Development of Wave-Sea Ice Interactions in the ECMWF Earth System Model

Josh Kousal, Jean Bidlot

ECMWF

Scope

Attenuation

(attenuation of waves by sea ice)

Sea ice break up

(wave-induced sea ice break up)

Stresses to the sea ice

(wave radiative stresses to the sea ice)

Sea ice strength

(a modified sea ice strength for the marginal ice zone)

ECMWF

Attenuation

attenuation of waves by sea ice

- Waves are attenuated in the sea ice due to processes such as scattering, under-ice friction, in-ice friction, …

- Attenuation of waves by sea ice is generally represented as

$$S_{ice} = -2C_g k_i E$$

$$k_i(f) \propto f^n$$

$C_g = group\ velocity$
$k_i = imaginary\ wave\ number$
$\quad = attenuation\ rate$
$E = energy\ spectrum$
$f = frequency$
$\omega = angular\ frequency$

ECMWF

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- Rogers et al. (2021)
  - large attenuation dataset created by applying model-data inversion to observations of waves in sea ice
  - finds that many of the models fit the general range of attenuation, but no single model can accurately represent all conditions
- Yu et al. (2022), hereafter YEA22
  - applies a non-dimensional analysis to this dataset
  - arrived at a model which is substantially better than all preceding models

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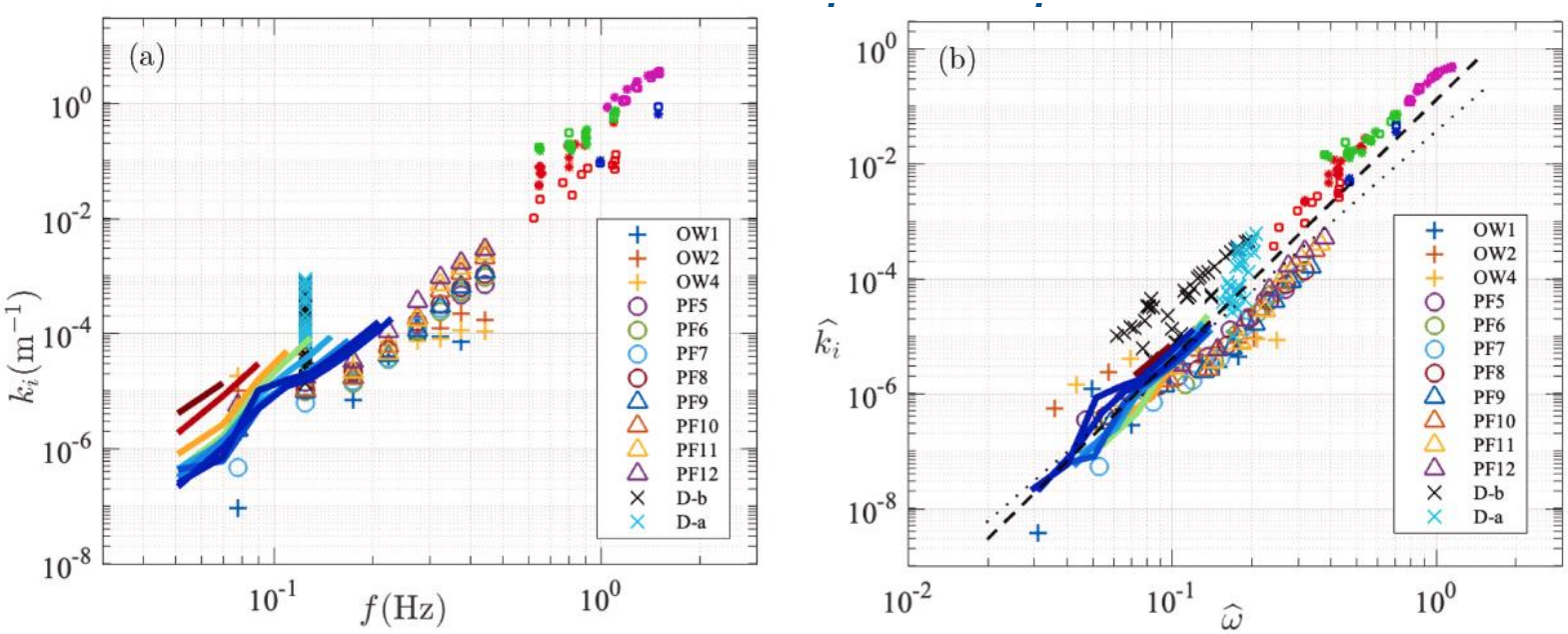
Attenuation



A new method for parameterization of wave dissipation by sea ice

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$$k_i = Ch_{ice}^{1.25} f^{4.5}, \quad \text{where} \quad C = 0.1274\left(2\pi/\sqrt{g}\right)^{4.5}$$

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Sea ice break up

wave-induced sea ice break up

- waves propagating through a sheet of continuous sea ice can break it into a series of smaller floes

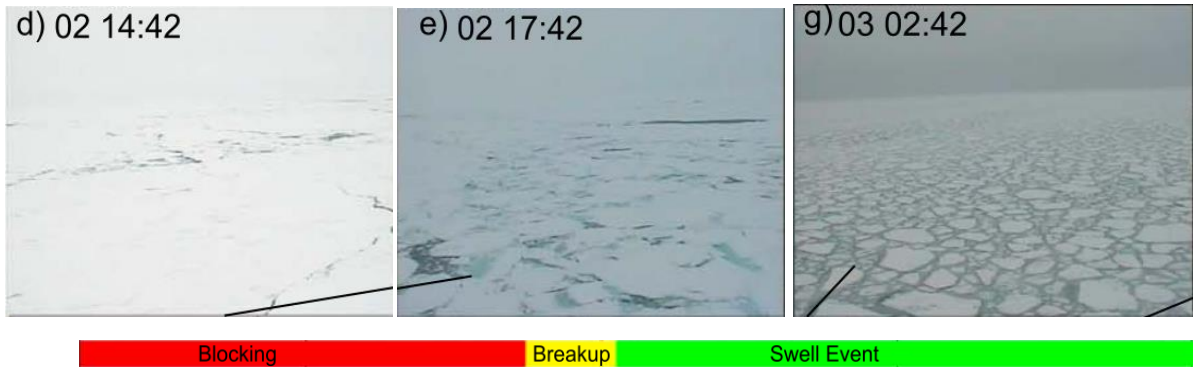

Fig. 5. Observed wave height (solid line; left) and sea ice (right) and during a break up event [4]

[4]Collins et al. (GRL 2015), [5]Ardhuin et al. (GRL 2020), [6]Voermans et al. (TC 2021)

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wave-induced sea ice break up

The Cryosphere, 14, 4265–4278, 2020
https://doi.org/10.5194/tc-14-4265-2020

The Cryosphere
Open Access
EGU

Experimental evidence for a universal threshold characterizing wave-induced sea ice break-up

Joey J. Voermans[1], Jean Rabault[2,3], Kirill Filchuk[4], Ivan Ryzhov[4], Petra Heil[5], Aleksey Marchenko[6], Clarence O. Collins III[7], Mohammed Dabboor[8], Graig Sutherland[9], and Alexander V. Babanin[1,10]

$$I_{\mathrm{br}} = \frac{a h_i Y}{\sigma \lambda^2}$$

$$I_{\mathrm{br\_crit}} = 0.014$$

The sea ice at any point is classed as “broken” when it exceeds its critical threshold, i.e. when

$$I_{br} > I_{br\_crit}$$

$a = wave\ amplitude$
$Y = Young's\ modulus$
$h_i = sea\ ice\ thickness$
$\sigma = flexural\ strength$
$\lambda = wavelength$

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Sea ice break up, what does it effect?

$$SIMEM = sea\ ice\ break\ up\ memory$$

$$SIMEM \longrightarrow ?$$

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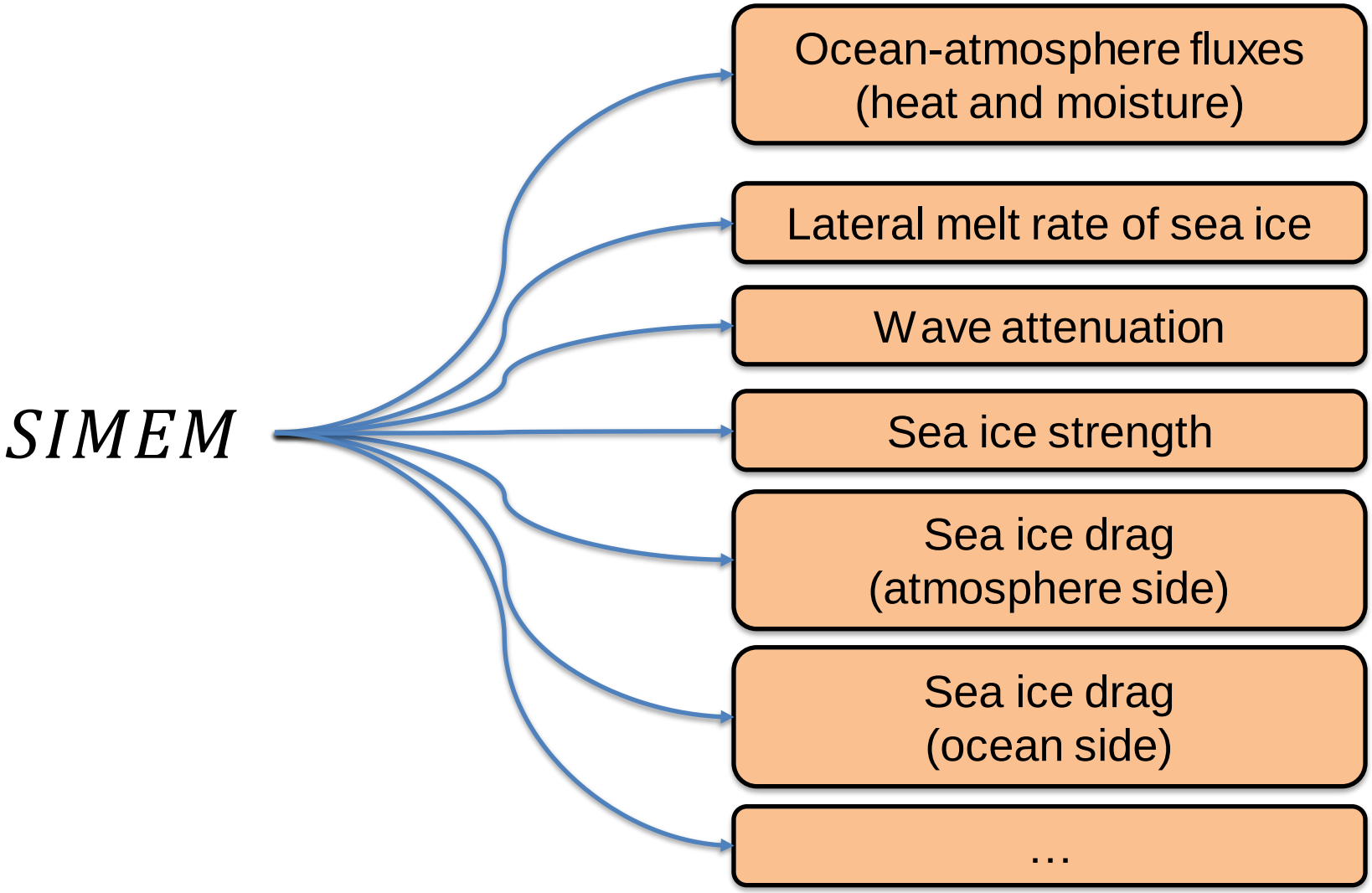
Sea ice break up, what does it effect?



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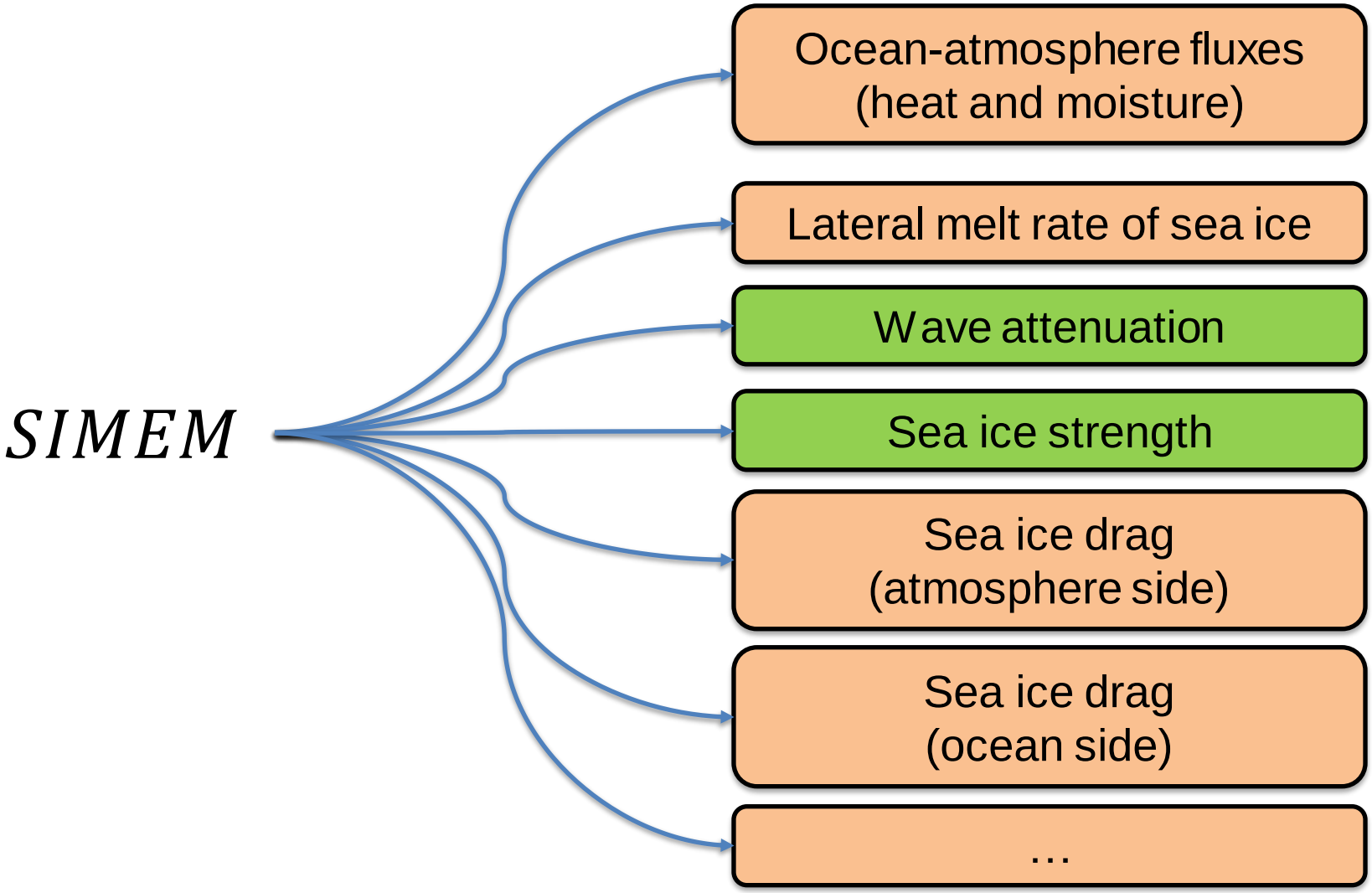
Sea ice break up, what does it effect?



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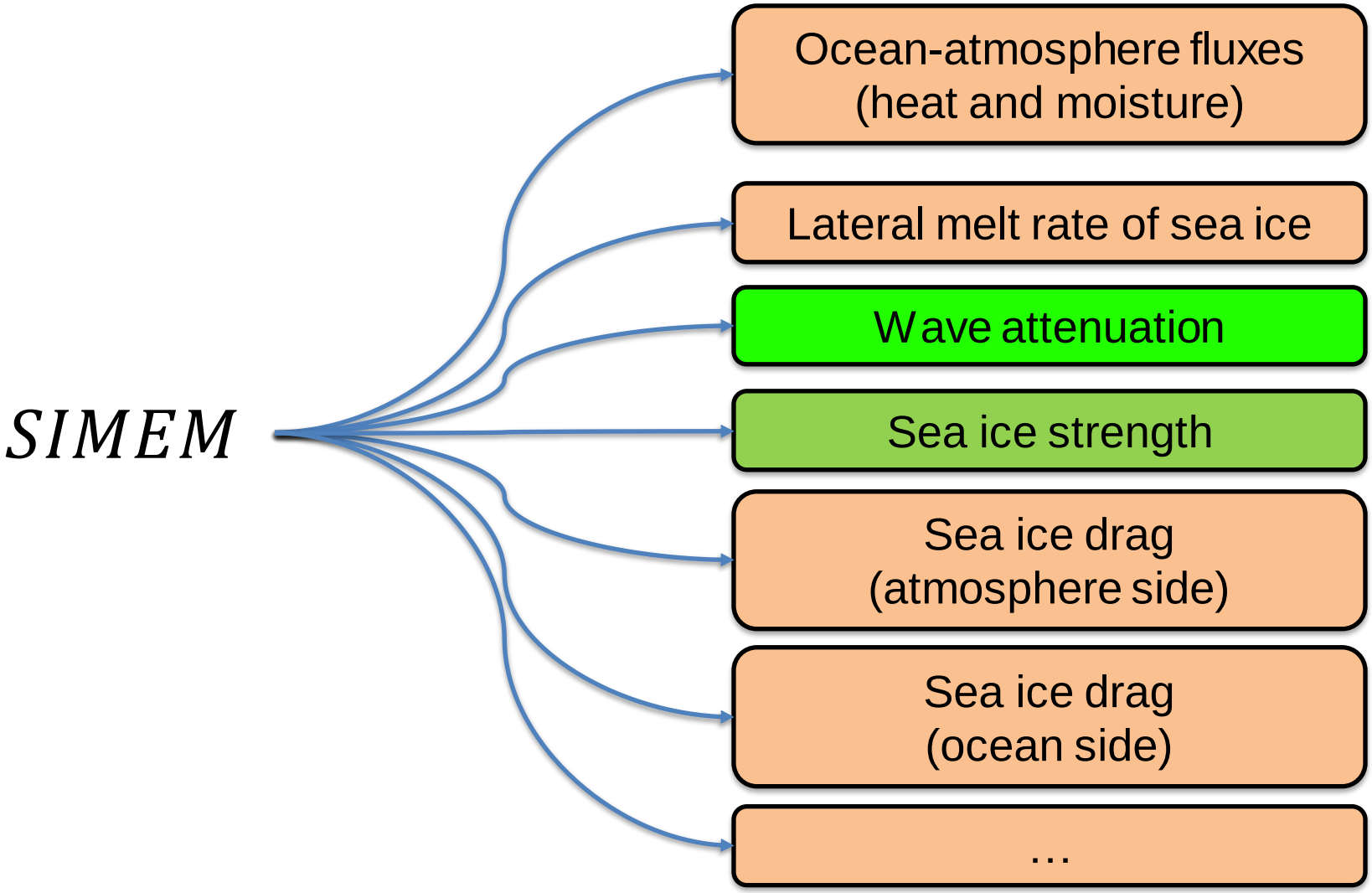

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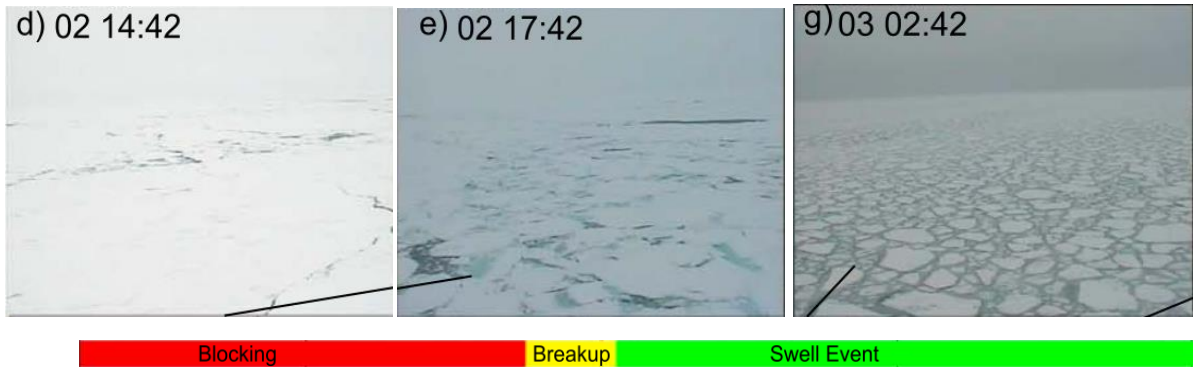

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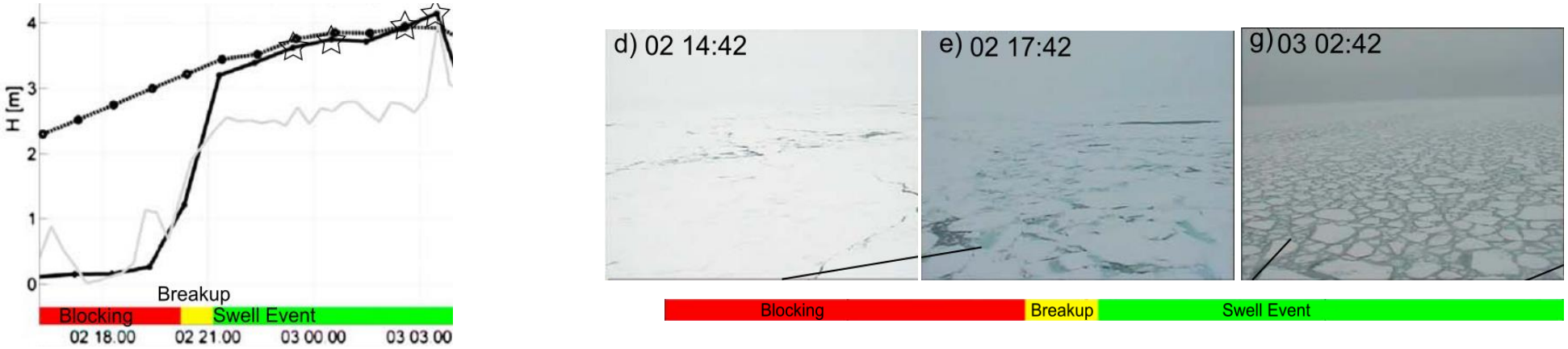
Sea ice break up AND Attenuation

- waves propagating through a sheet of continuous sea ice can break it into a series of smaller floes
- ***sea ice state*** (i.e. whether the ice is broken) ***is a dominant process in wave attenuation***[4,5,6]



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$H = significant\ wave\ height$

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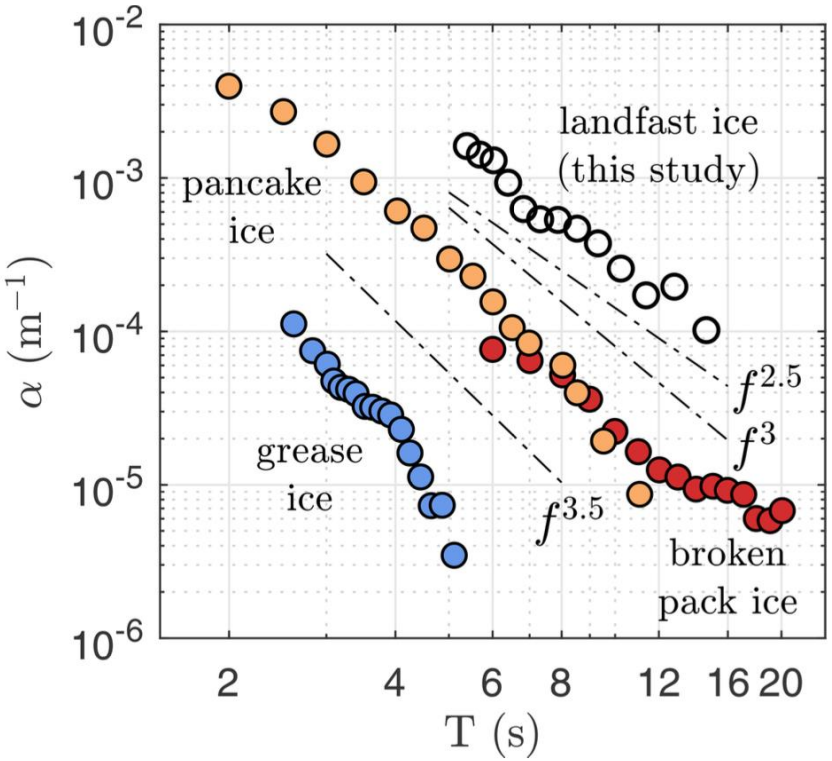

Wave dispersion and dissipation in landfast ice: comparison of observations against models

Joey J. Voermans[1], Qingxiang Liu[2,1], Aleksey Marchenko[3], Jean Rabault[4,5], Kirill Filchuk[6], Ivan Ryzhov[6], Petra Heil[7], Takuji Waseda[8], Takehiko Nose[8], Tsubasa Kodaira[8], Jingkai Li[2], and Alexander V. Babanin[1,9]

$\alpha = attenuation\ rate$
$T = wave\ period$

[4]Collins et al. (GRL 2015), [5]Ardhuin et al. (GRL 2020), [6]Voermans et al. (TC 2021)

Sea ice break up AND Attenuation

- Can we improve the YEA22 model by including information about the ice state (i.e. broken/solid)

- Does it make sense, considering that the YEA22 model is a data based model and therefore process agnostic?

- Let’s take another look at the YEA22 paper

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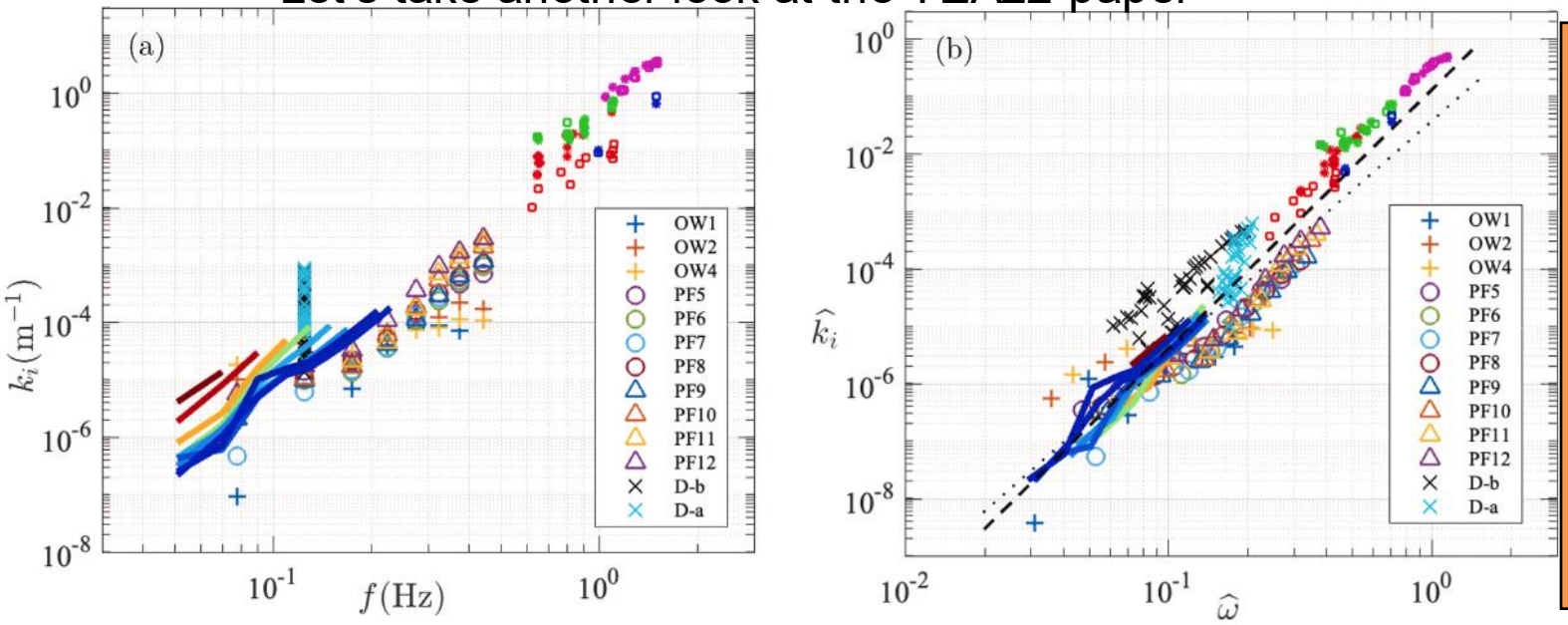

Fig. 4. (a) Dimensional plot of the PIPERS dataset (thick solid), and the field and lab datasets (symbols) from Fig. 1. (b) Normalized datasets; see Yu et al. (2019) for h_{ice} associated with the datasets from Fig. 1. Dashed: $\widehat{k_i} = 0.1274\widehat{\omega}^{4.5}$ (new model $n = 4.5$, $m = 1.25$). Dotted: $\widehat{k_i} = 0.0366\widehat{\omega}^{4}$ (case $n = 4$, $m = 1$).

- YEA22 model is a best fit through various measurement campaigns of attenuation rates.

- Been able to make a step forward thru non-dimensional scaling (fig. 4a. vs b.)

- Perhaps we still see ***evidence for two regimes***: two curves either side of the YEA22 line of best fit. This ***could be due to*** broken/solid ***ice type***

$$k_i = Ch_{ice}^{1.25} f^{4.5}, \quad \text{where} \quad C = 0.1274\left(2\pi/\sqrt{g}\right)^{4.5}$$

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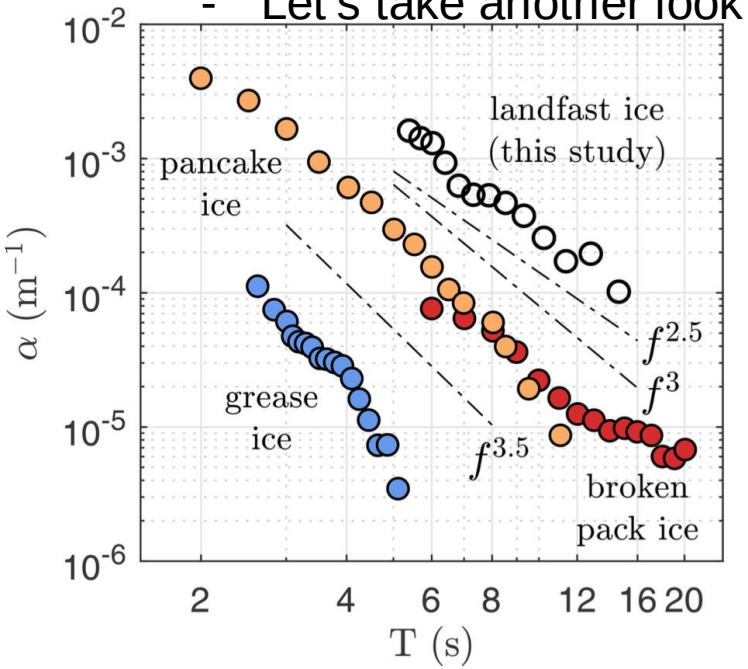

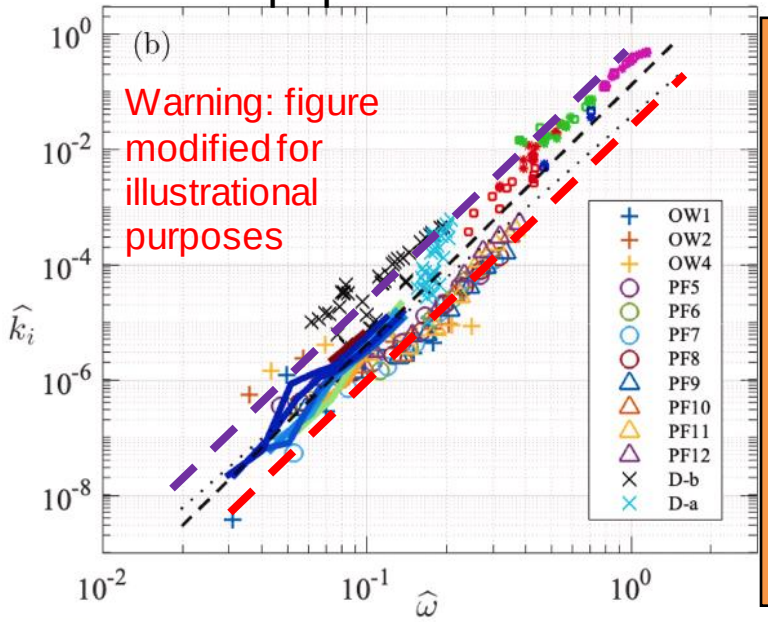

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Sea ice break up AND Attenuation

- Therefore, we implement the following…

$$k_i = \begin{cases} k_{i_{solid}} : & \beta\, \alpha_{YEA22} \\ k_{i_{broken}} : & \dfrac{1}{\beta}\, \alpha_{YEA22} \end{cases} , \quad \sim 2 < \beta < \sim 4$$

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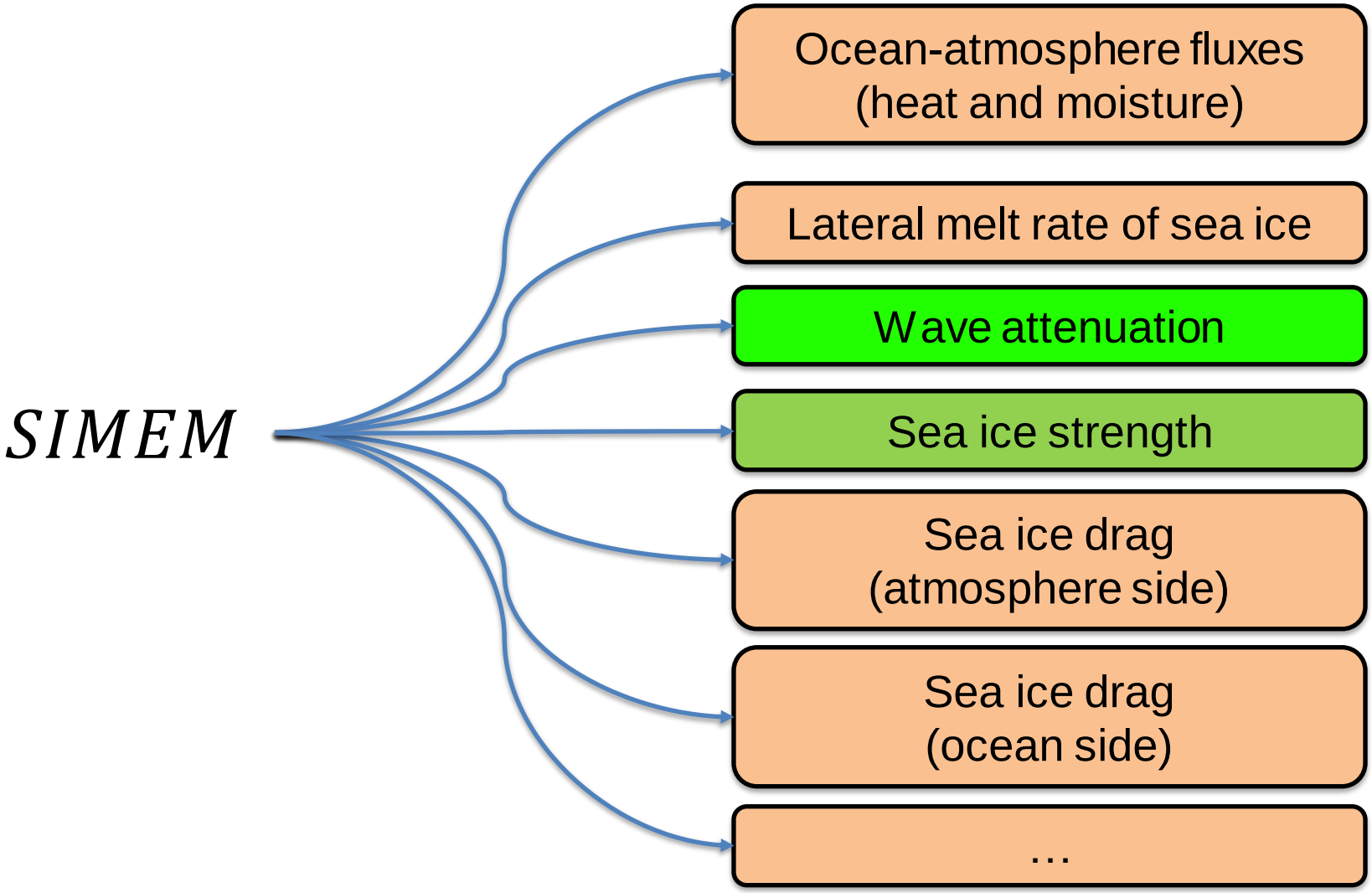
Sea ice break up, what does it effect?



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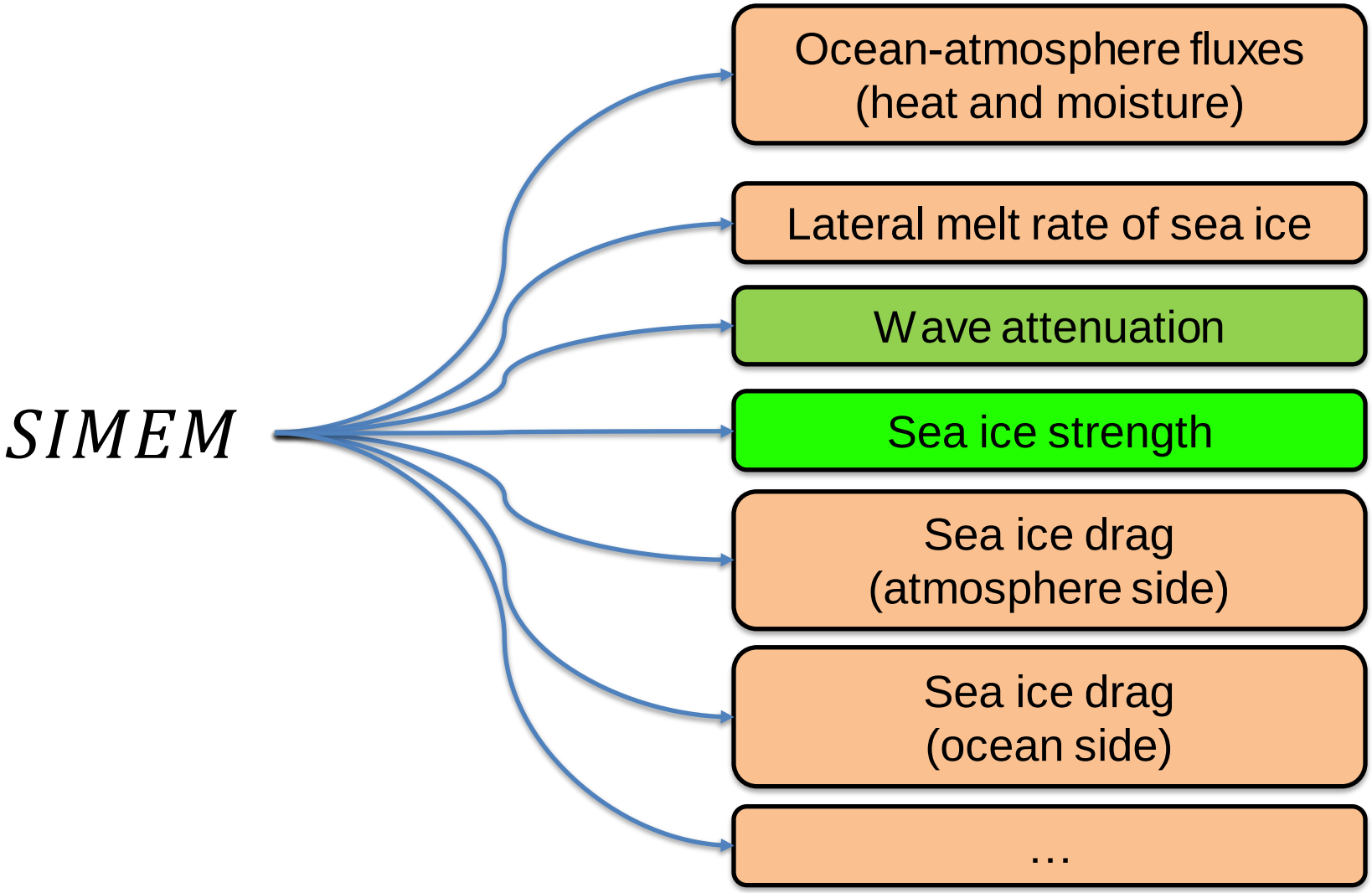

$SIMEM = sea\ ice\ break\ up\ memory$

Sea ice break up AND Sea ice strength

- The ice strength P in sea ice models represents the plastic failure criterion[6,**]

$$P = P_{H79} = P^* h_i e^{-C(1-A)}$$

- In practical terms, it determines how easy the ice breaks and therefore how easy it is to push together (allowing for ridging and rafting)

- But in the marginal ice zone (MIZ), this is much lower due to the ice already being broken up[7,8]

- Therefore, we implement the following…

$$P = \begin{cases} P_{solid}: & P_{H79} \\ P_{broken}: & \mu P_{H79} \end{cases}$$

$h_i = ice\ thickness$
$A = ice\ area$
$P^* = empirical\ constant$
$C = empirical\ constant$
$\mu = empirical\ constant = O(0.1)$

** *N. B.* sea ice is generally modelled as a highly viscous fluid, and therefore this plastic failure is not actually occurring within the model, but this is rather a parameterization of such a process

[6]Hibler (1979), [7]Auclair et al. (2021), [8]Sutherland & Dumont (2018)

Attenuated energy, where to?

$$S_{ice} \longrightarrow ?$$

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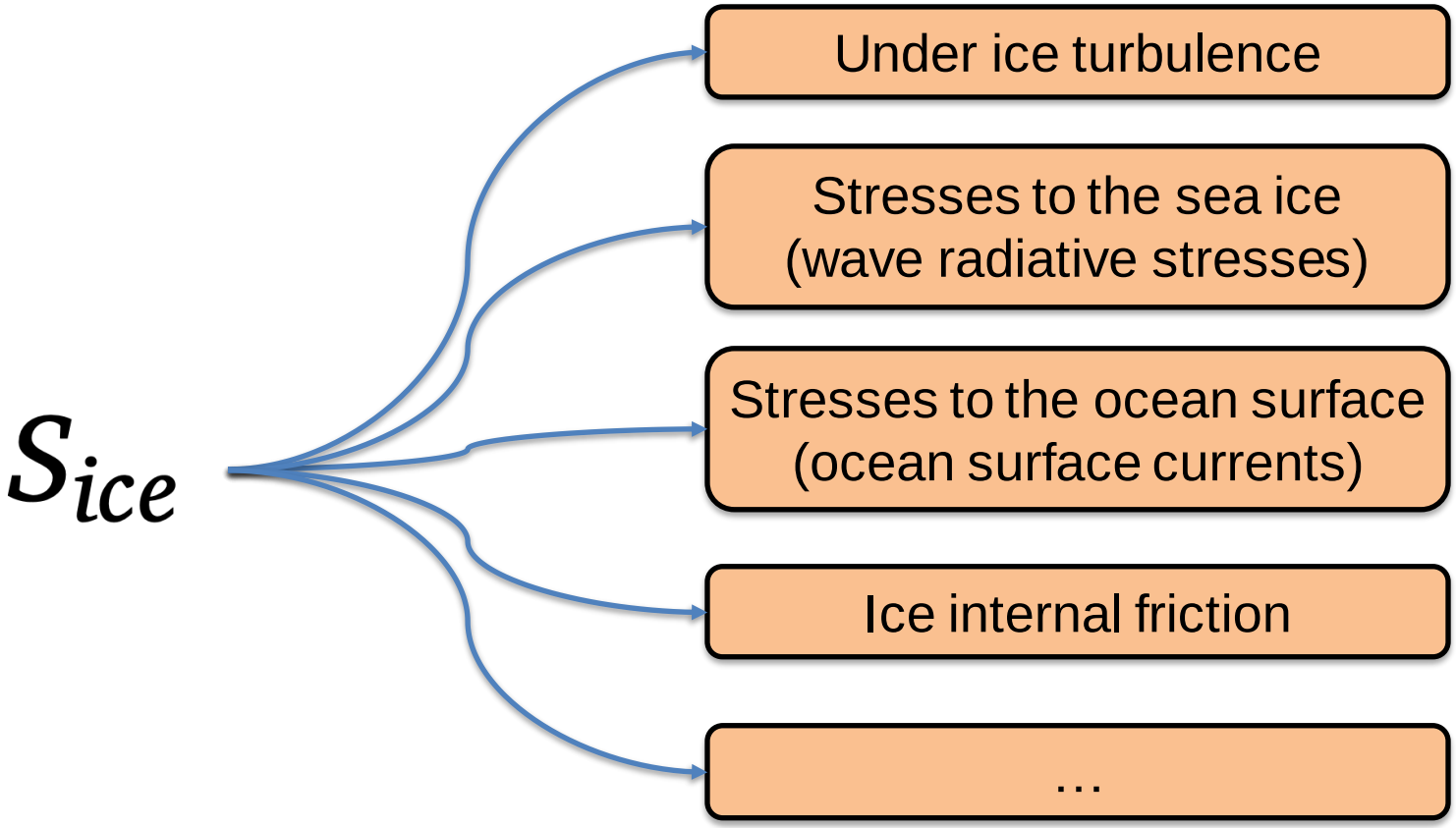
Attenuated energy, where to?



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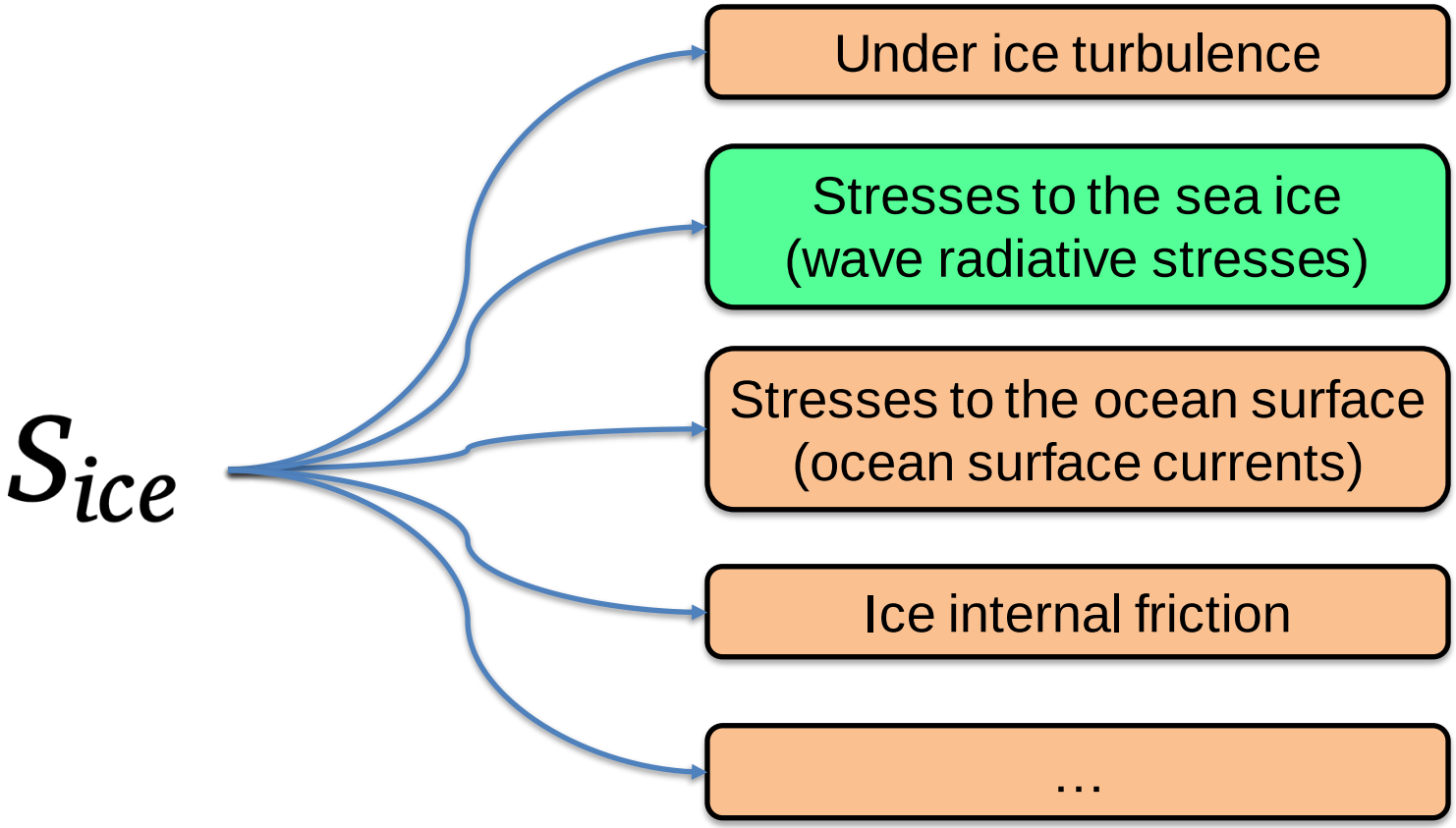
Attenuated energy, where to?



Stresses to the sea ice

wave radiative stresses to the sea ice (WRS)

- waves transport momentum; when they are attenuated in the MIZ, part of their momentum goes into sea ice

- Following Williams et al. (2017), it can be computed as**

$$\tau_{\mathrm{w},i} = \rho_{\mathrm{w}} g \int_0^{\infty} \int_0^{2\pi} \frac{-S_{\mathrm{ice}}(\boldsymbol{x};\omega,\theta)}{\omega/k} (\cos\theta, \sin\theta) \mathrm{d}\theta \mathrm{d}\omega, \qquad (1)$$

- Which can then be sent to the sea ice model and added as an additional term in the momentum equation

$$m D_t \boldsymbol{u} = \nabla \cdot \boldsymbol{\sigma} + c(\tau_{\mathrm{a}} + \tau_{\mathrm{o}}) + \tau_{\mathrm{w},i} - m f \boldsymbol{k} \times \boldsymbol{u} - m g \nabla \eta, \quad (2)$$

** *N. B.* Using the full S_{ice} term here assumes that all attenuated wave energy is converted to WRS (neglecting processes highlighted on the previous slide). This formulation for WRS should rather be treated as an upper bound.

$\tau_{w,i} = wave\ stress\ to\ ice$
$\rho_w = water\ density$
$g = gravity$
$\theta = wave\ direction$

$m = mass\ (ice\ and\ snow)$
$\boldsymbol{u} = ice\ velocity\ vector$
$\boldsymbol{\sigma} = internal\ stress\ tensor$
$f = Coriolis\ parameter$
$\boldsymbol{k} = unit\ vector\ pointing\ upwards$
$\eta = sea\ surface\ elevation$
$c = sea\ ice\ concentration$
$\tau_a = atmospheric\ stress\ to\ ice$
$\tau_o = ocean\ stress\ to\ ice$

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Formulation and explanation taken from Boutin et al. (2020) for convenience

Wave-Sea ice coupling in the ECMWF earth system model

Operational** setup (CY49R2)

ecWAM (wave model)

- $SIC < 30\%$: no wave attenuation by sea ice
- $SIC > 30\%$: wave model masked; full wave attenuation by sea ice

SI3 (sea ice model)

SIC

**not yet actually operational, but this cycle is taken for illustrative purposes as this is the launching point for this work

Wave-Sea ice coupling in the ECMWF earth system model

Proposed setup for next cycle (CY50R1)

Control

ecWAM (wave model)

New features

- Wave in sea ice attenuation routine $YEA22$

SI3 (sea ice model)

Effect

- wave attenuation SIC, SIT

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Wave-Sea ice coupling in the ECMWF earth system model

Proposed setup for future cycle (CY51R1+)

Full wave-sea ice coupling

Effect
- sea ice break up H_s, k_p
- wave radiative stress $\tau_{w,i}$

ecWAM (wave model)

New features
- Wave in sea ice attenuation routine $YEA22$
- Attenuation modified by sea ice state $SIMEM$

SI3 (sea ice model)

New features
- Prognostic sea ice breakup memory $SIMEM$
- $strength$ reduced for broken ice μ

Effect
- wave attenuation $SIC, SIT, SIMEM$

$$k_i = \begin{cases} k_{i_{solid}} : & \beta\, \alpha_{YEA22} \\ k_{i_{broken}} : & \frac{1}{\beta}\, \alpha_{YEA22} \end{cases}, \quad \sim 2 < \beta < \sim 4$$

$SIMEM$
- Percentage of grid cell that is solid ice
- Advected field
- Broken by waves
- Healed in conditions of ice formation

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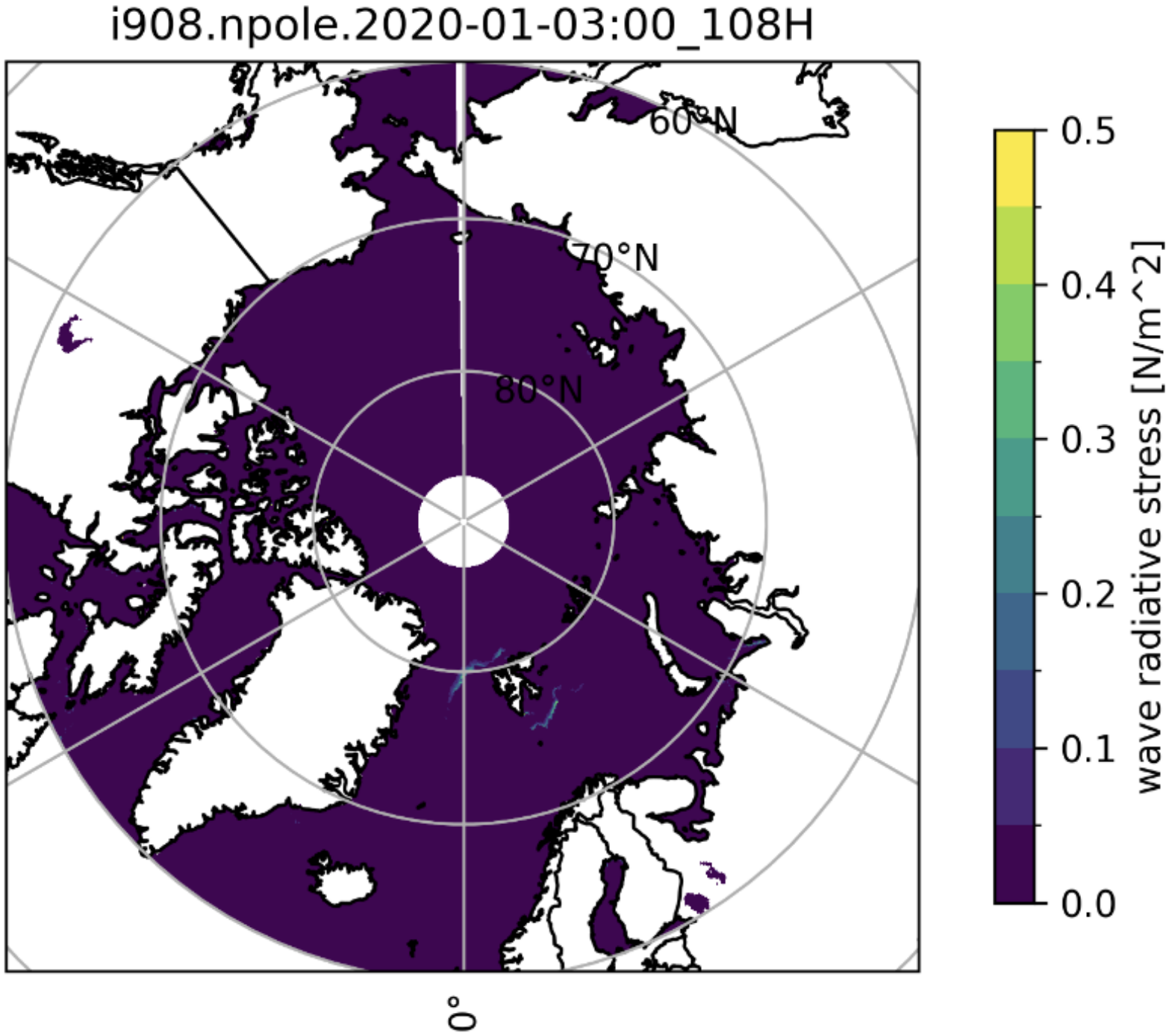
Does it do anything?

Does it do anything?

$\tau_{w,i}$



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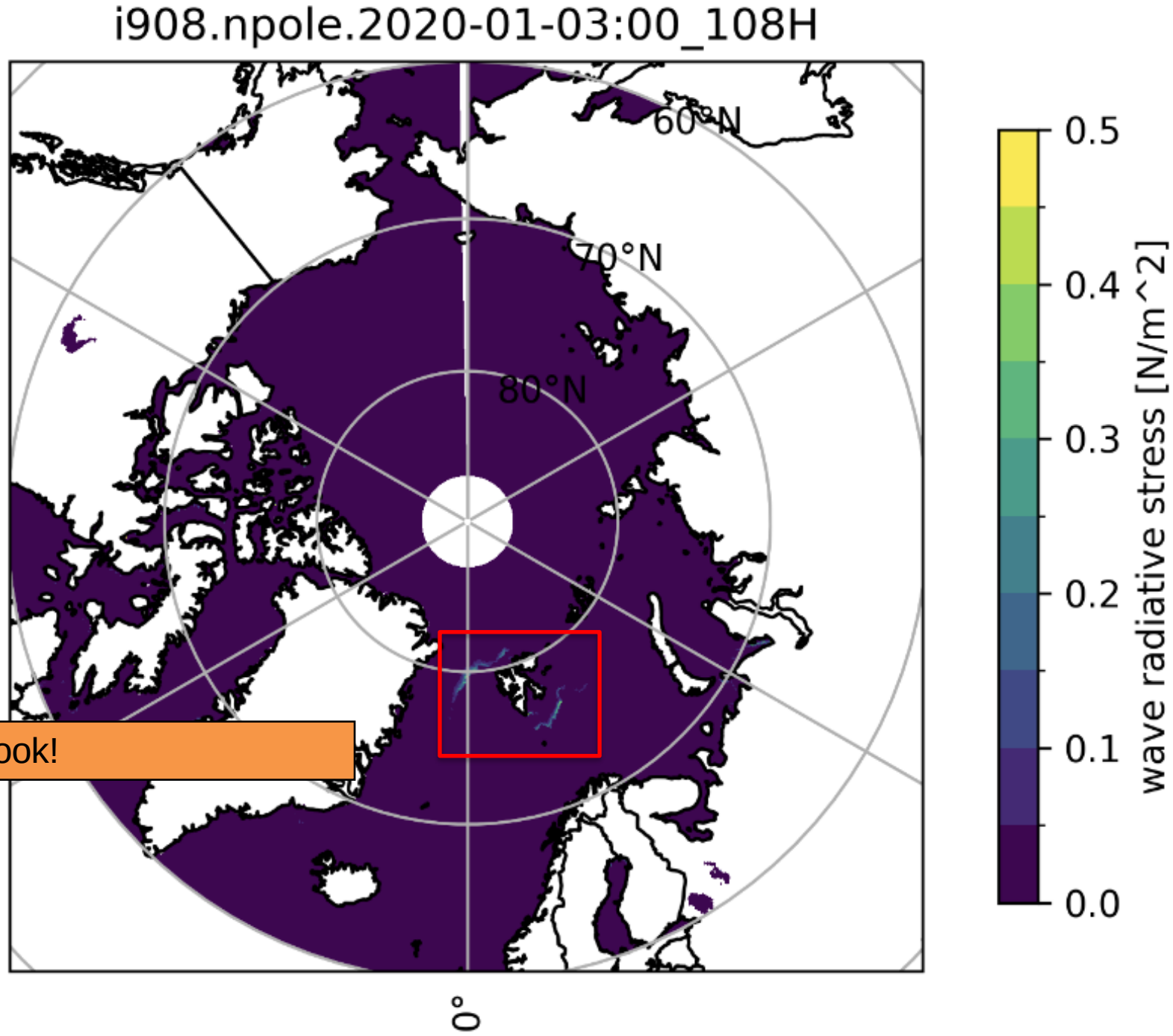
Does it do anything?

$\tau_{w,i}$

Wow! Let's take a closer look!



ECMWF

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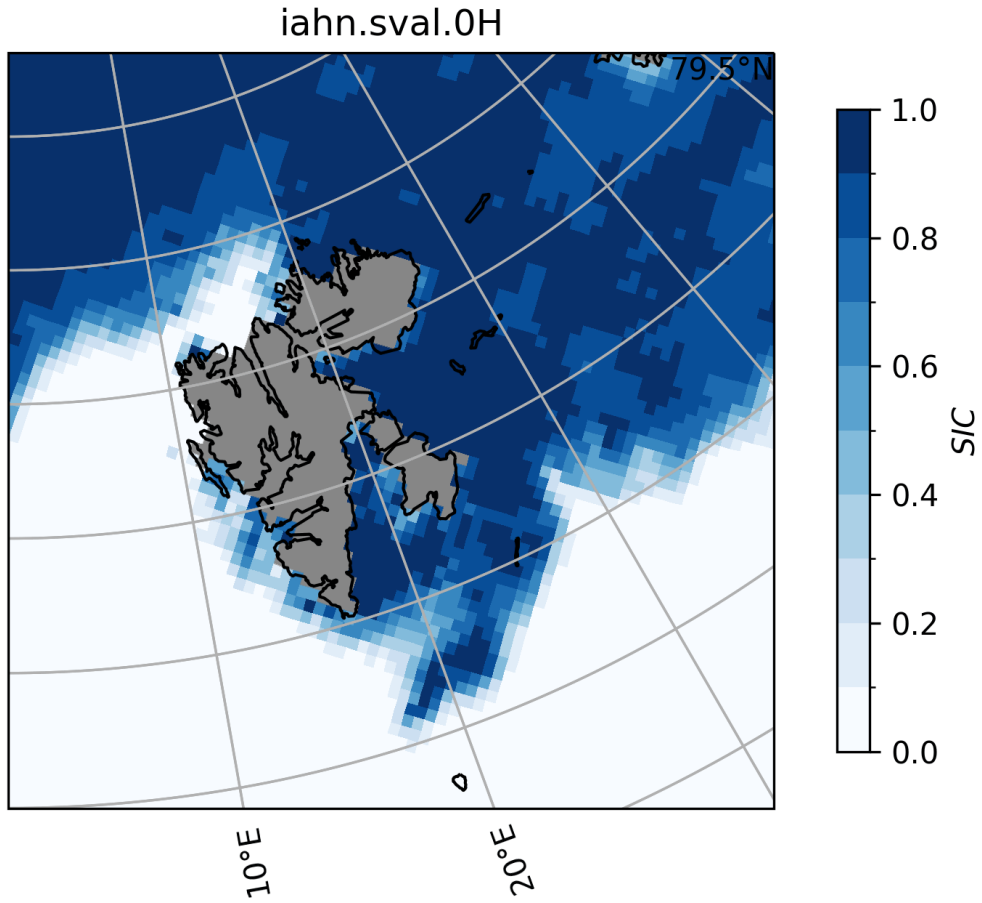
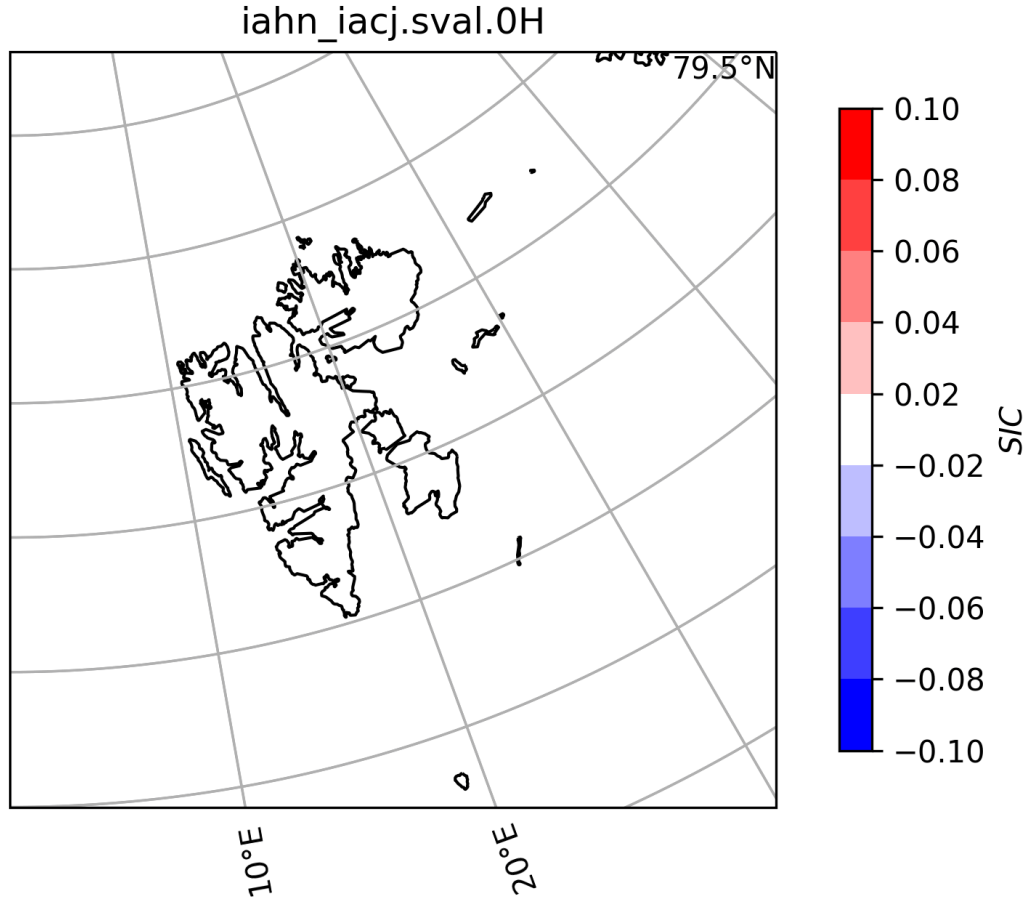
Control



SIC diff
(Full wave-sea ice coupling minus **control)**



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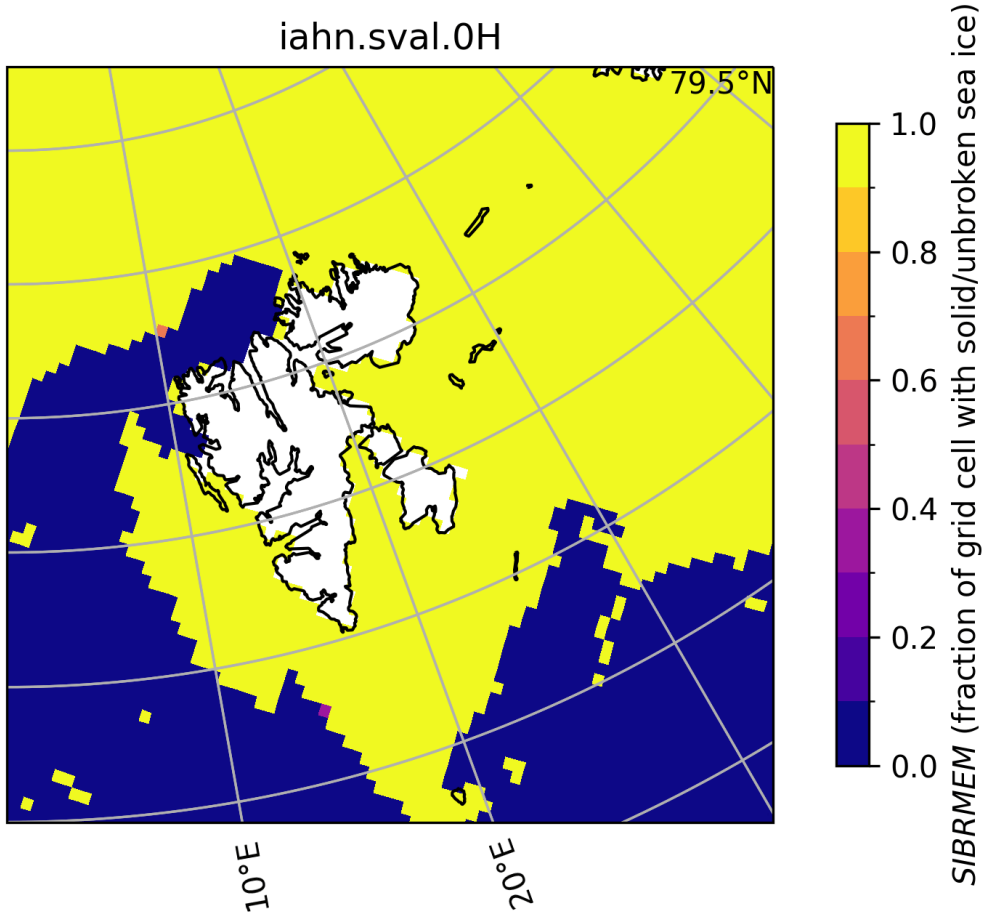
SIMEM
(Full wave-sea ice coupling)



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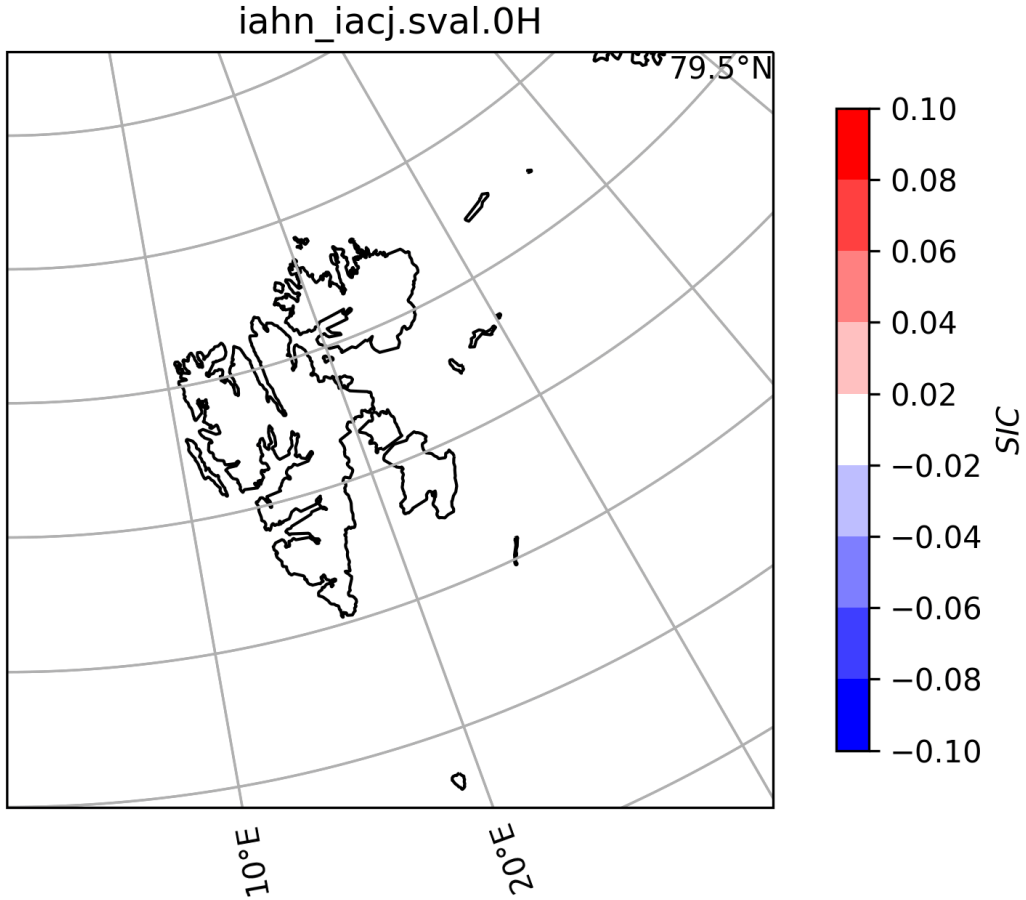

ECMWF

Sensitivity: ***wave radiative stress***

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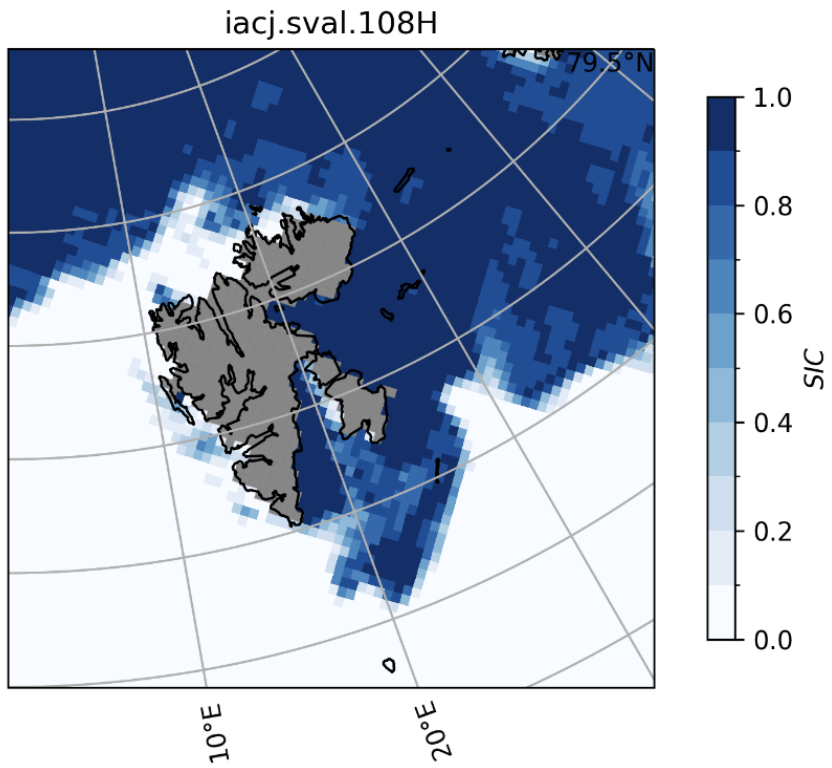
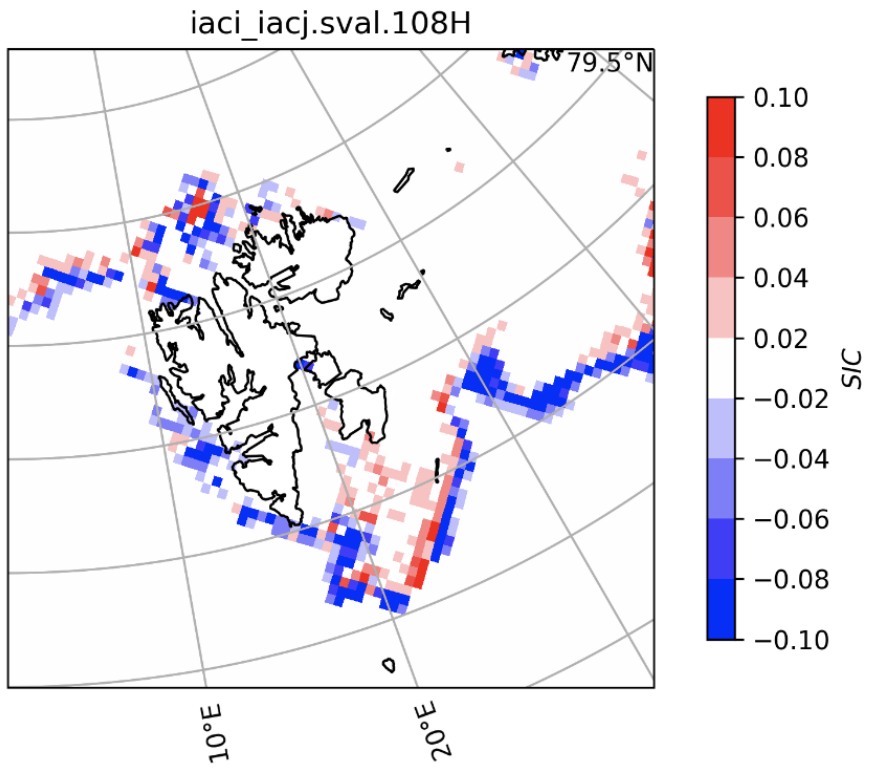
Control



Difference



- WRS compacts the MIZ
- consistent with Williams et al. (2017) and Boutin et al. (2020)

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Sensitivity: ***ice breakup and strength modification***

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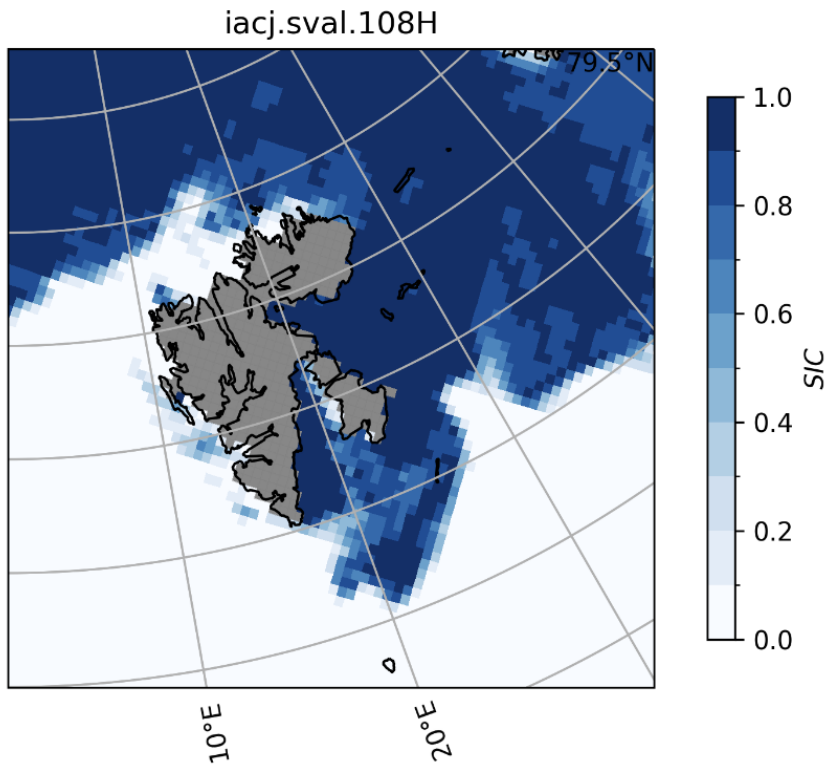
Control



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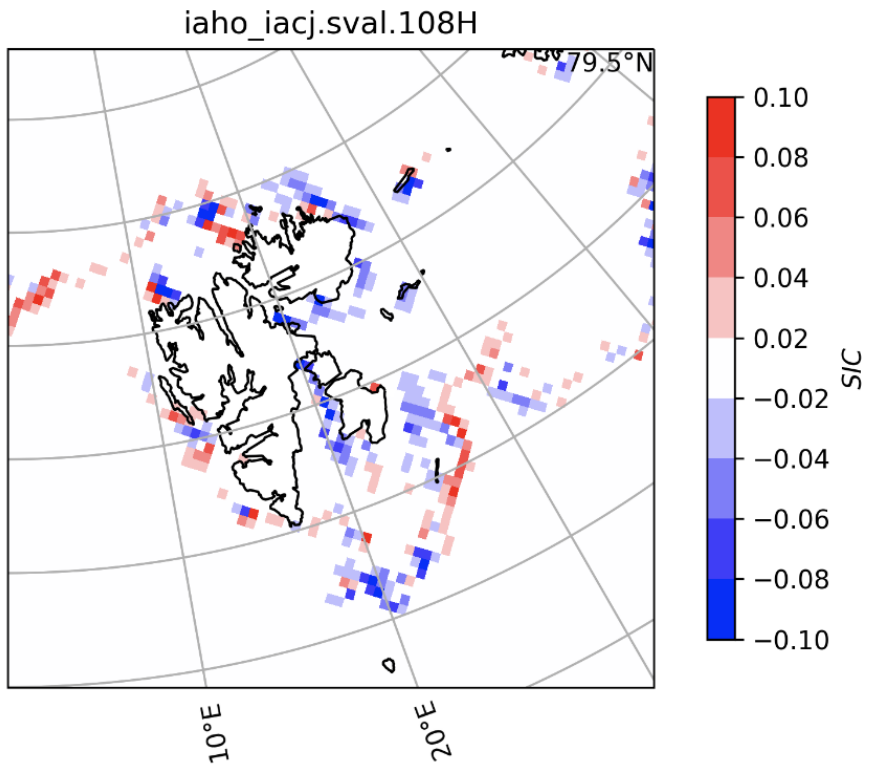

- Leads to formation of more ice in the MIZ
- Leads to reduction of ice in the ice pack
- Does this make sense?

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Sensitivity:

wave radiative stress +

ice breakup and strength modification

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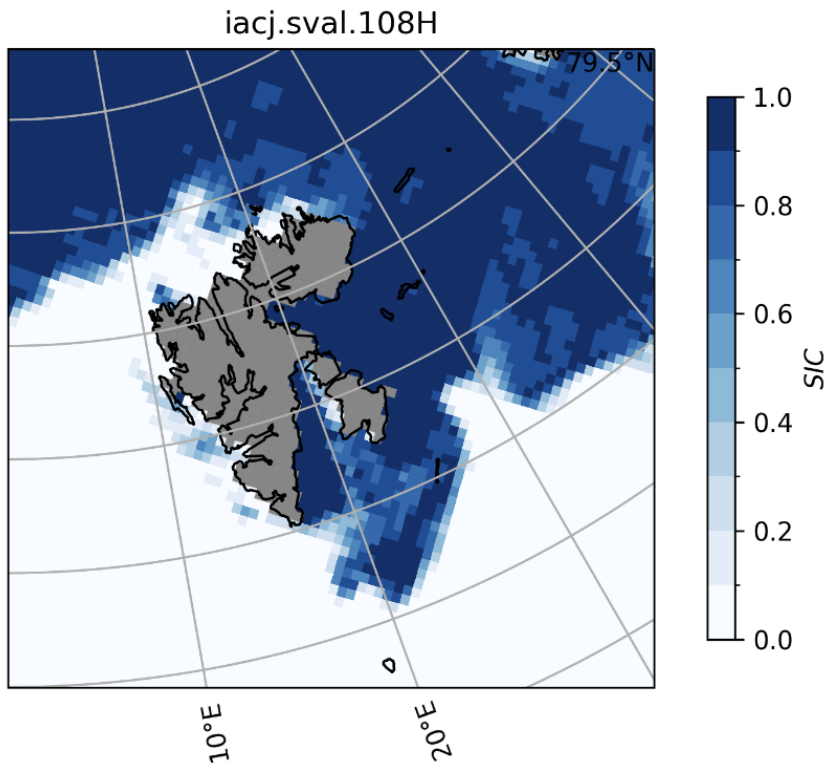
Control



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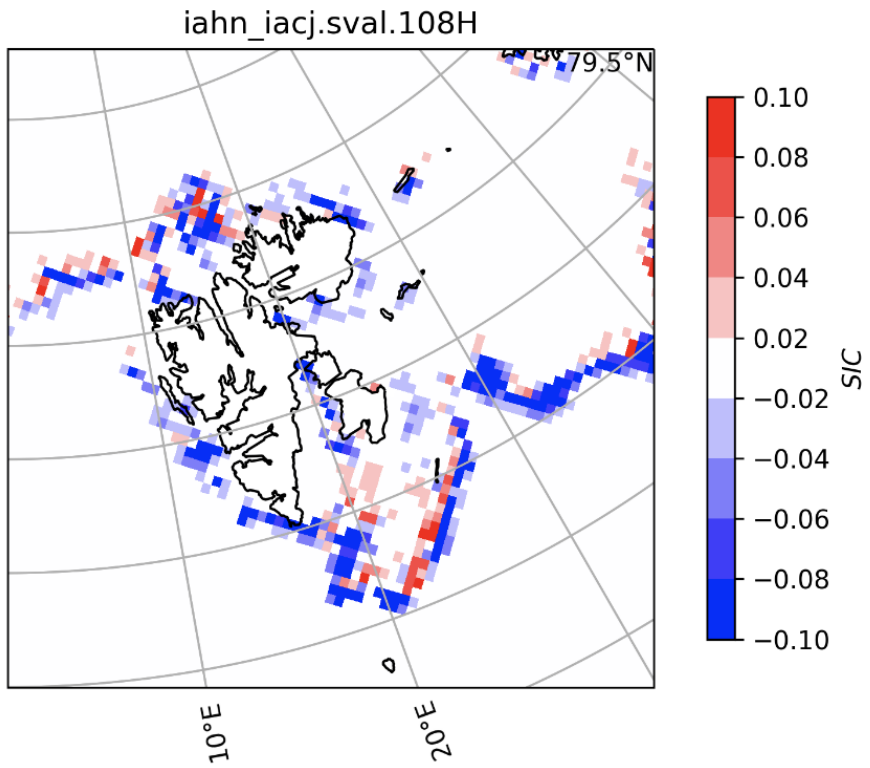

- Combined effect looks largely to be dominated here by WRS

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Sensitivity:
wave attenuation modulation by $SIMEM$

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β=1

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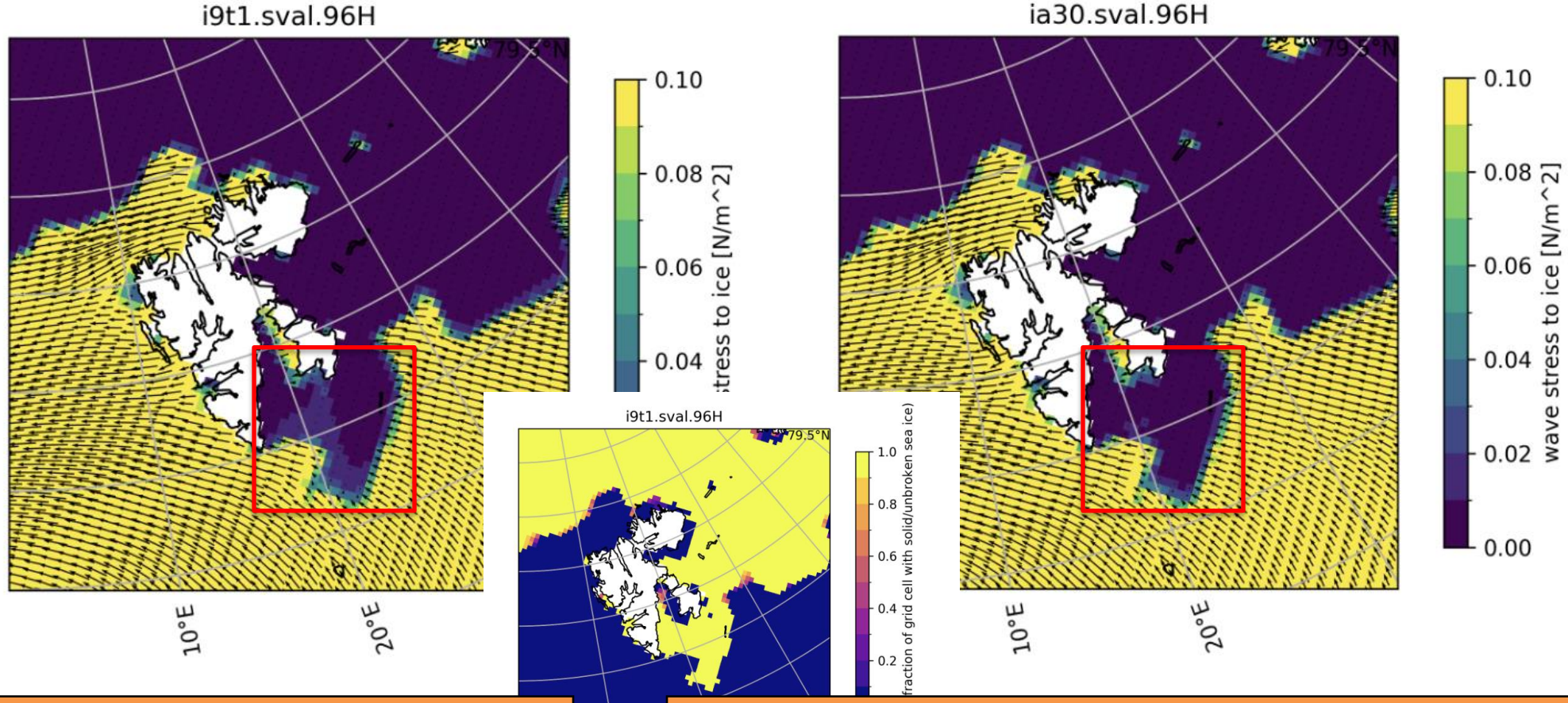
β=4



- Attenuation is the same everywhere
- Energy and stresses imparted throughout ice

- Attenuation strong internally within the ice, weak in MIZ
- All energy and stresses imparted at ice edge

Anything else?

- Further Development
  - Implement healing/refreeze of $SIMEM$
- Verification
  - Time scales: seasonal, case studies
  - Observational Products:
    - Wave buoys in sea ice (Rabault et al., 2023)
    - satellite altimeter database: surprisingly useful for verifying amount of wave energy that passes through the sea ice and re-enters the open ocean (see extra slide on this)
  - Model Analysis: run new model setup with the ECMWF data assimilation system and compare model forecast against model analysis
- Tuneable parameters (parameters with uncertainty)
  - Sea ice properties Y, σ
  - Strength modulation μ
  - Attenuation modulation β
- Floe size distribution… will be implemented within the ECMWF-NEMO/SI3 system sometime in the future. Provides a good opportunity for further research and development in this space.

Summary

Summary

Full wave-sea ice coupling

Effect
- sea ice break up H_s, k_p
- wave radiative stress $\tau_{w,i}$

ecWAM (wave model)
New features
- Wave in sea ice attenuation routine $YEA22$
- Attenuation modified by sea ice state $SIMEM$

SI3 (sea ice model)
New features
- Prognostic sea ice breakup memory $SIMEM$
- $strength$ reduced for broken ice μ

Effect
- wave attenuation $SIC, SIT, SIMEM$

$$k_i = \begin{cases} k_{i_{solid}} : & \beta\, \alpha_{YEA22} \\ k_{i_{broken}} : & \frac{1}{\beta}\, \alpha_{YEA22} \end{cases}, \quad \sim 2 < \beta < \sim 4$$

$SIMEM$
- Percentage of grid cell that is solid ice
- Advected field
- Broken by waves
- Healed in conditions of ice formation

ECMWF

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Extra Slides

Effect of ***sea ice*** on ***waves***

NEW minus OPER **CY48_v7**

OPER=ecWAM operates for SIC<30%; no attenuation by ice

NEW=ecWAM operates for SIC<100%; new attenuation by ice

mean diff ecWAM hindcast **rmse diff**

- YEA22 reduces amount of wave energy that leaves the marginal ice zone (MIZ) and passes back into the global ocean

ECMWF

Effect of ***sea ice*** on ***waves***

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OPER=ecWAM operates for SIC<30%; no attenuation by ice

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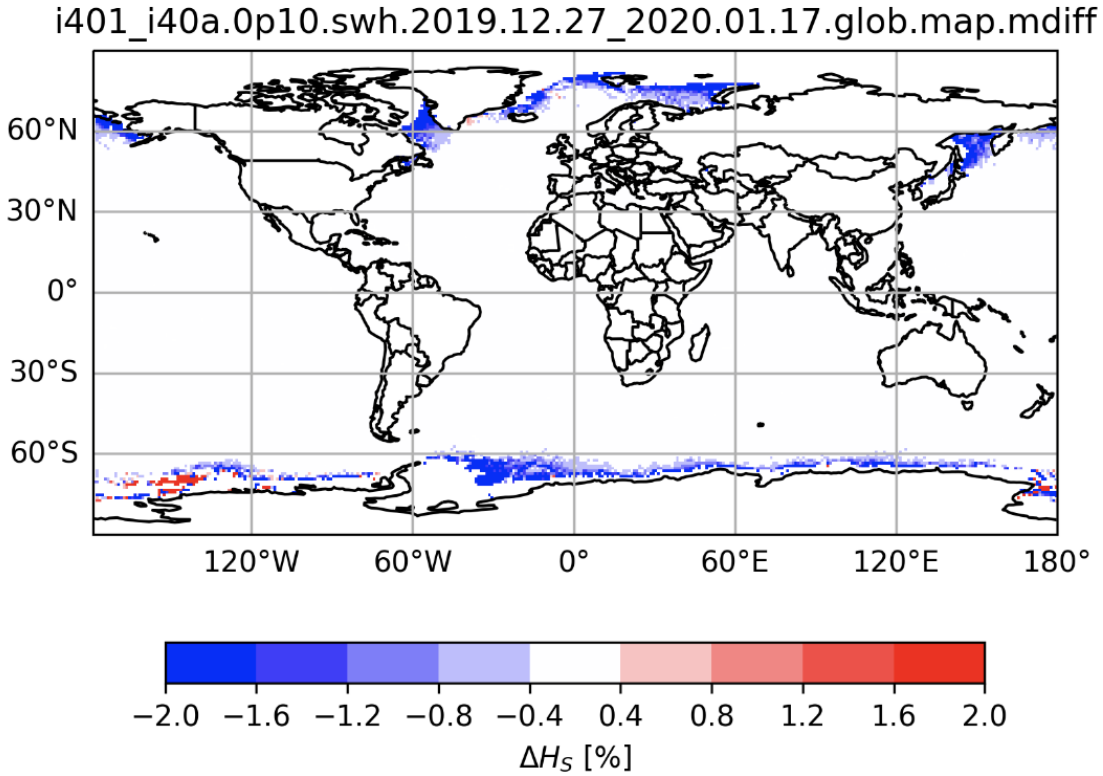
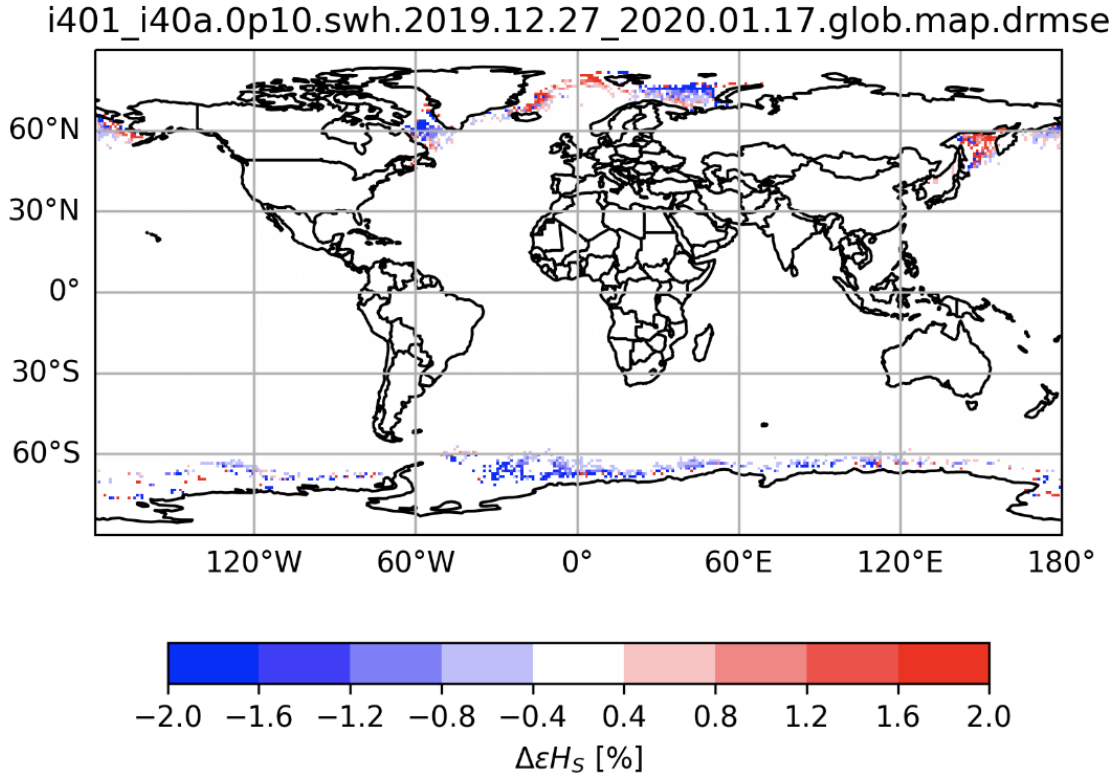
mean diff

ecWAM hindcast**

rmse diff





- YEA22 reduces amount of wave energy that leaves the marginal ice zone (MIZ) and passes back into the global ocean

ECMWF

****refers here to stand alone ecWAM forced by operational analysis**

Effect of ***sea ice*** on ***waves***

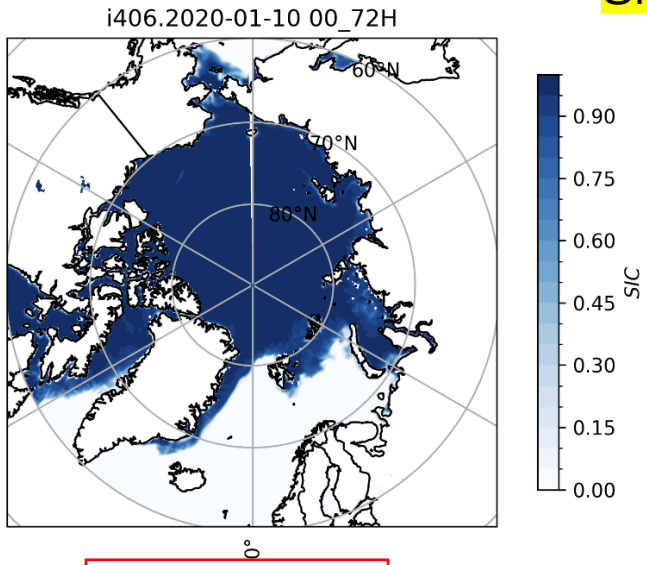
NEW minus OPER **CY48_v7**

OPER=ecWAM operates for SIC<30%; no attenuation by ice

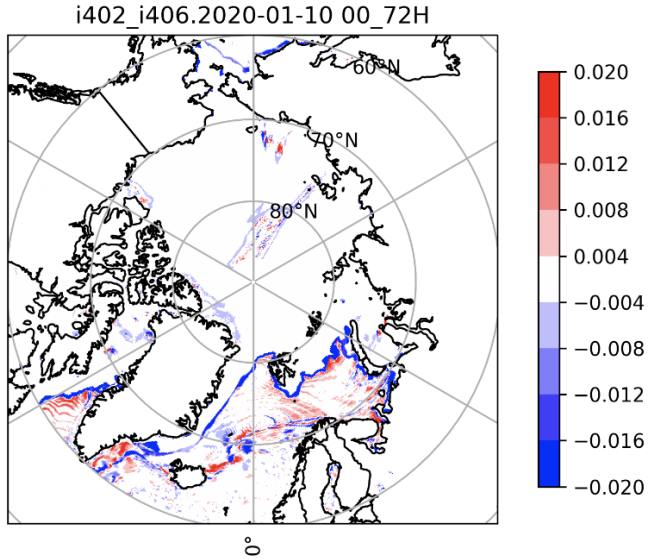
NEW= ates for SIC<100%; new attenuation by ice

SIC

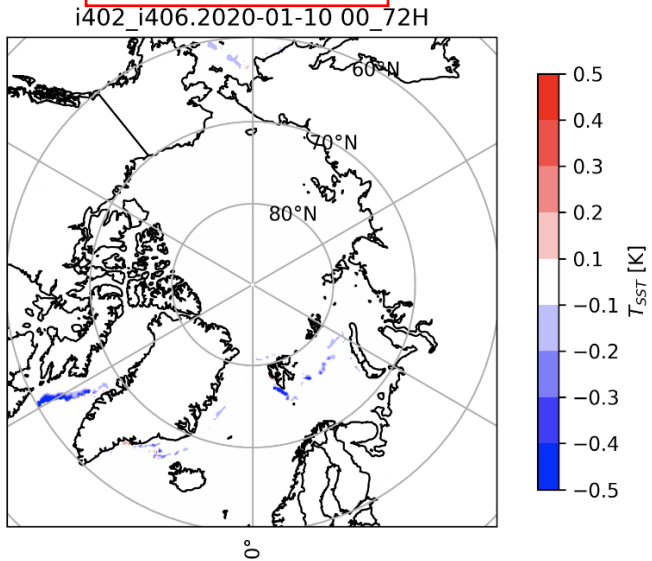
IFS forecast (day 3)
SNAPSHOT



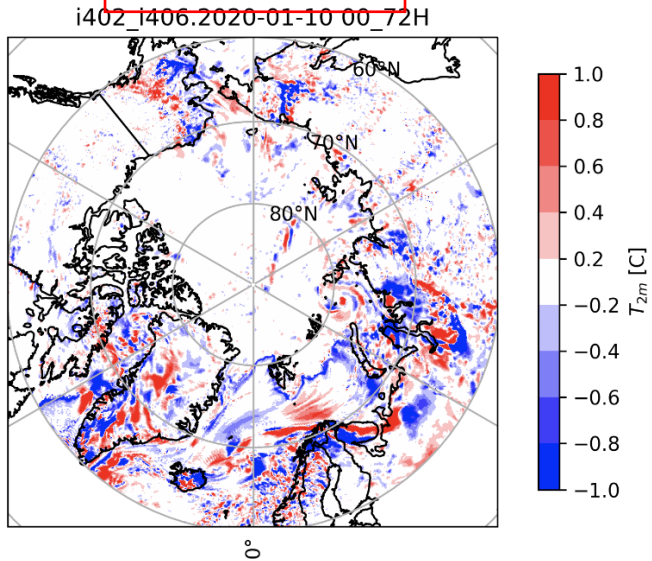
Δ charnock



Δ sst



Δ t2m



Coupled system: start to see much more happening around the MIZ…

- Charnock reduces
- Wind increases
- Cooling of t2m and sst

The main cause of these changes in the atmosphere is removing the mask for SIC>30% in ecWAM

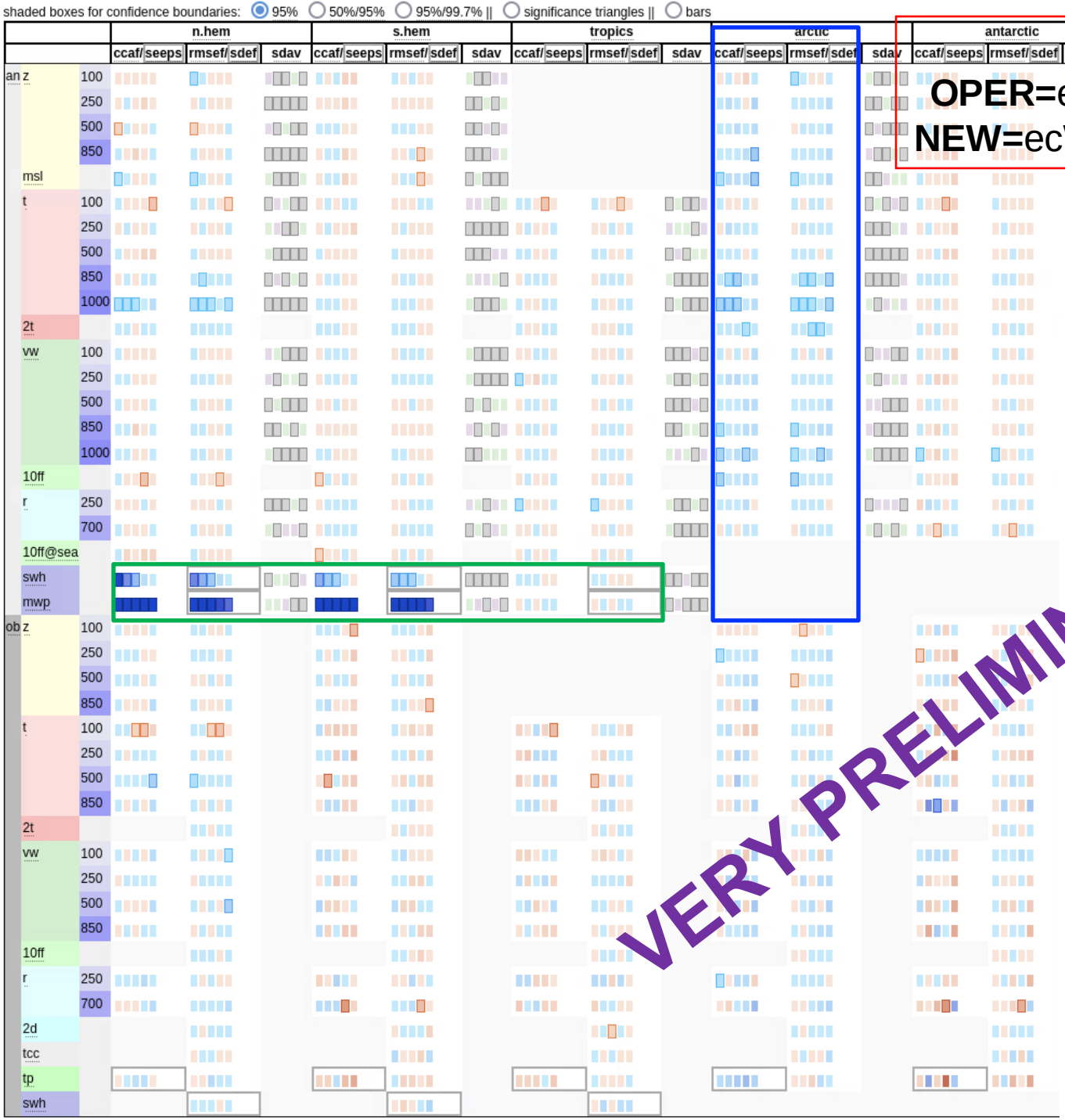
- Ensures ecWAM (and not parameterisations) is the air-sea-ocean interface

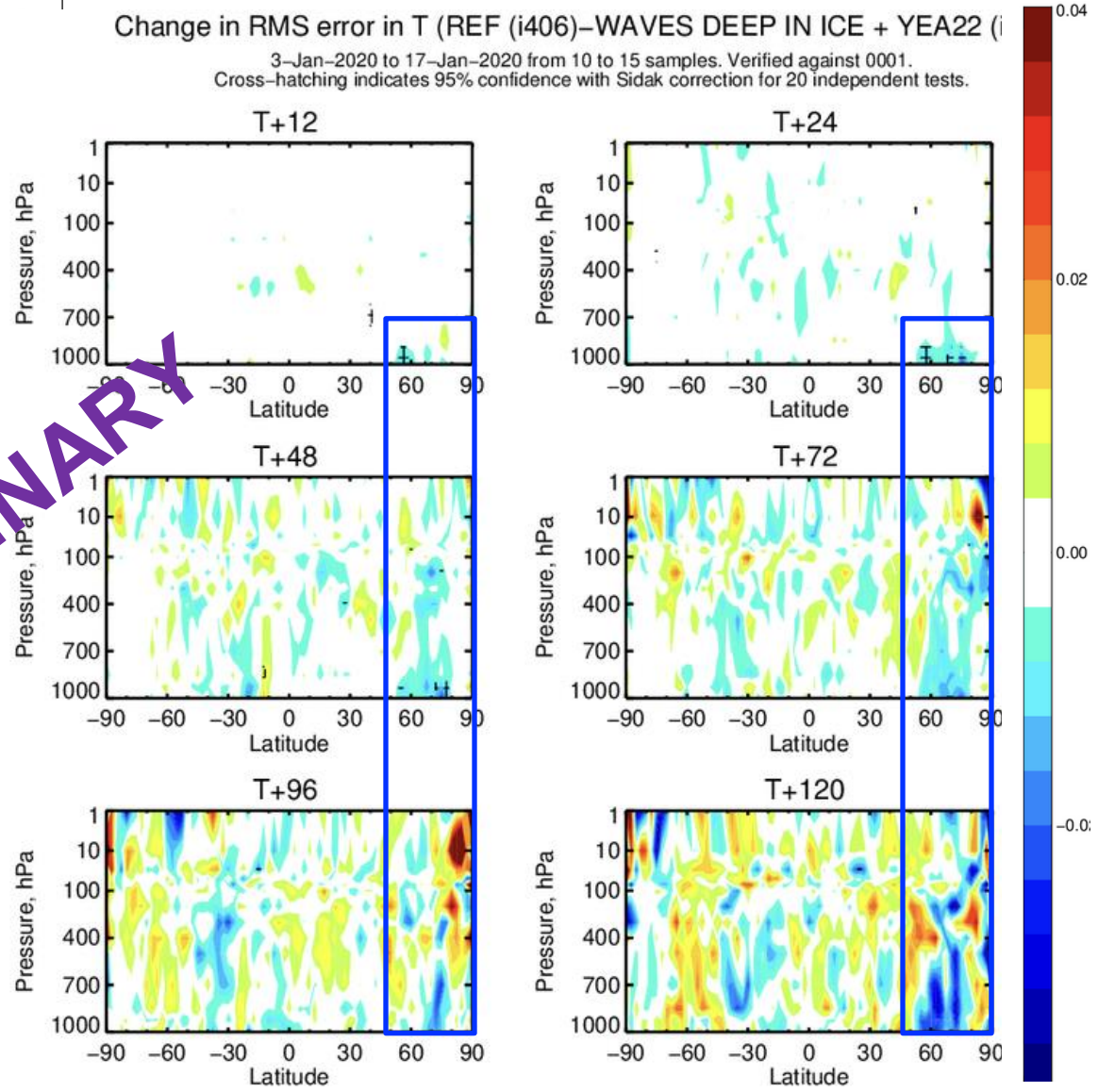
NEW minus OPER

CY48_v7

OPER=ecWAM operates for SIC<30%; no attenuation by ice

NEW=ecWAM operates for SIC<100%; new attenuation by ice





Sea ice break up AND Attenuation

- Therefore, we implement the following…

- Therefore, we implement the following…

- β^2 aims to represent the difference in attenuation rates between solid and broken ice
- Can infer $\beta^2 = O(10)$ from figure in Voermans et al. (2021)

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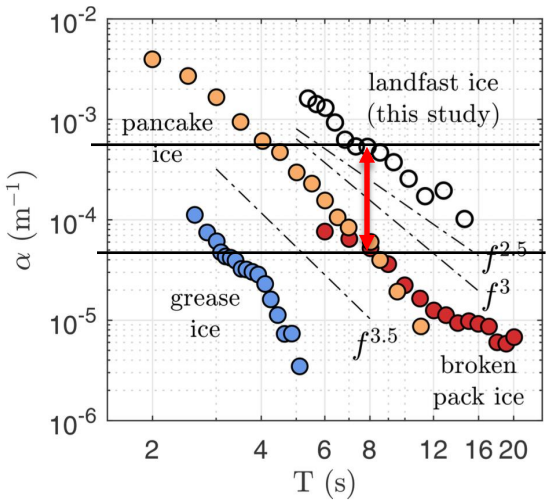
- Can infer $\beta^2 = O(10)$ from figure in Voermans et al. (2021)



Warning: figure modified for illustrational purposes

ECMWF

Sea ice break up AND Sea ice strength

In his seminal paper, Hibler [30] defined the ice strength P_p as follows:

$$P_{\text{Hibler}} = P^* h \, \mathrm{e}^{-C(1-A)}, \tag{2.14}$$

where P^* and C are the strength and concentration parameters, respectively. This formulation has been widely adopted and applied to represent compact ice conditions of the inner ice pack in large-scale ice models. In the MIZ, where sea ice is usually fragmented in small pieces (floes) that heave, tilt and surge in response to waves, ice thickens homogeneously as a result of floe rafting and brash convergence instead of breaking at localized ridging lines [23]. For such cases, a Mohr-Coulomb formulation developed for river ice jumbles [33] provides an appropriate description of

$$P_{\text{hybrid}} = P^* h \tanh(\gamma h) \, \mathrm{e}^{-C(1-A)}, \tag{2.17}$$

ECMWF

Taken from Auclair et al. (2021)

Sea ice break up AND Sea ice strength

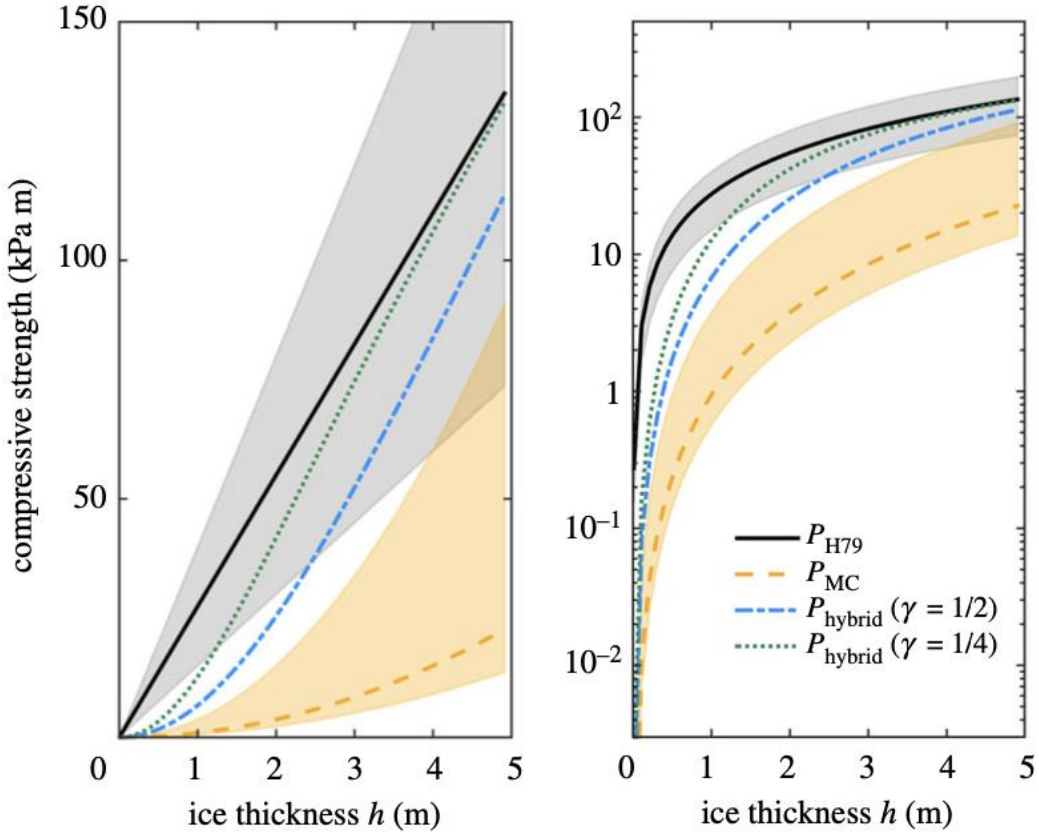


Figure 1. Parameterizations of ice compressive strength as a function of ice thickness in linear (left) and logarithmic (right) scales: P_{H79} refers to equation (2.14) (black solid line), P_{MC} to equation (2.15) (yellow dashed line) and P_{hybrid} to equation (2.13) for $\gamma = 1/2$ (blue dash-dotted line) and $\gamma = 1/4$ (green dotted line). Shaded areas represent the range of possible values found in the literature. (Online version in colour.)

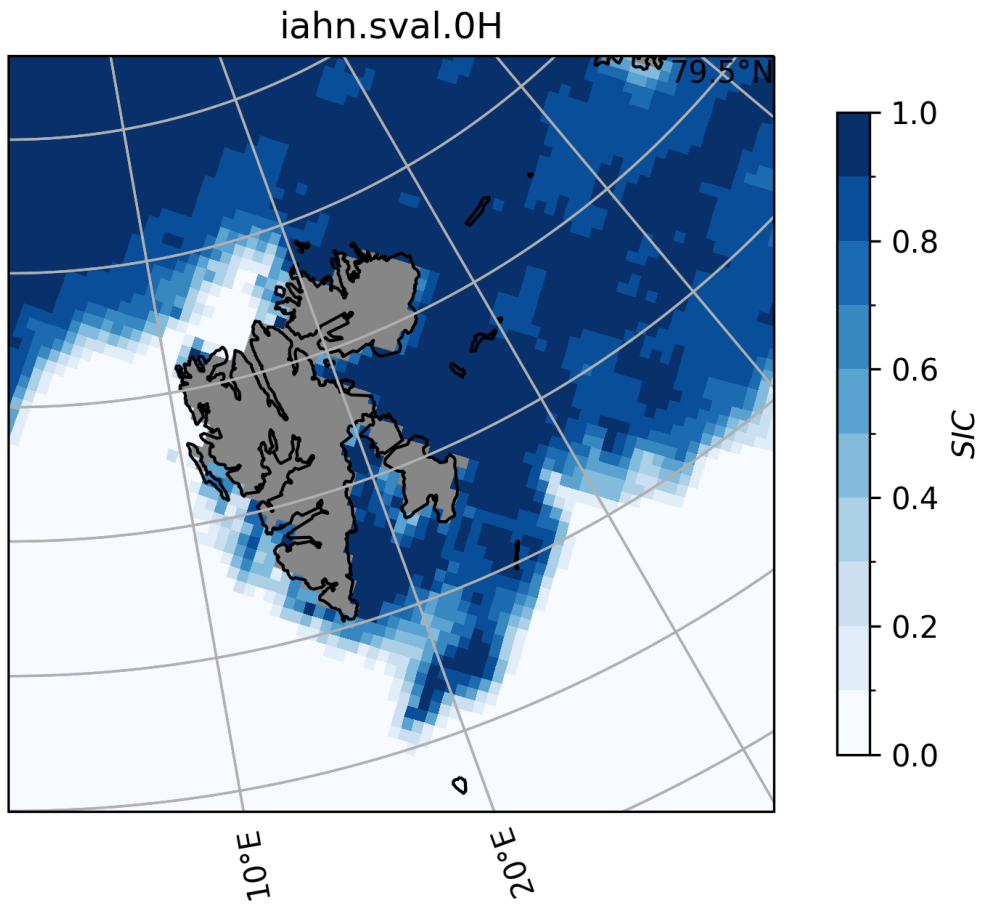
ECMWF

Taken from Auclair et al. (2021)

sea ice concentration

fc 2020-01-04

Control



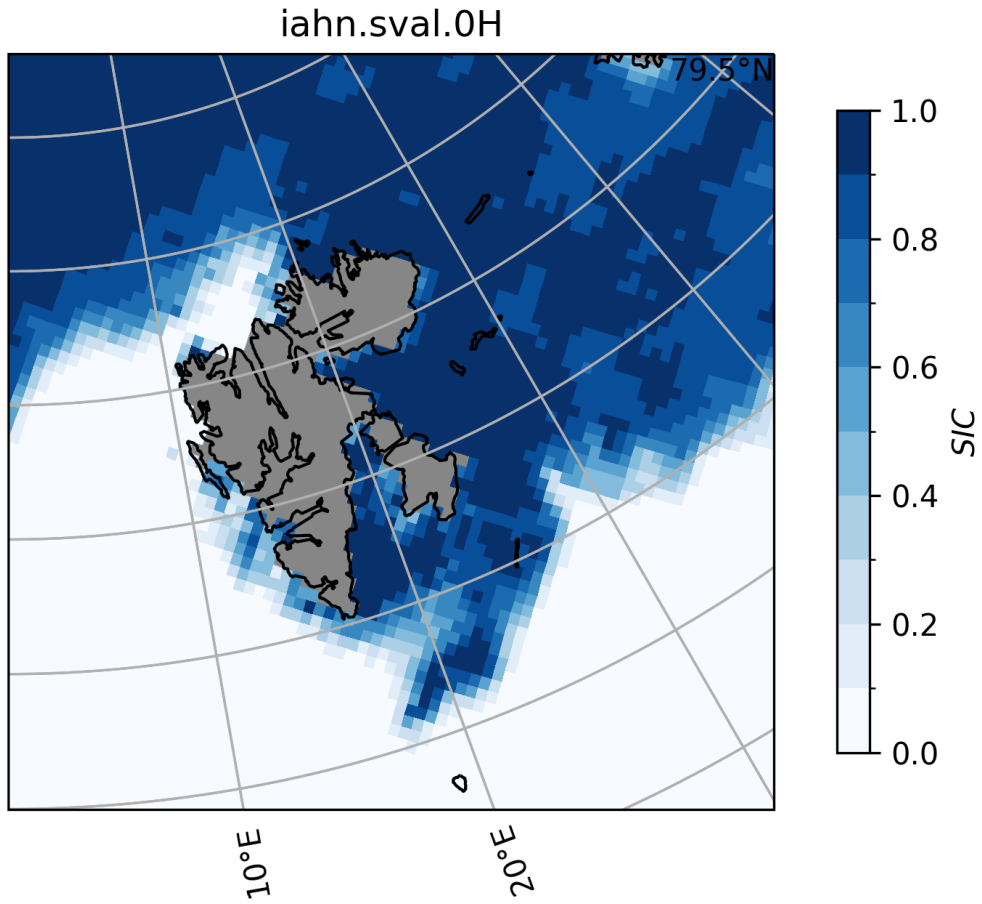
- Svalbard, winter, 10 day forecast
- Sea ice field evolving with storm (both advancing and retreating)

ECMWF

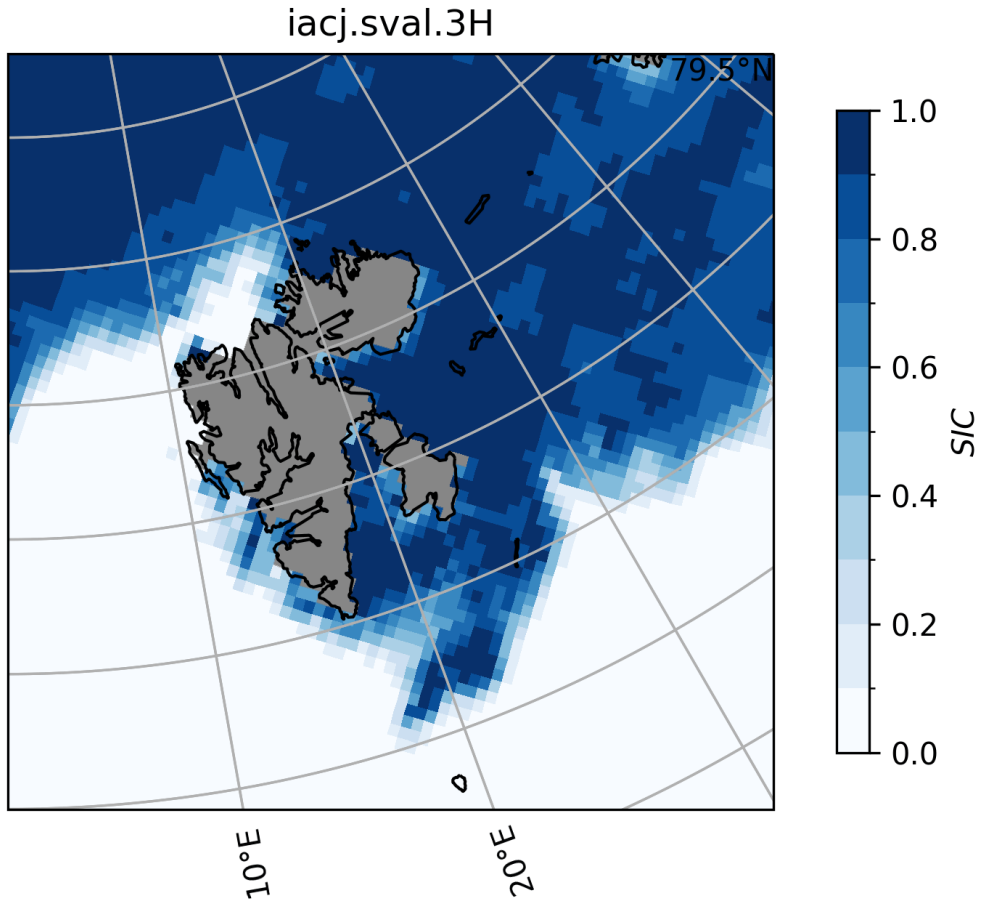
sea ice concentration

fc 2020-01-04

Control



Full wave-sea ice coupling

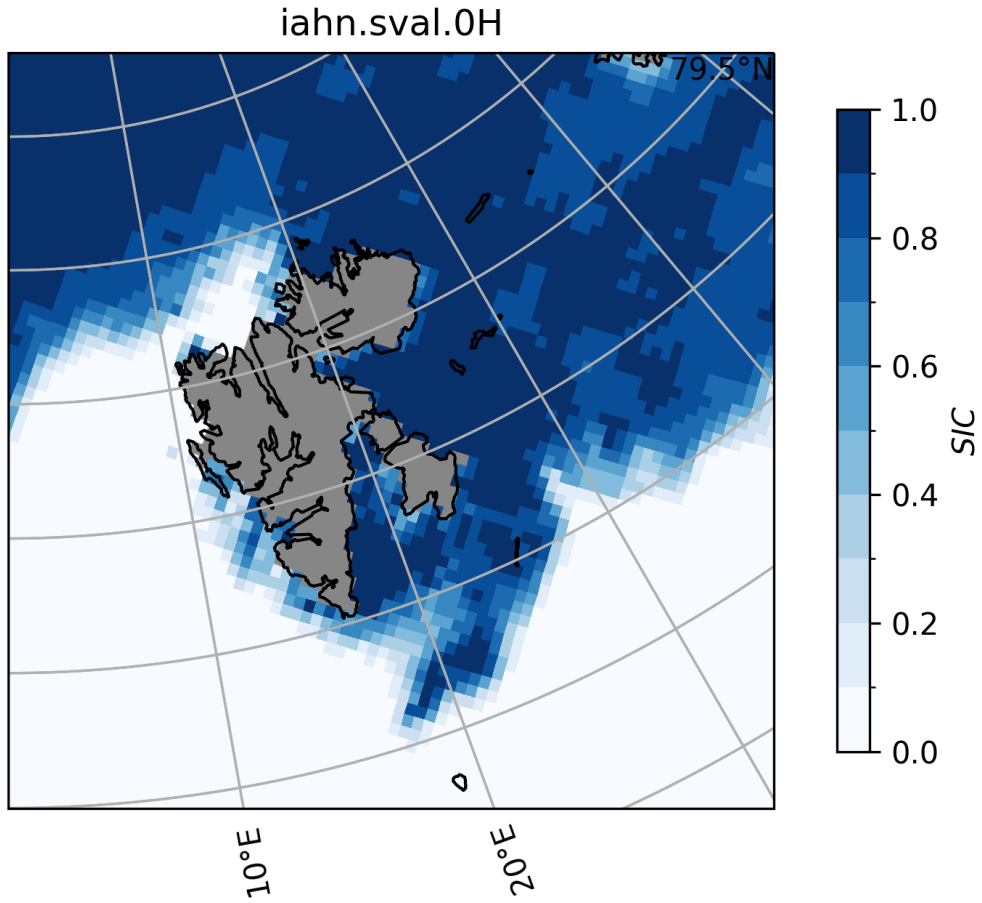


ECMWF

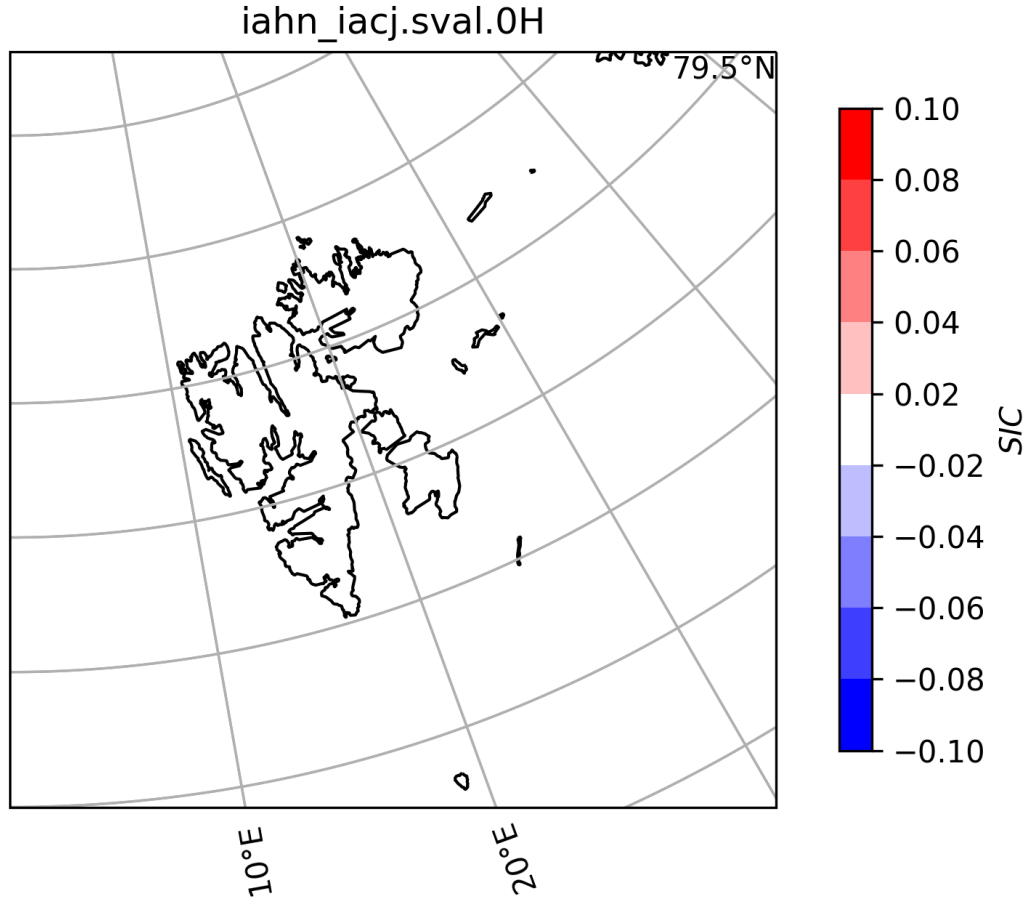
sea ice concentration

fc 2020-01-04

Control



SIC diff
(Full wave-sea ice coupling minus **control)**

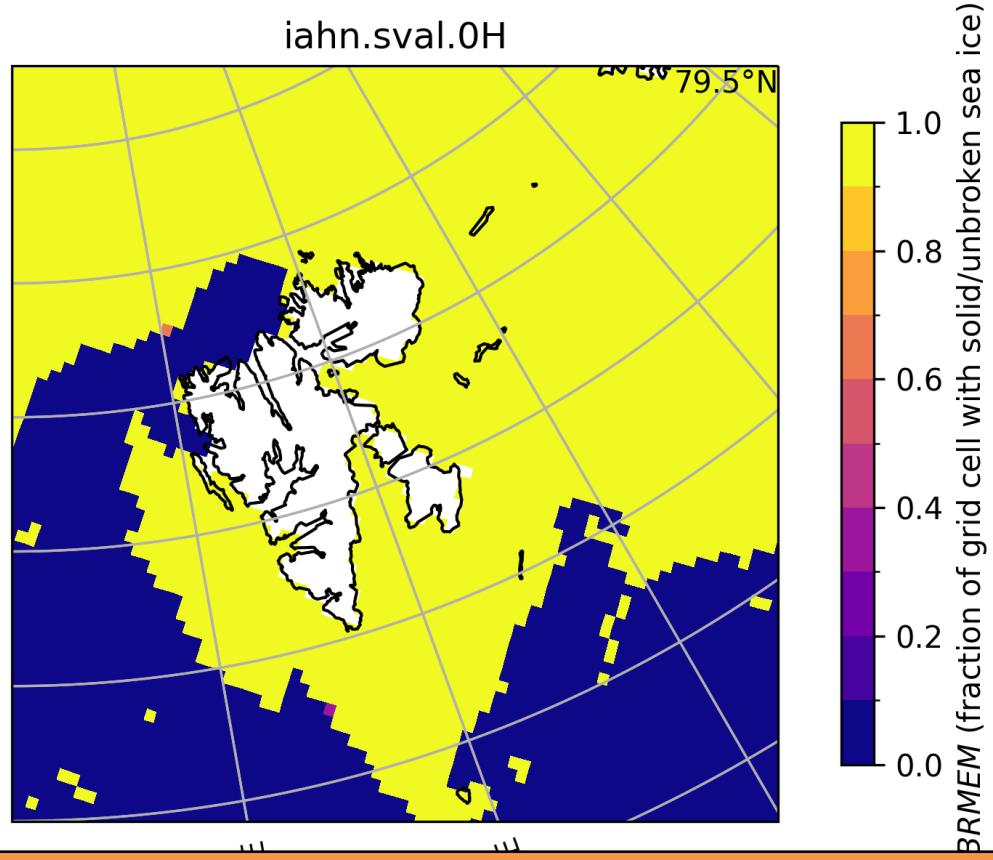


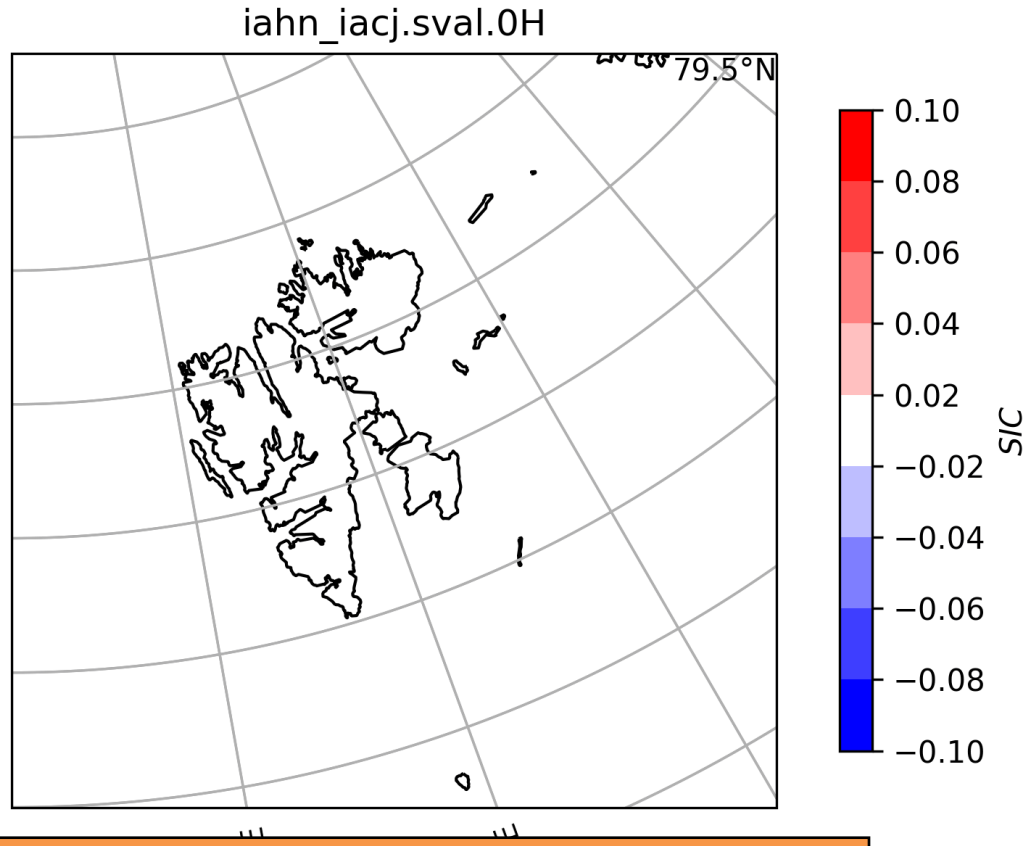
ECMWF

$SIMEM$

SIC diff
(Full wave-sea ice coupling minus **control)**

fc 2020-01-04



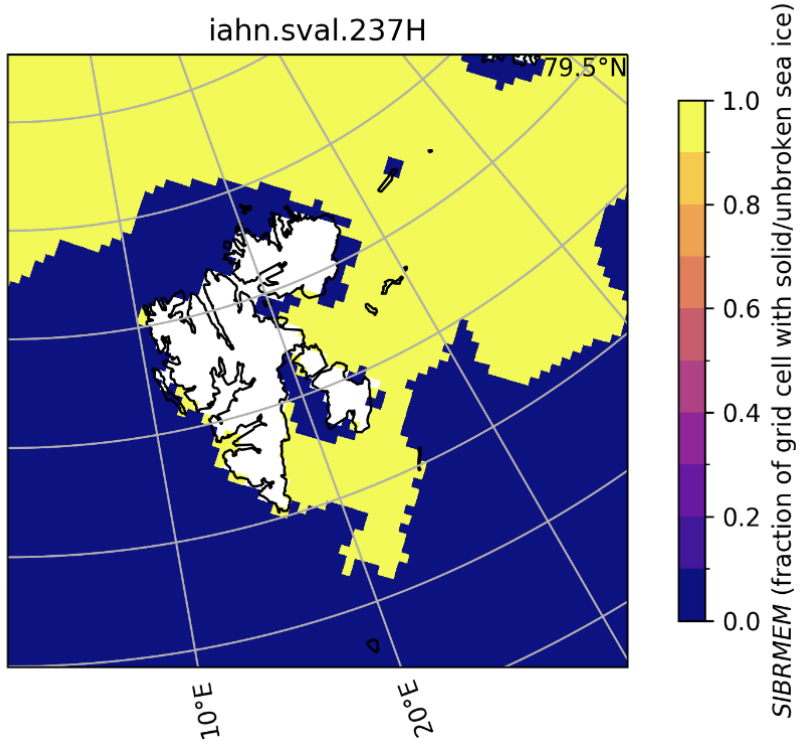


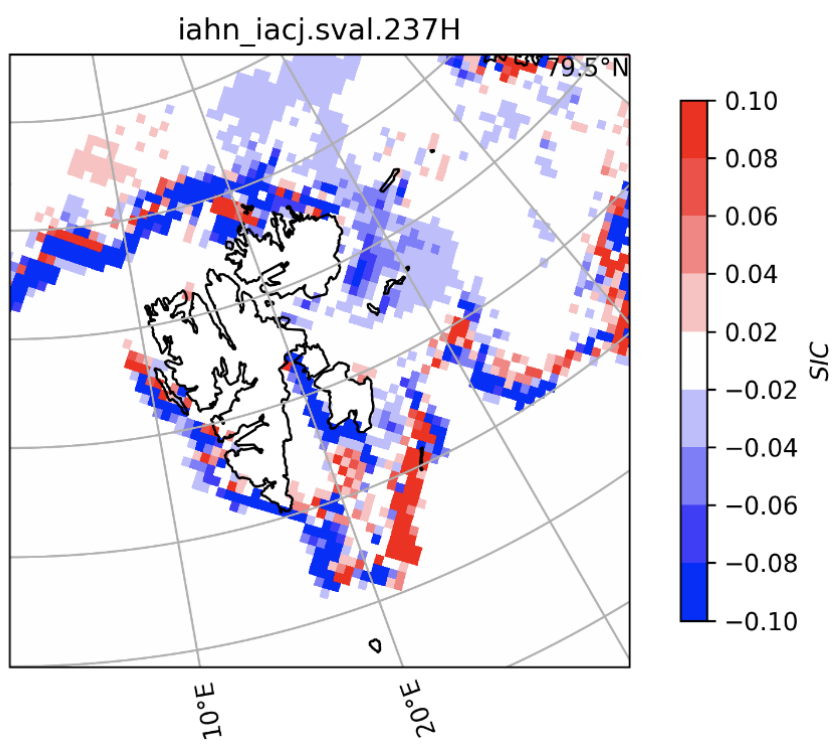
- Interactions are occurring in the MIZ
  - over 10 days, this spreads deeper into the pack ice (and throughout the whole earth system)
  - over seasonal timescales, we would expect this impact to be more important
- Takes some time (~2-3 days) for $SIMEM$ to start to look reasonable
- Neglect of ***sea ice healing*** is a deficiency (todo)

$SIMEM$

SIC diff
(Full wave-sea ice coupling minus **control)**

fc 2020-01-04





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Sensitivity of components

ECMWF

Sensitivity: ***wave radiative stress***

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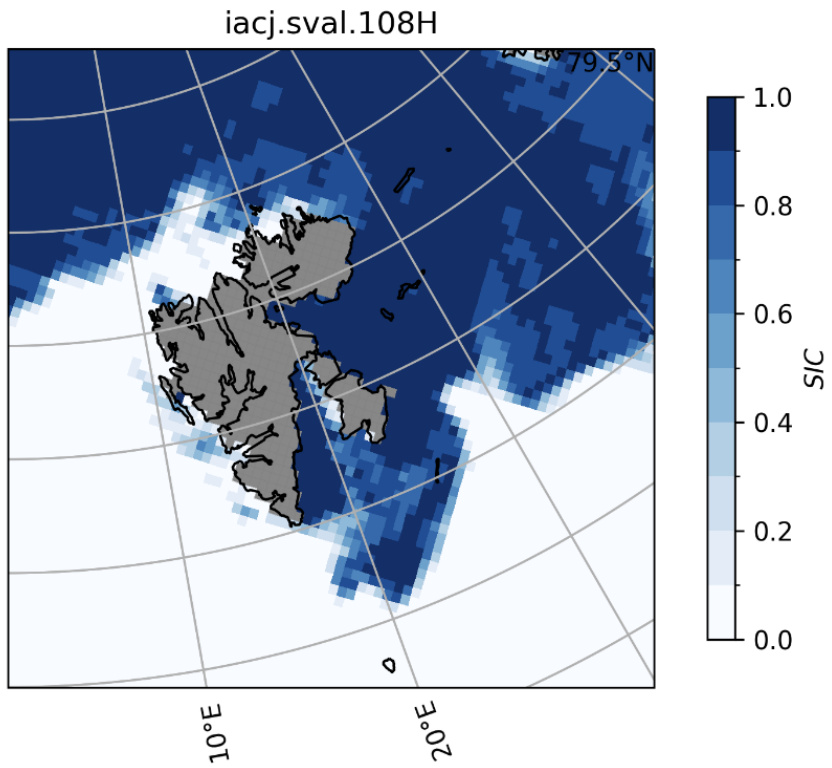
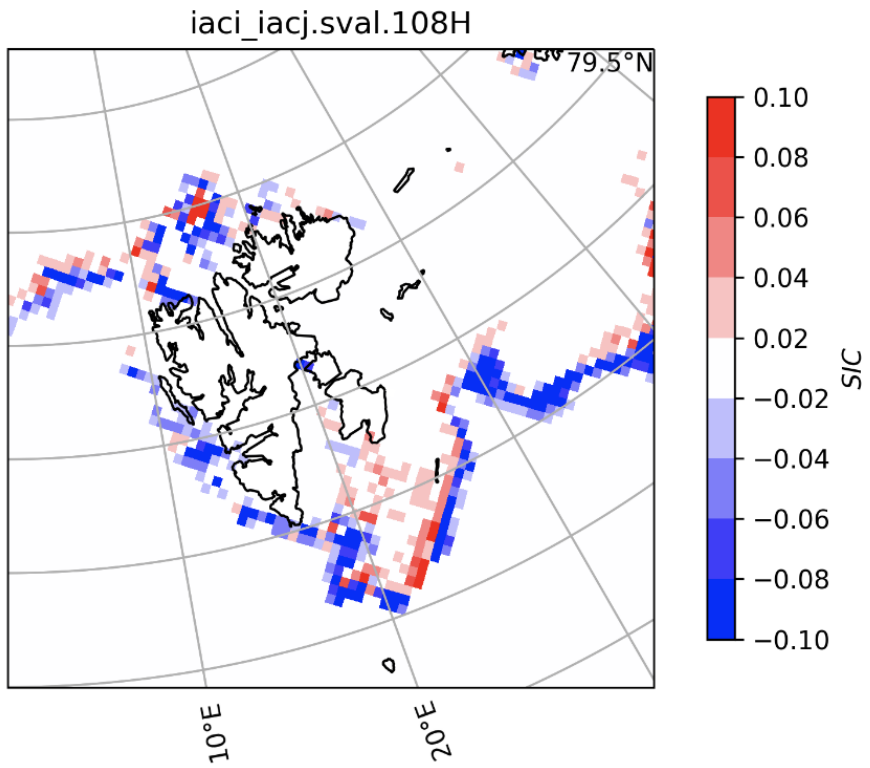
Control



Difference



- WRS compacts the MIZ
- consistent with Williams et al. (2017) and Boutin et al. (2020)

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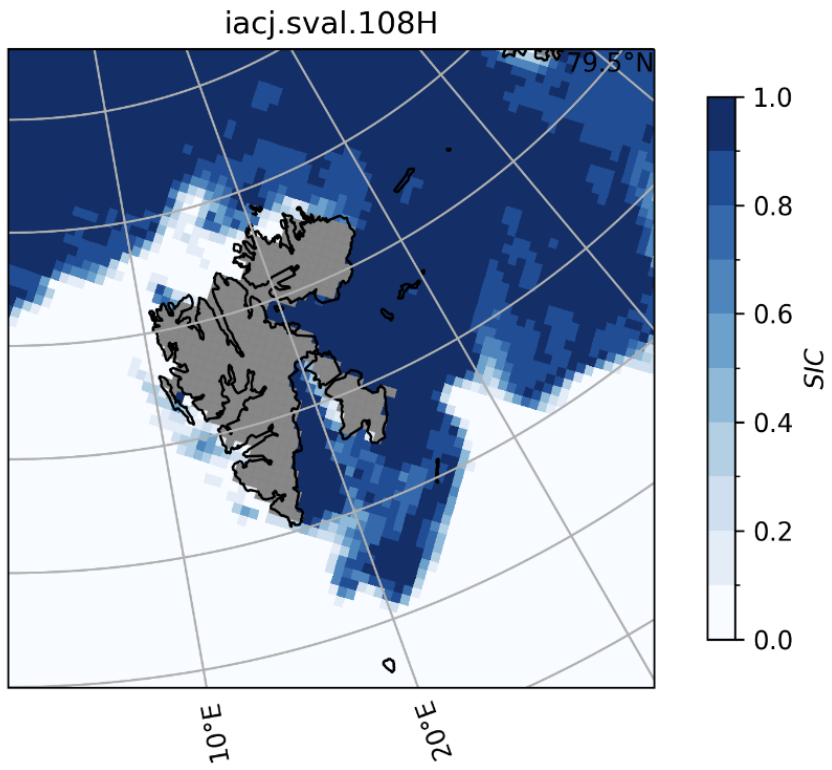
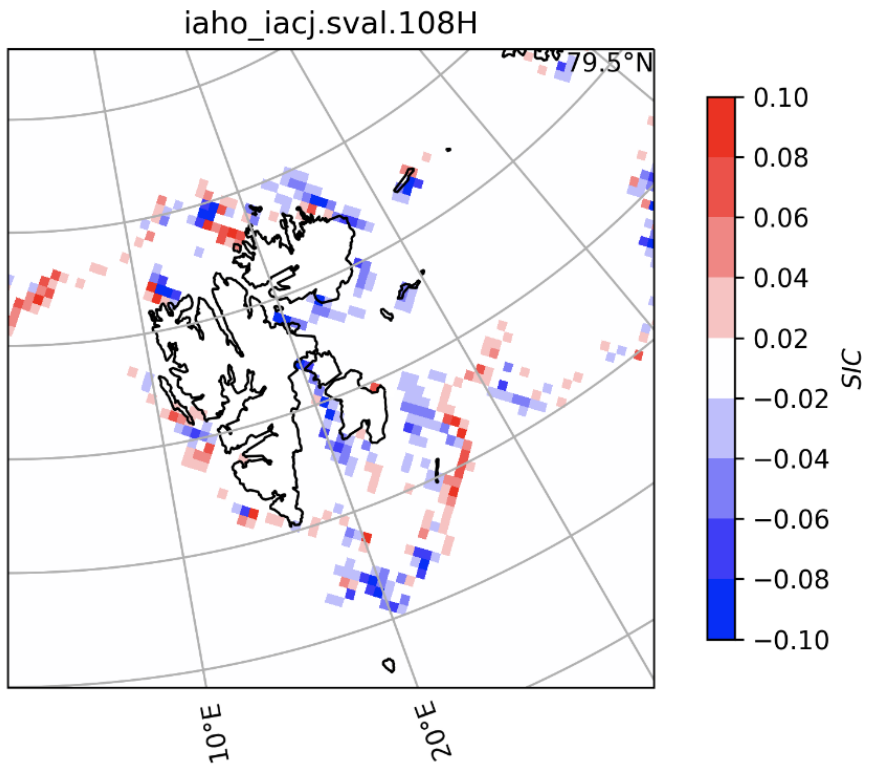
Sensitivity: ***ice breakup and strength modification***

Control



Difference



- Leads to formation of more ice in the MIZ
- Leads to reduction of ice in the ice pack
- Does this make sense?

ECMWF

Sensitivity:

wave radiative stress +

ice breakup and strength modification

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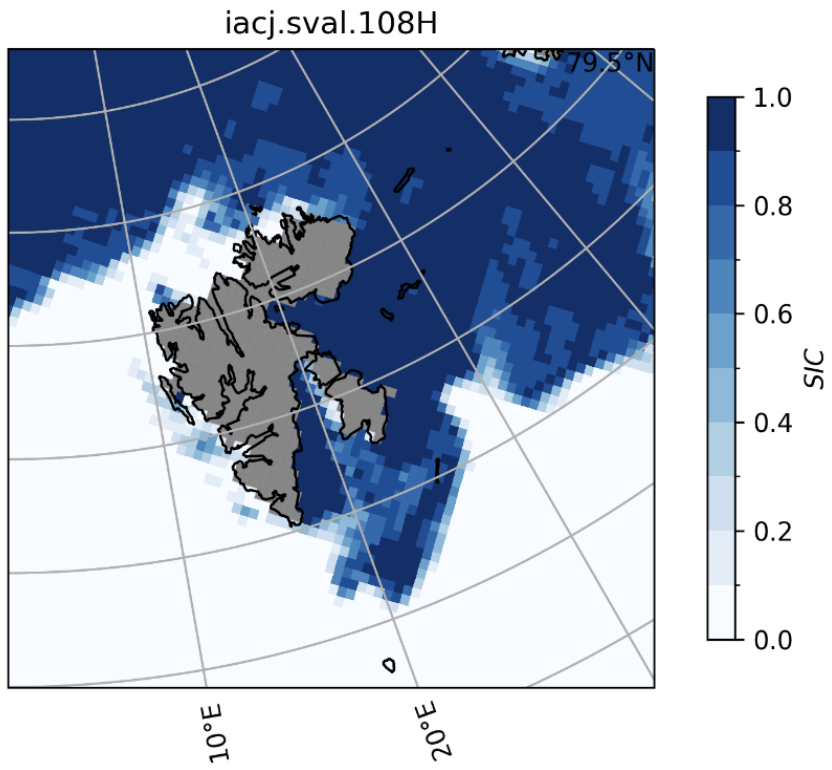
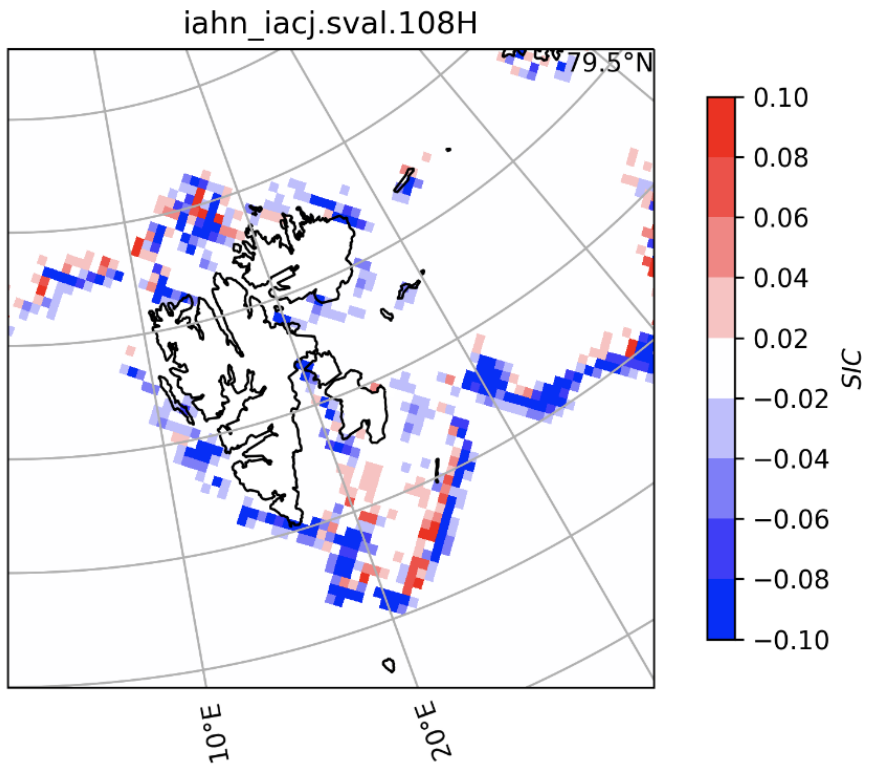
Control



Difference



- Combined effect looks largely to be dominated here by WRS

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Sensitivity:
wave attenuation modulation by $SIMEM$

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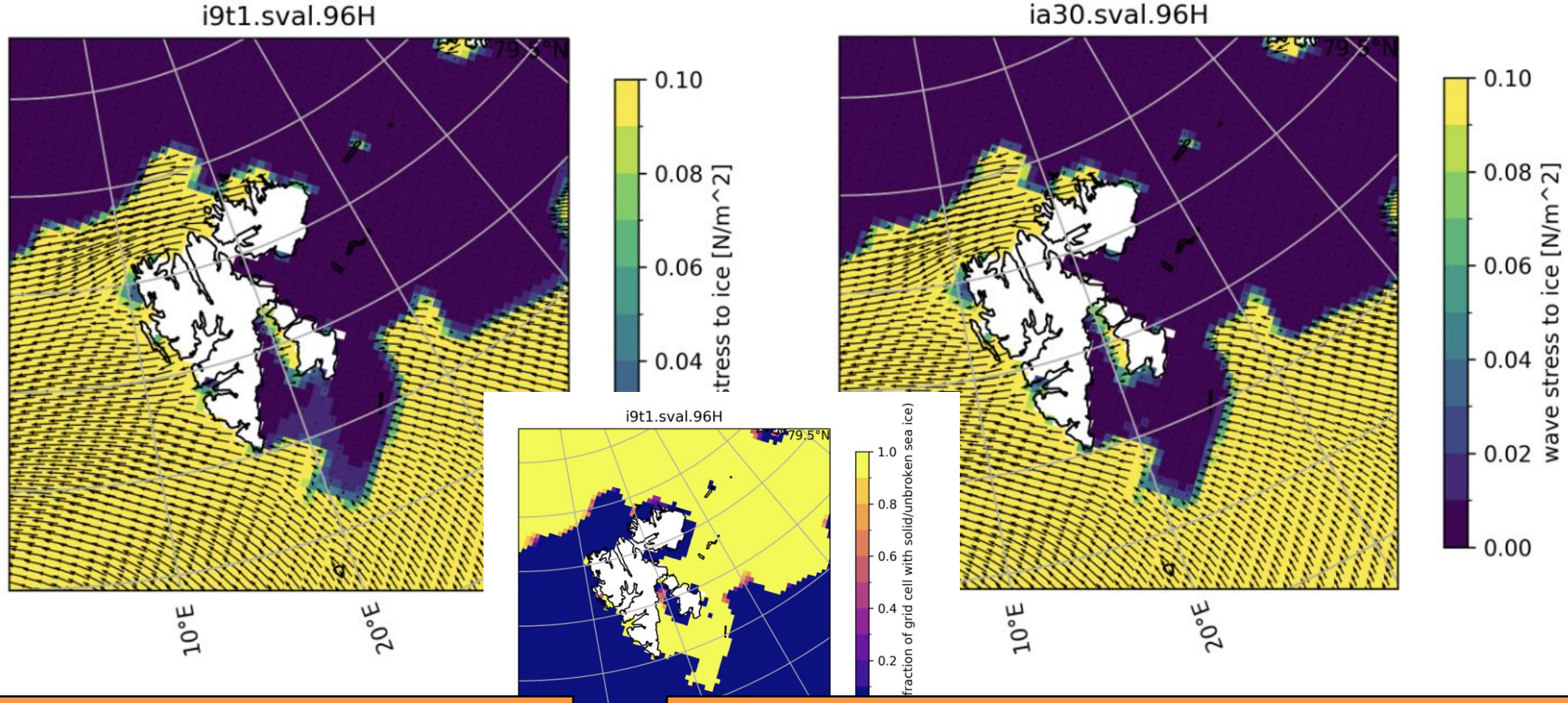
β=1

$$k_i = \begin{cases} k_{i_{solid}} : & \beta\,\alpha_{YEA22} \\ k_{i_{broken}} : & \frac{1}{\beta}\,\alpha_{YEA22} \end{cases}, \quad \sim 2 < \beta < \sim 4$$

β=4



- Attenuation is the same everywhere
- Energy and stresses imparted throughout ice

- Attenuation strong internally within the ice, weak in MIZ
- All energy and stresses imparted at ice edge