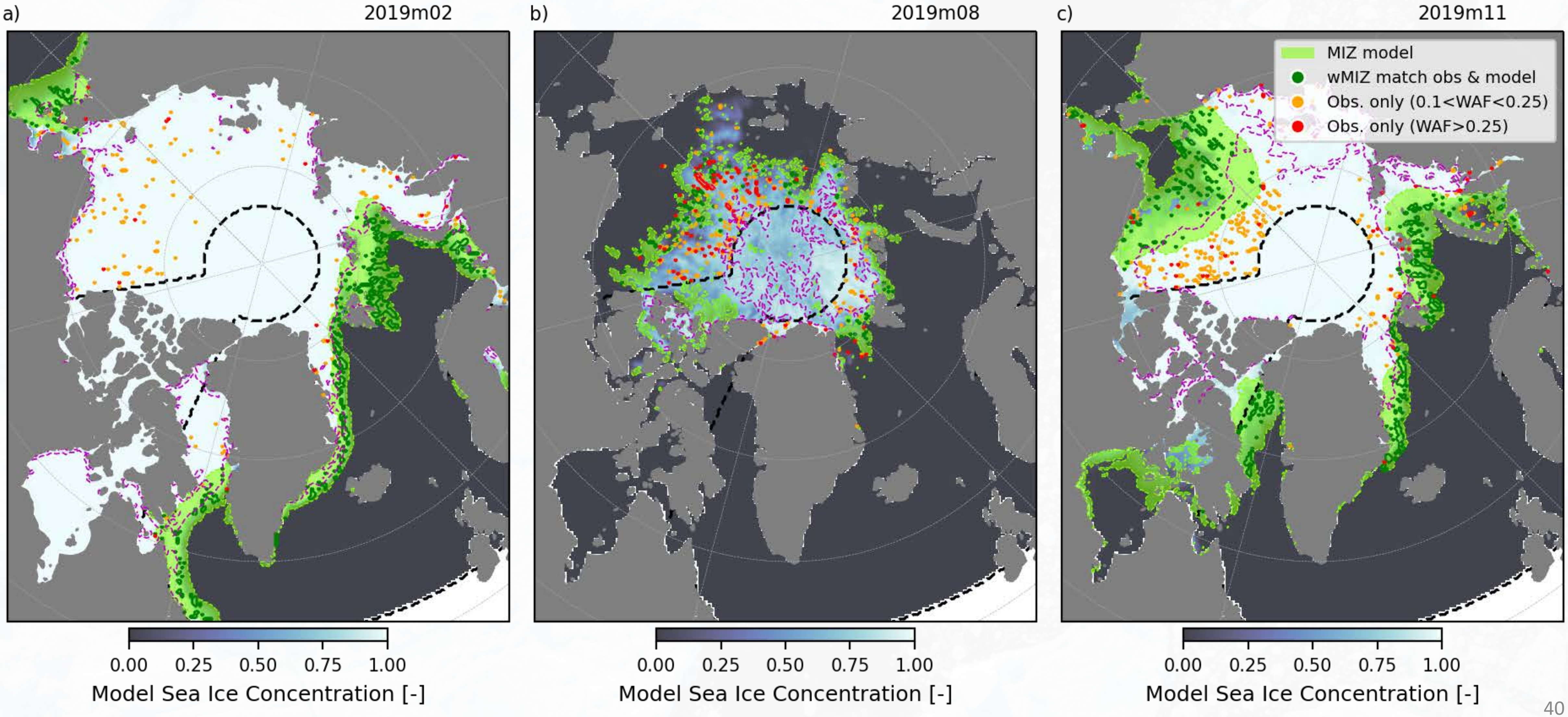

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HBMX	0.78	0.64	0.50	0.75	0.26	0.77	0.64	0.75
NIDIS	0.82	0.44	0.57	0.61	0.36	0.76	0.76	0.66

NIDIS = No Inelastic dissipation

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NIDIS	0.82	0.44	0.57	0.61	0.36	0.76	0.76	0.66

Relatively to REF: **+5%** **-33%**

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Analysing Results

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Relatively to REF:	**+5%**	**-33%**					**+15%**	**-15%**

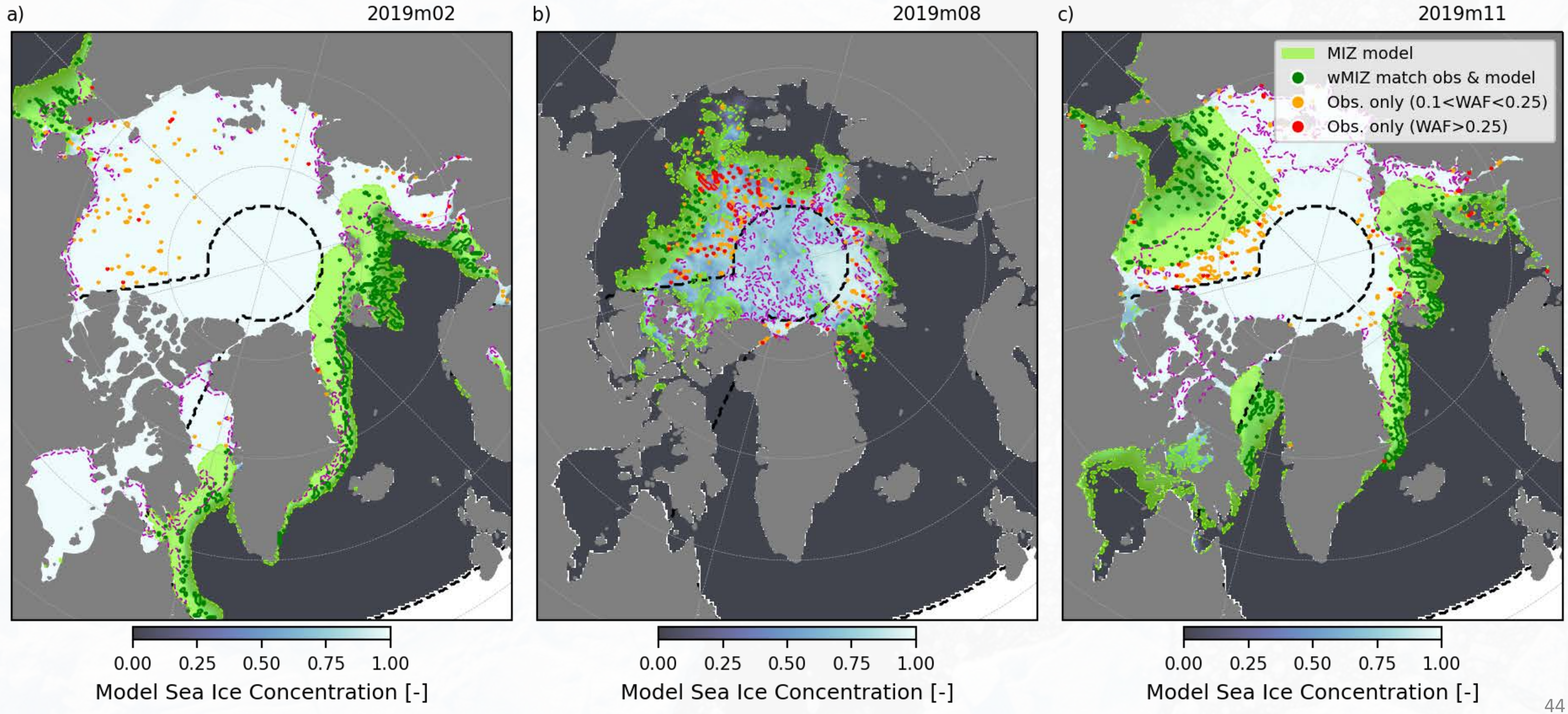
NIDIS = No Inelastic dissipation

In winter, NIDIS overestimates the wMIZ extent

Potentially better in summer/autumn

Analysing Results

NIDIS



Analysing Results

NIDIS

As expected from metrics, REF better than NIDIS

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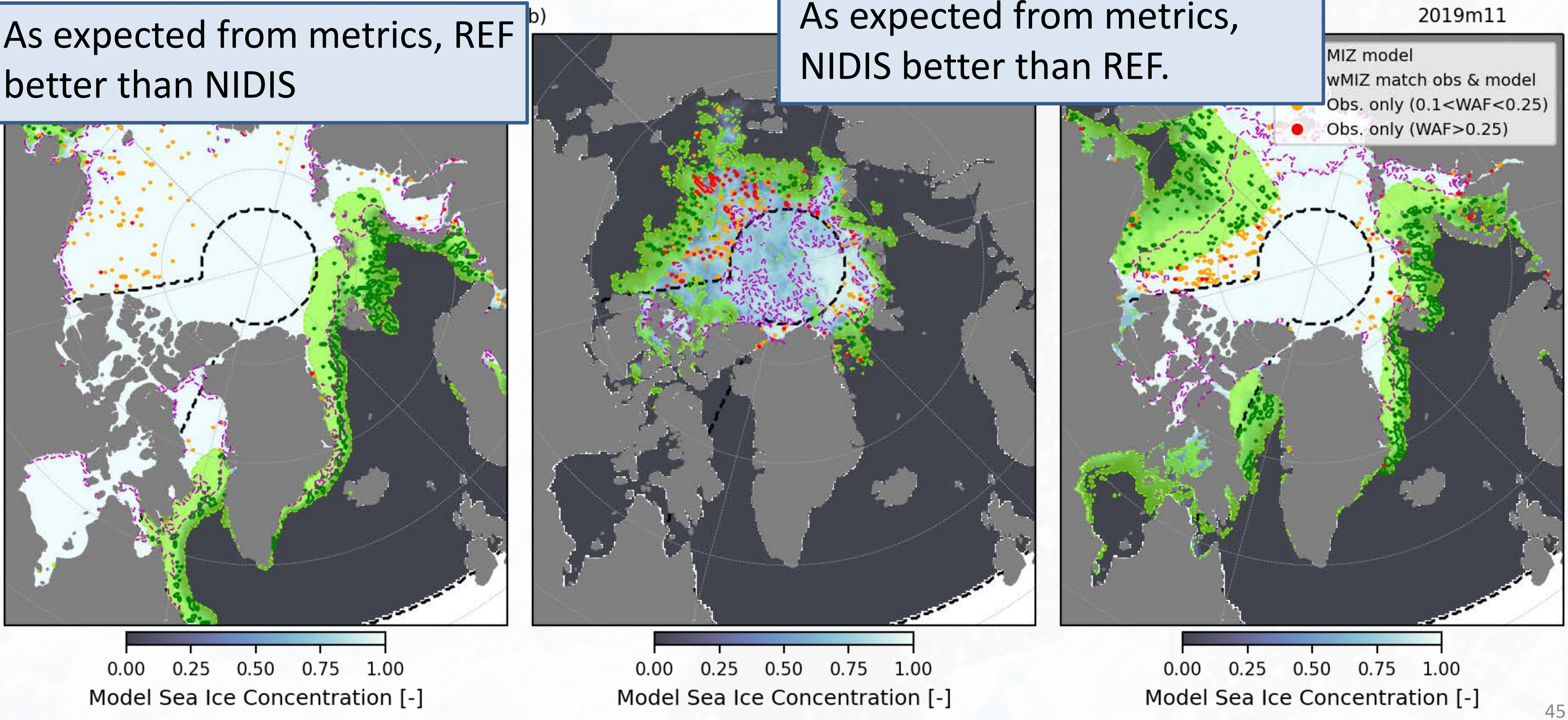

Discussion

- Inelastic dissipation is a very strong attenuation term, efficient on long swells in thick pack ice
- **It appears such a term is needed in winter, particularly in the Atlantic Sector**
- Only applies for large floes, ice behaving like an elastic plate → less relevant in summer and autumn

Analysis: summary

- Inelastic dissipation is a very strong attenuation term, efficient on long swells in thick pack ice
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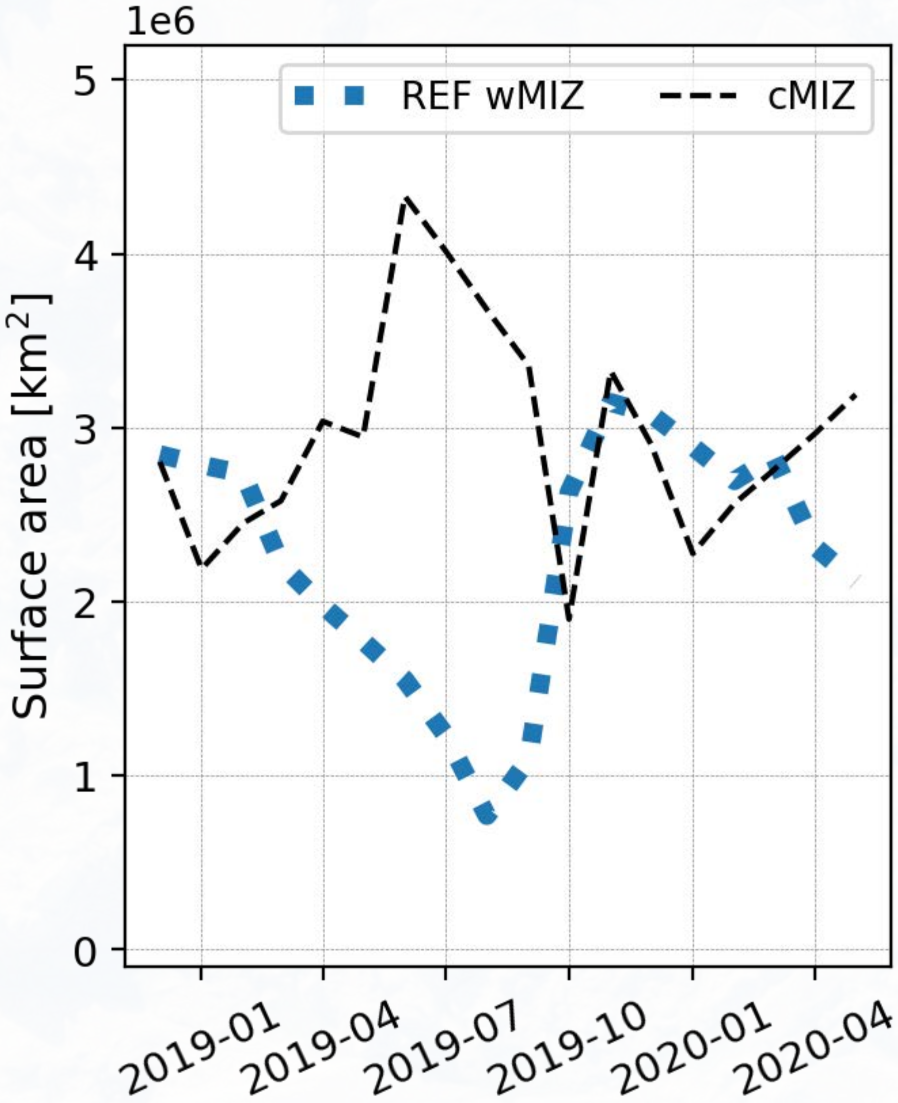
In summer and autumn:

- We have not taken into account effects of lateral melting, brittle failure on floe size → might overestimate wave attenuation
- Cooper et al., 2022 → Waves in pack ice in the Beaufort Sea in summer/autumn are locally generated

Modelling of wave generation in ice might need to be revised

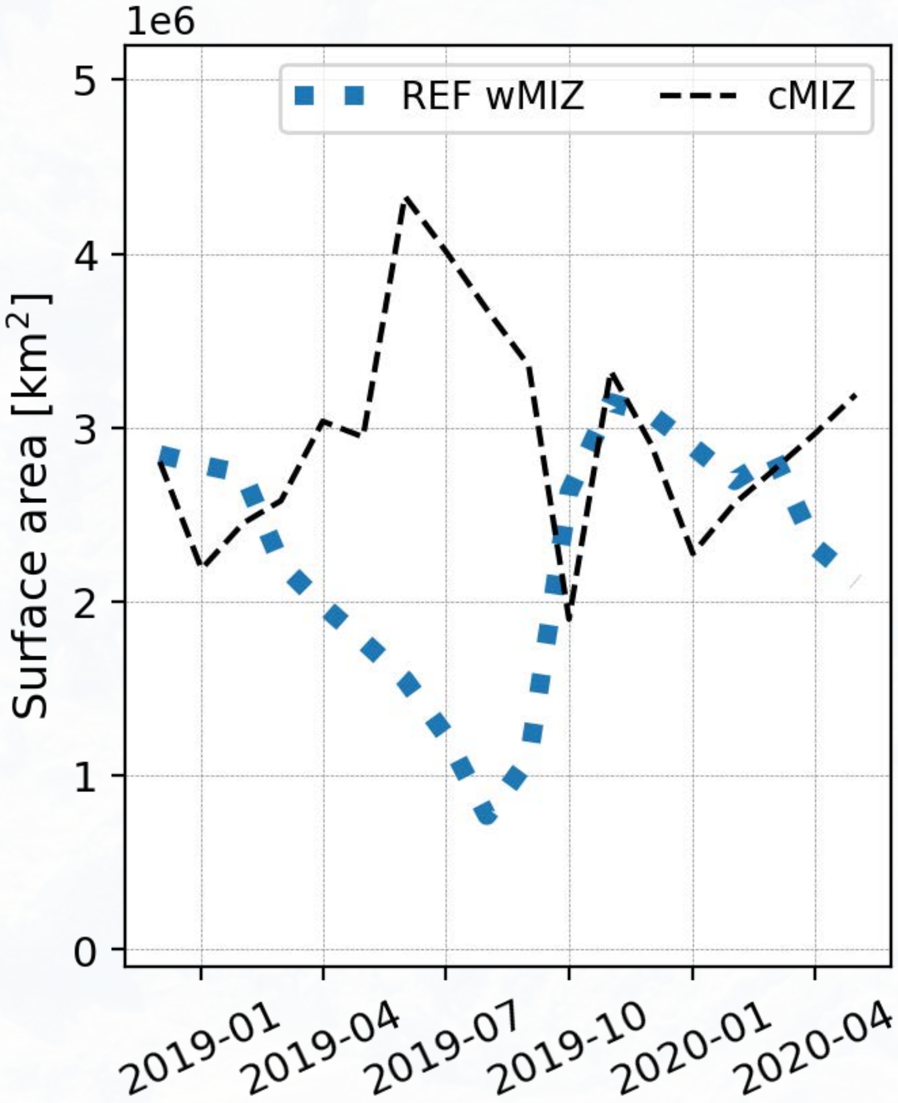
Discussion



wMIZ vs **cMIZ**

Our results suggest the wMIZ and the cMIZ are not so different in winter

Discussion



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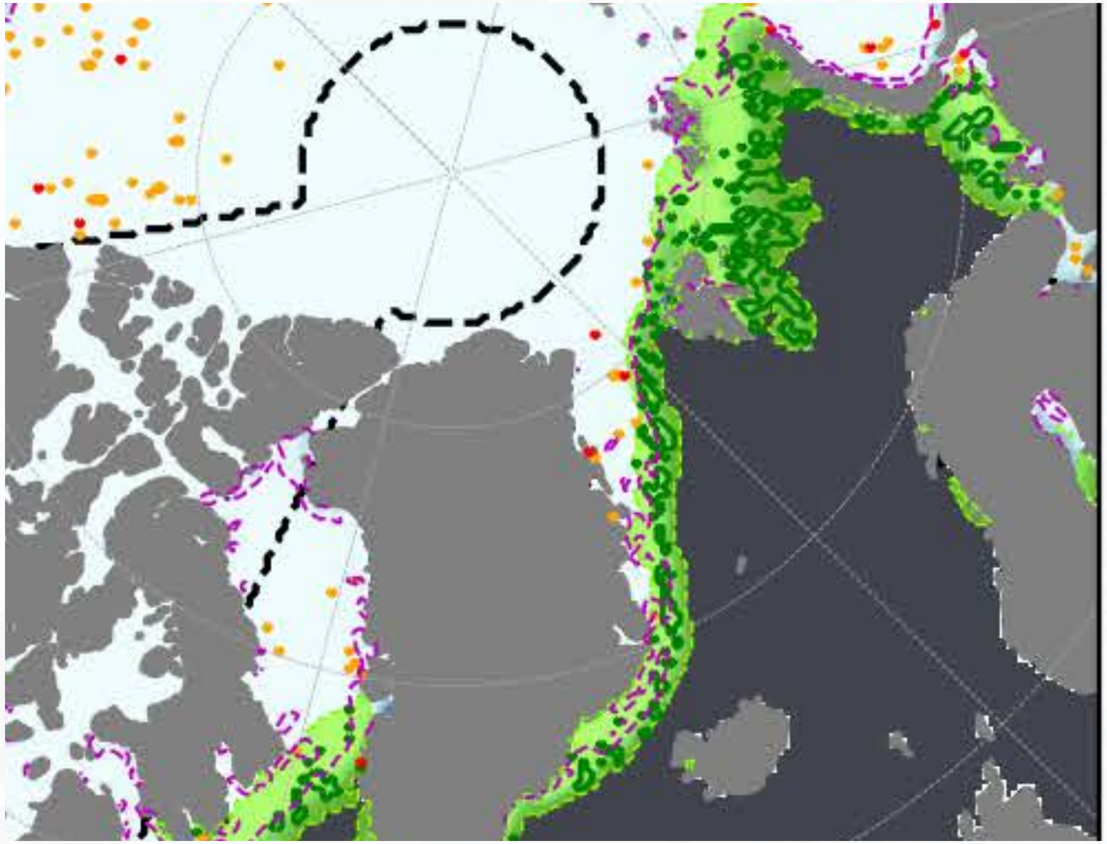

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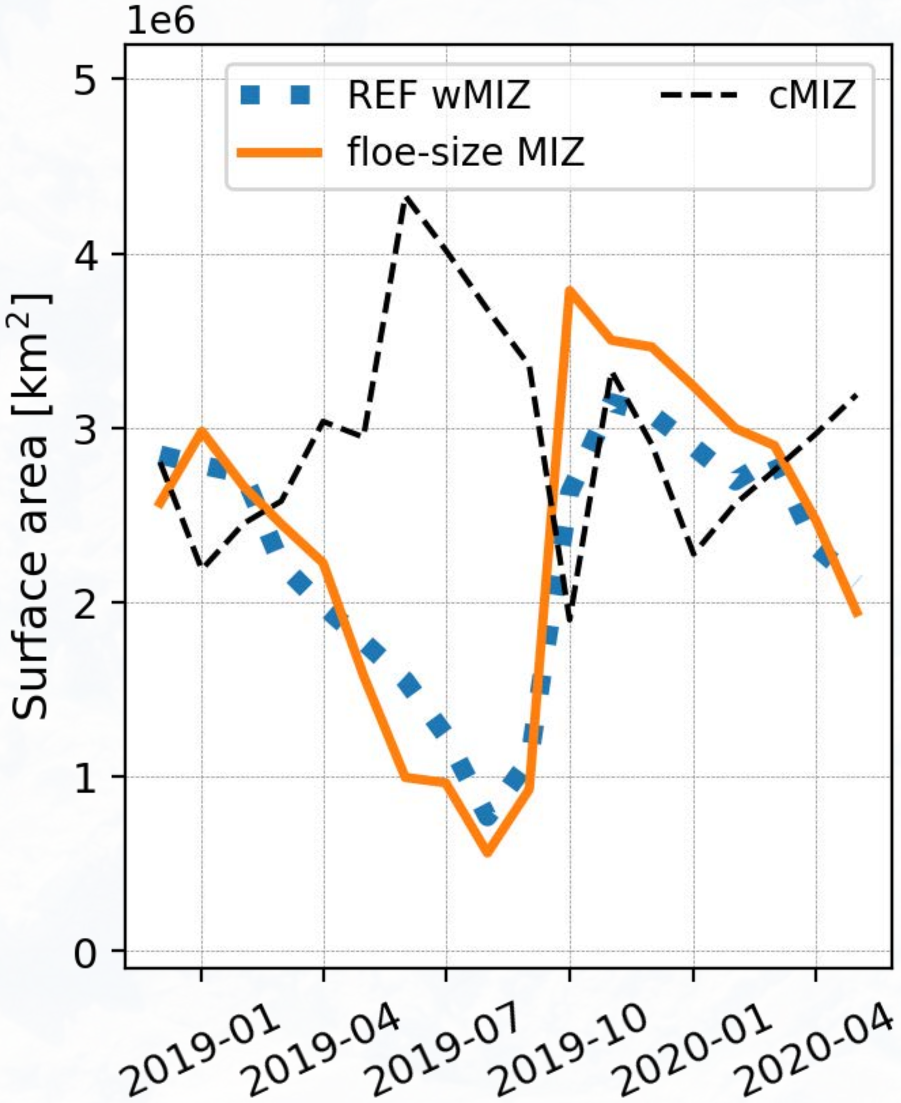

wMIZ vs **cMIZ**

Our results suggest the wMIZ and the cMIZ are not so different in winter

wMIZ vs **floe-size MIZ**

Our results suggest the wMIZ corresponds to a MIZ with an average maximum floe size of ~100m

→ Next step: Use FSD observations and see if we are right!

Discussion

Impact on sea ice dynamics

- The wMIZ mostly overlaps with the cMIZ in winter.

- In summer, the cMIZ encompasses the wMIZ.

This impact is only visible in autumn/winter, and only significant locally in time and space

Discussion

Impact on sea ice dynamics

- The wMIZ mostly overlaps with the cMIZ in winter.

- In summer, the cMIZ encompasses the wMIZ.

This impact is only visible in autumn/winter, and only significant locally in time and space , **in the Arctic**

CONCLUSION

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- We provide a method to evaluate the wMIZ extent in models
- Our results highlight the **need for a strong attenuation term** in compact, thick ice in winter
- Consequence is that **wMIZ does not extend much further than cMIZ** in general **in the Arctic** **(Antarctic→Brouwer et al., 2022)**

Our method can be applied again with another model, or in the Antarctic!

CONCLUSION

- Our reference simulation does generally well, especially in winter

- Underestimation of wave–affected area in the Pacific Sector could be due:
  - locally generated waves in ice-covered areas... (Cooper et al.2022)
  - ... misrepresented in the model...
  - not enough input ? Too much attenuation ? Overestimated floe size ?

Emerging remote sensing of floe size, comparison with *in-situ* measurements should give us more insight!

Thank you for your attention

References:

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MODIS (worldview.earthdata.nasa.gov*)*