Waves and sea ice interactions : coupling of the wave model WW3 with NEMO-LIM3

LIM3 DAY
07/11/2017

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Starting point

What do we know ?

- Waves are attenuated when travelling in ice covered seas.
- The attenuation rate depends on the wave frequency and ice properties.
- Waves are responsible for ice floes breaking in the Marginal Ice Zone (MIZ)

Does it significantly impact the ice dynamic at large scale ?

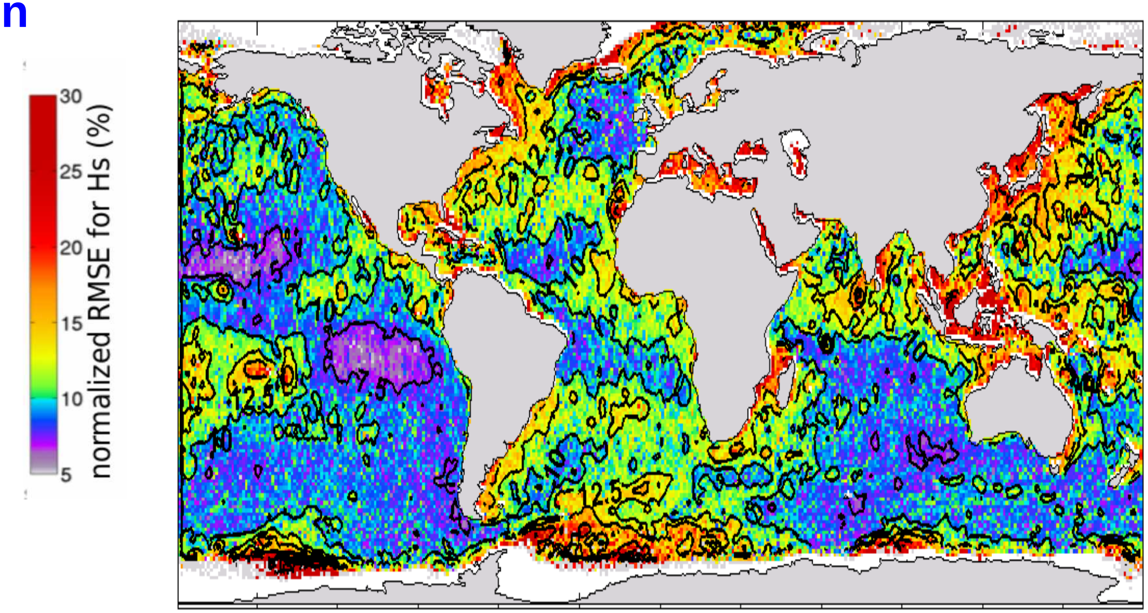
Dealing with waves

A spectral wave model : WAVEWATCH III

$$\underbrace{\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{\mathbf{x}} N + \frac{\partial}{\partial k}\dot{k} N + \frac{\partial}{\partial \theta}\dot{\theta} N}_{\text{Action advection}} = \frac{S}{\sigma}$$

Sources and sinks

Action advection



Ardhuin et al. 2010
Resolution :0,5°
Validation with JASON-1, ENVISAT, GFO data

Talk plan:

#1 Introduction (done)

#2 Sea ice in WW3

- Representation
- Focus on break-up and Floe size Distribution
- Wave attenuation processes

#3 WW3 / NEMO LIM3 coupling (Work in progress)

- Principle
- Simplified geometry tests with SAS
- Runs on CREG025

#4 Conclusion

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Floe size effect on wave-ice interactions : possible effects, implementation in wave model and evaluation

G. Boutin, F. Ardhuin, D. Dumont, C. Sévigny, F. Girard-Ardhuin, M. Accensi
JGR 2018

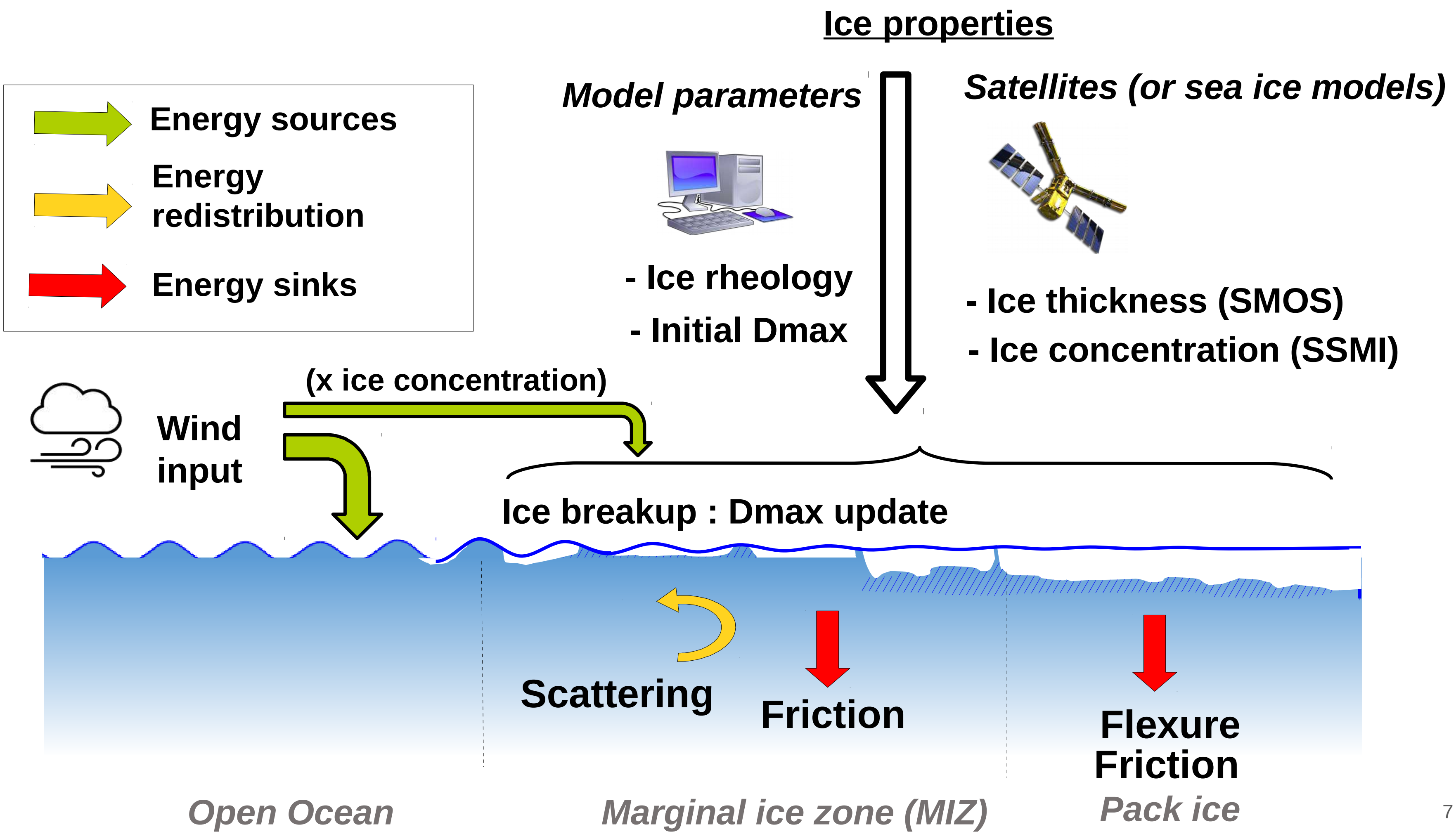
Adding ice in Wavewatch III

Motivations

- Sea ice melt increases the available fetch for waves in the Arctic. (Thomson and Rogers, 2014)
- Waves influence sea ice variability (Asplin et al., 2012 ; Stopa et al., 2016)
- Increasing number of human activities in the Arctic

Summary of sea ice in WW3

Sea ice implementation in WAVEWATCH III



The MIZ in WW3

A simplified rheology (Williams et al, 2013):

Hypothesis :

- *Ice floes are elastic*
- *They break due to flexural failure*

Requirement

- A Young modulus, Y
- A flexural strength , σ_c

Limits

- No fatigue
- Doesn't take into account ice variability (Temperature...)
- Not in agreement with some processes of wave attenuation...

To summarize, our ice is always the same. Thickness is given as a forcing, and only the floe size is affected by the waves

The Marginal Ice Zone (MIZ)

MIZ properties :

- Ice concentration
- Ice thickness
- Ice rheology
- Floe size distribution

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Forcings (satellites, sea ice models...)

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Constants parameters

The Marginal Ice Zone (MIZ)

MIZ properties :

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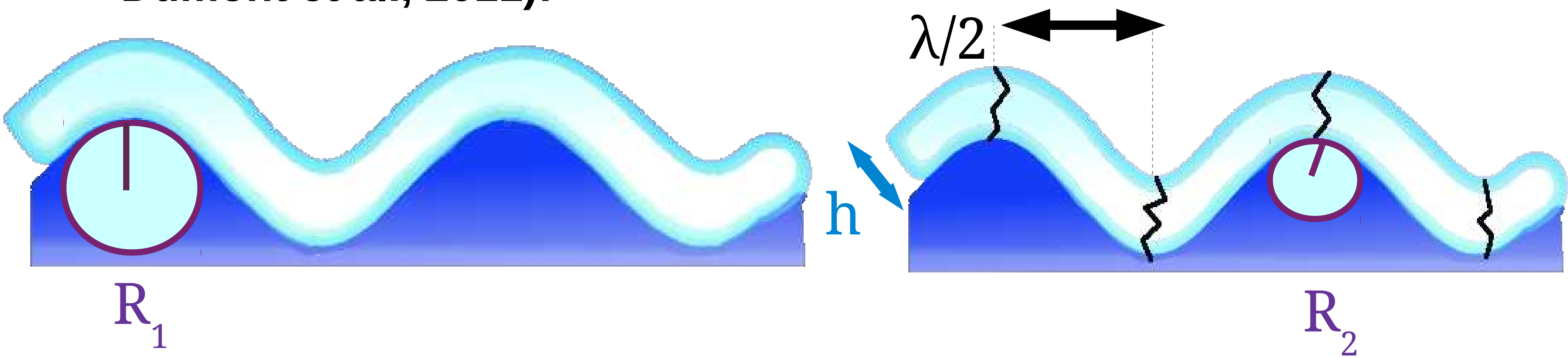
Forcings (satellites, sea ice models...)

Constants parameters

Depends on the sea state

Sea ice break-up

Ice breaking and Floe size distribution (Totoya et al. , 2011 ; Dumont et al., 2011):



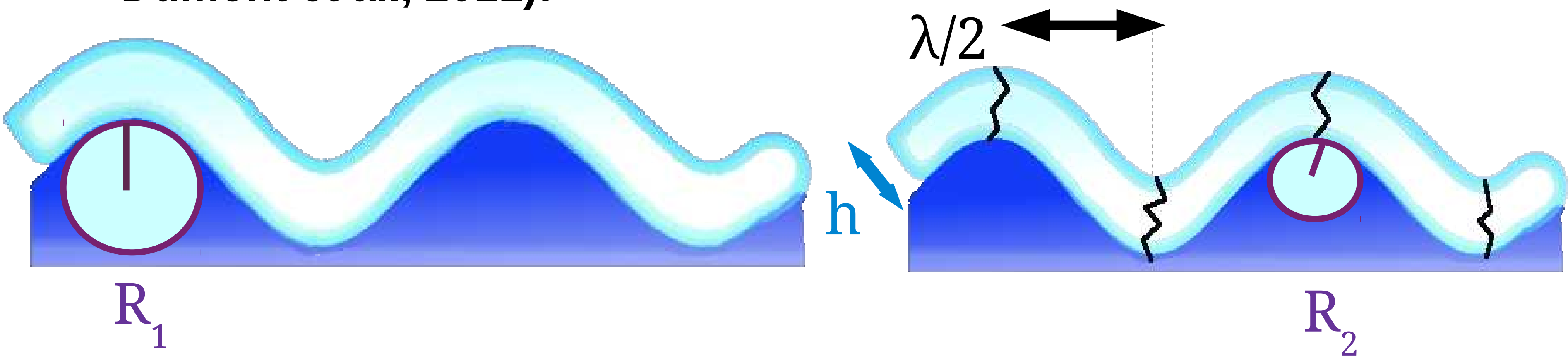
ε_c: critical strain for a thin elastic plate.

$$h^2/(4R_1^{\,2}) < \varepsilon_c < h^2/(4R_2^{\,2})$$

But with statistics, of course (local variance)

Sea ice break-up

Ice breaking and Floe size distribution (Totoya et al. , 2011 ; Dumont et al., 2011):

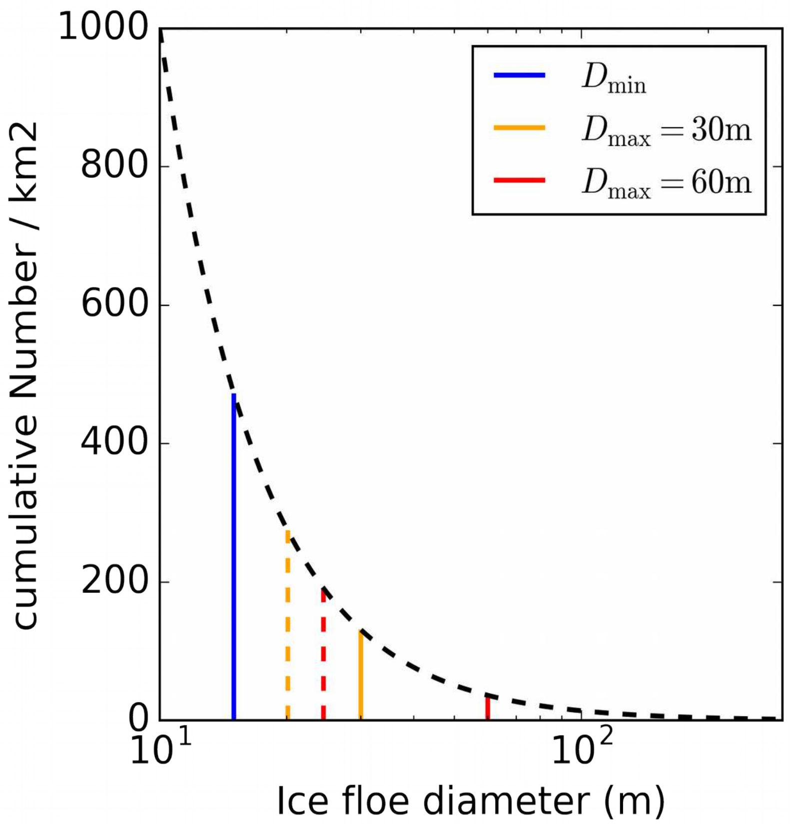


λ/2 for which the condition is fulfilled gives the new max. floe size D_{max}

The MIZ in WW3 (Sea ice break-up #3)

Floe Size Distribution (Totoya et al, 2011):

The FSD follows a power law : $N(D) \approx D^{-\gamma}$



$D_{\max}$ is used by flexure induced dissipation

if $0.3\lambda \geq D_{\max}$ then :

Floes act as **rigid bodies**

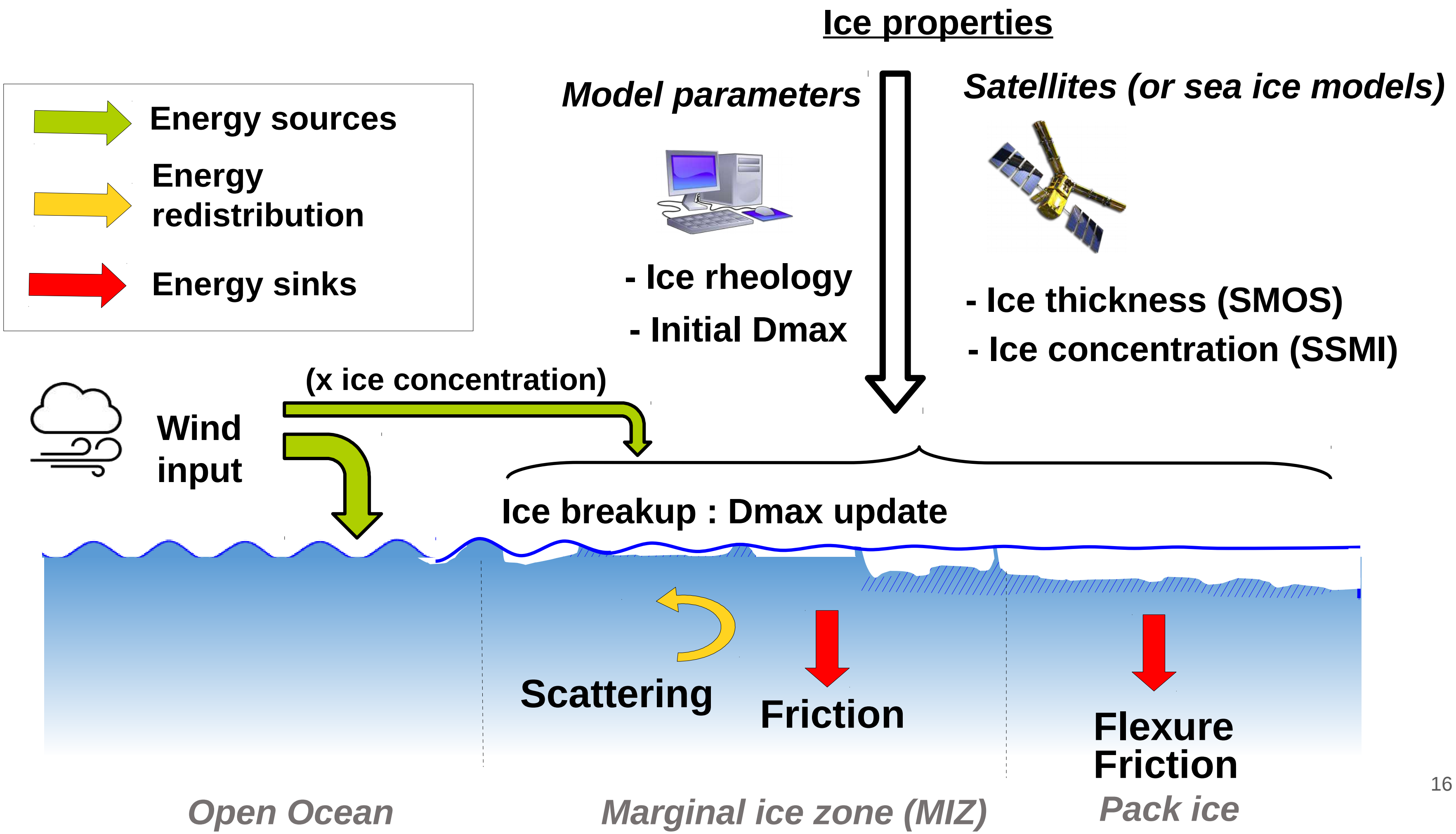
Flexure dissipation **vanishes**

$\langle D \rangle$ is used by scattering

$N_{\mathrm{floes}} = cx/\langle D \rangle$

Waves attenuation in ice

Sea ice implementation in WAVEWATCH III



Waves attenuation in ice

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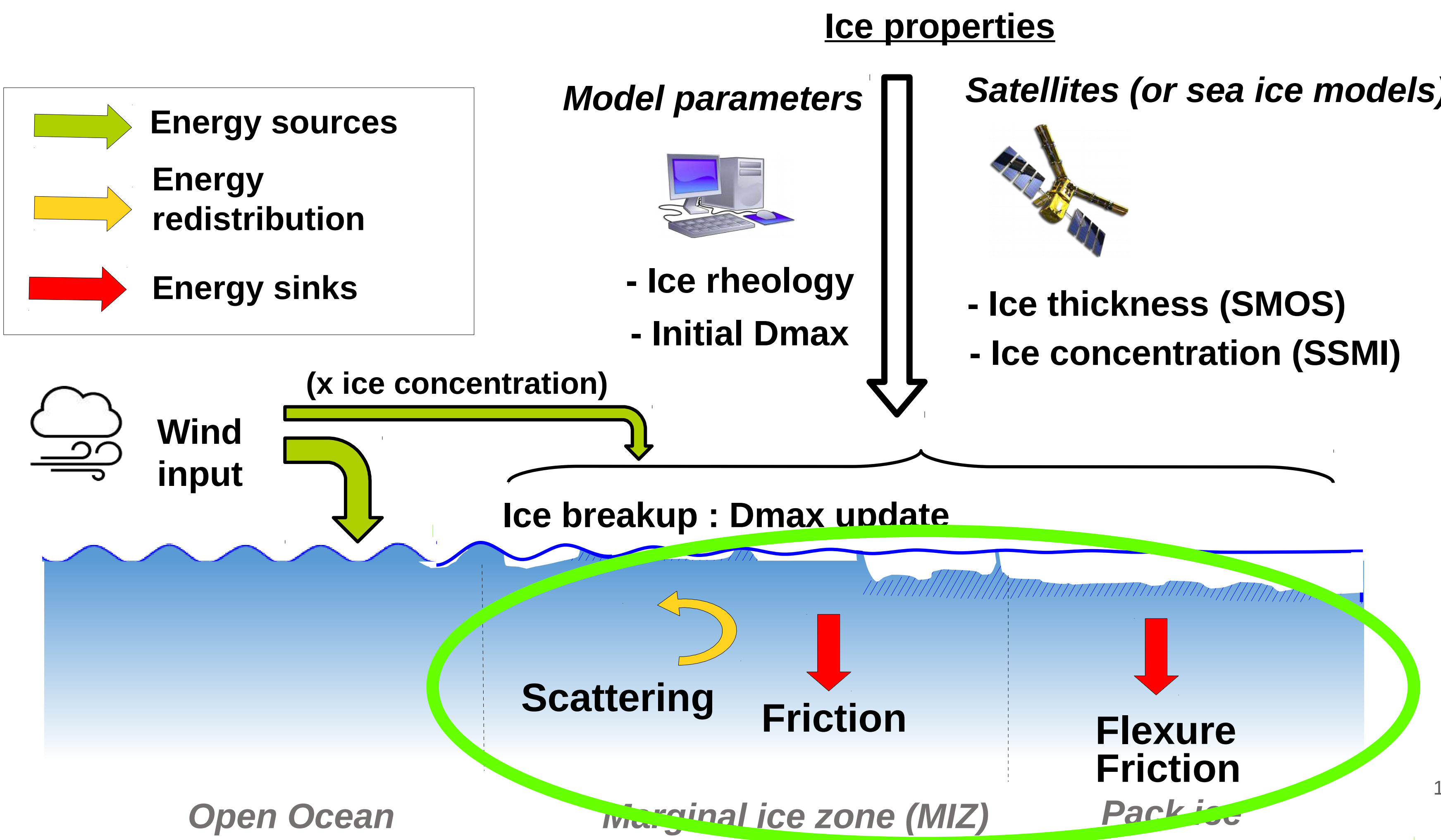

Waves attenuation in ice

Scattering

Conservative

Quite well referenced…

Kohout & Meylan (2008)
Williams et al. (2013ab)

Waves attenuation in ice

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Basal friction

Dissipative

Viscous + Turbulent part

Liu et Mollo-Christensen (1988)
Stopa et al. (2016)

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Inelastic attenuation

Dissipative

Not really expected...

Wadhams (1973)

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Inelastic attenuation

Dissipative

Not really expected...

Wadhams (1973)

Anelastic attenuation

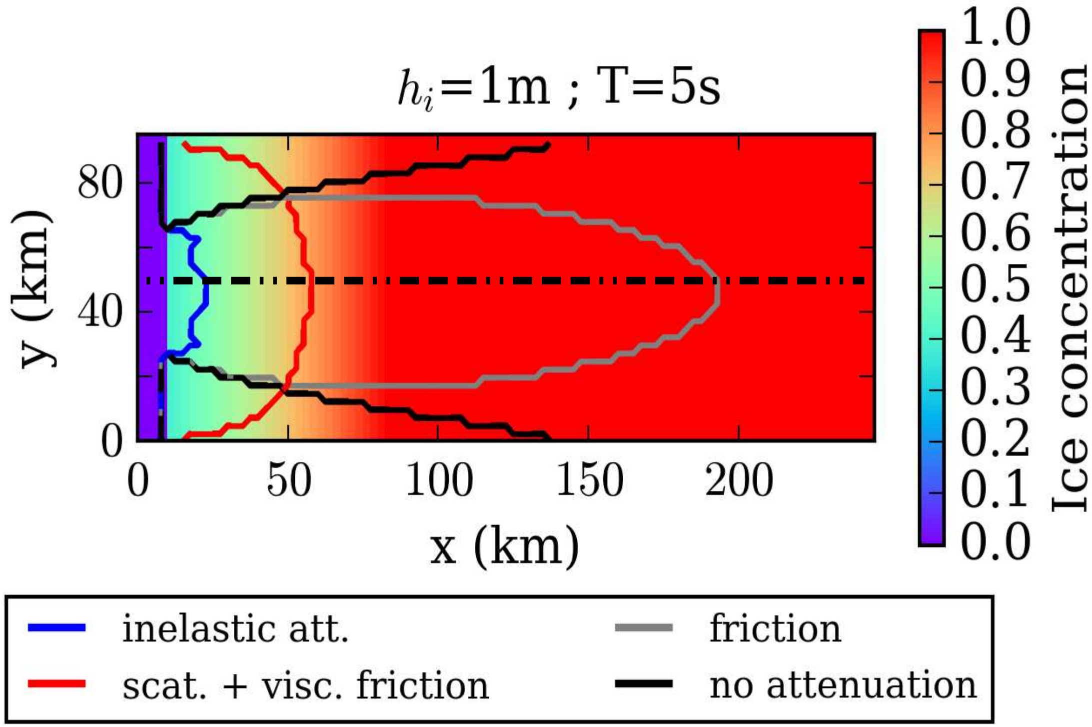
Dissipative

First attempt to model it for wave attenuation

Cole (1995)

Tests with a simplified geometry

Waves with Hs =3m radiate from the western border



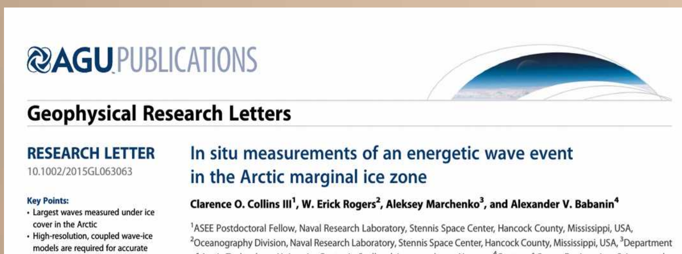
Ice concentration roughly represents a realistic MIZ

Ice thickness is constant

Floes are initially unbroken (Dmax=1000m)

Tests with simplified geometry but realistic forcing

Collins et al. (2015)


AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063063

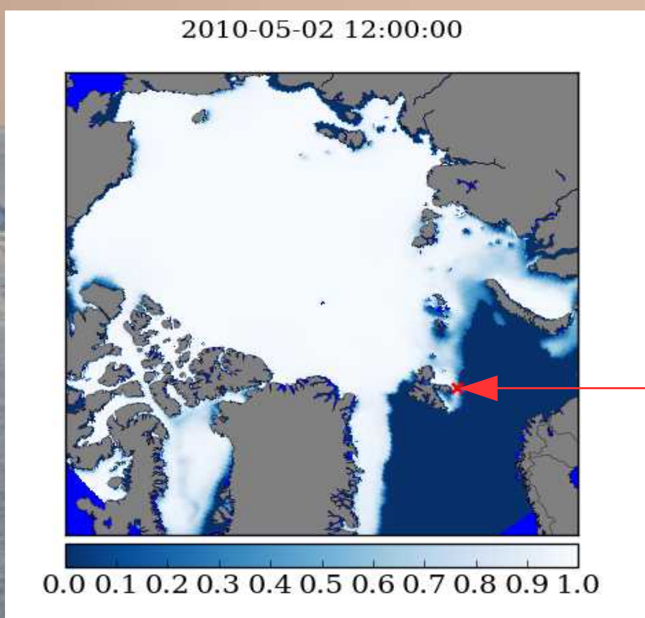
In situ measurements of an energetic wave event in the Arctic marginal ice zone

Clarence O. Collins III[1], W. Erick Rogers[2], Aleksey Marchenko[3], and Alexander V. Babanin[4]

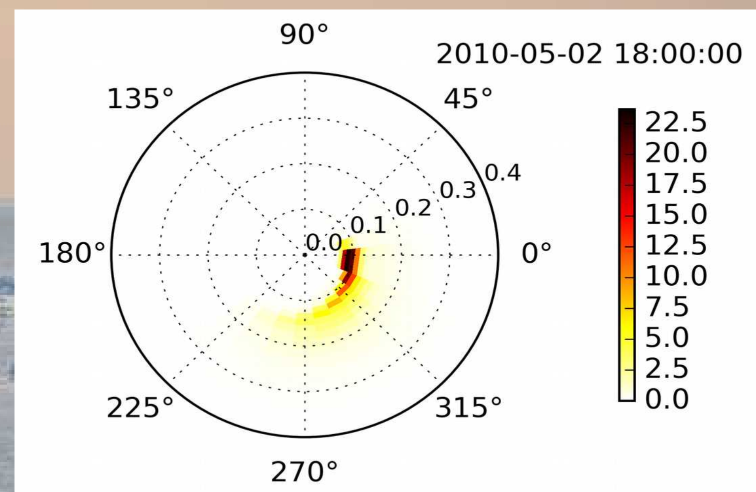
[1]ASEE Postdoctoral Fellow, Naval Research Laboratory, Stennis Space Center, Hancock County, Mississippi, USA, [2]Oceanography Division, Naval Research Laboratory, Stennis Space Center, Hancock County, Mississippi, USA, [3]Department

Key Points:
- Largest waves measured under ice cover in the Arctic
- High-resolution, coupled wave-ice models are required for accurate

Rotated spectra : eastward propagation



Ship

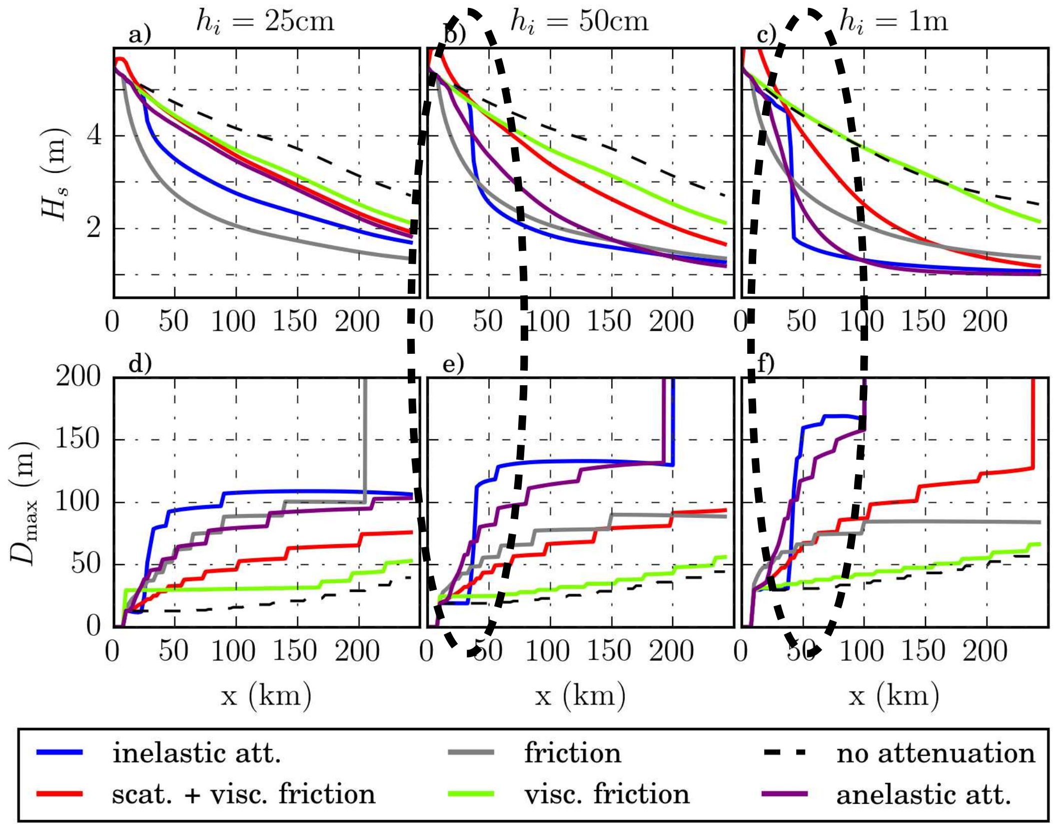


Ice thickness : 50-60cm

Main results

Collins et al. (2015)

Inelastic attenuation reproduce the observed sudden shift



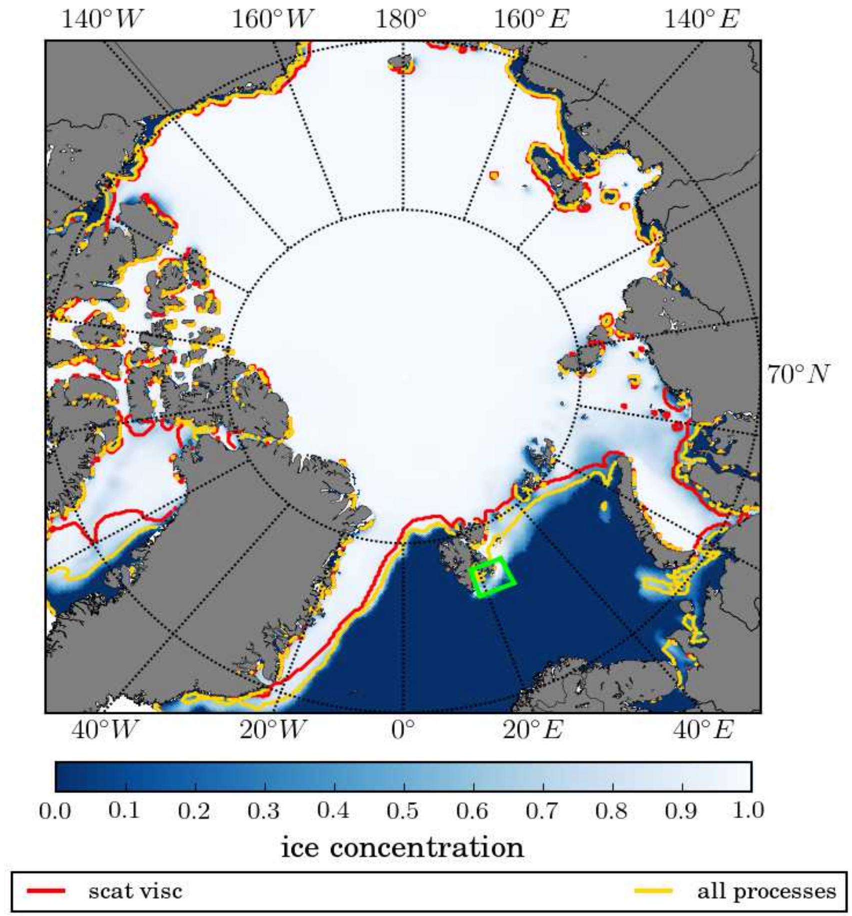
Arctic configuration

<u>How to define the MIZ ?</u>

- Breaking criterion (Dmax < D init)
- Concentration criterion (C>0.15)

To note: Inelastic att. cannot be used « alone » !

Values are in agreement with orders of magnitude expected



Limits

Ice types :

This model is not suitable for
pancake ice / frazil ice / grease ice

ONR campaign on Sikuliak

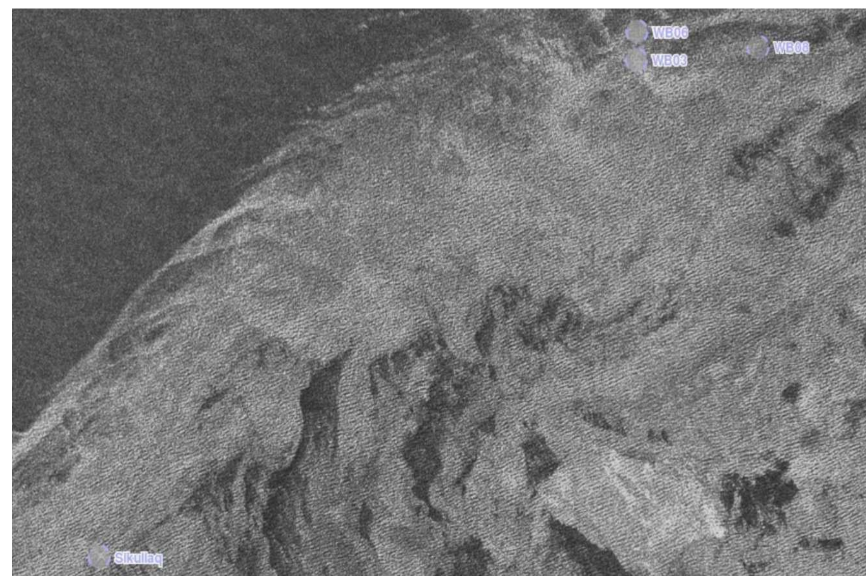
Broken floes :

What do they become after being broken ?

.

Validation :

SAR, buoys...



Sentinel 1-A, SAR, http://swarp.oceandatalab.com/

Sea ice in WW3 in 30s (1)

up to 3 (or 4) attenuation processes

sea ice break-up

FEEDBACK*

***Actually, feedbacks concern only flexure and scattering**

Sea ice in WW3 in 30s (2)

Sea ice is broken if the wave curvature exceeds a certain threshold

The maximum size for a floe is the half the wavelenght of the shortest wave that exceeds this threshold

The floe size distribution obeys a power-law

Conclusion of « Sea ice in WW3 »

- We included a sea ice representation in WW3 in which we tried to put some physics
- Inelastic attenuation could be interesting in some cases for which we observe very non linear attenuation
- Sea ice is still very simplified. It's a first step in modelling waves and sea ice interactions.

Conclusion of « Sea ice in WW3 »

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#3 WW3 / NEMO LIM3 coupling (Work in progress

- Principle
- Simplified geometry tests with SAS
- Runs on CREG025

#4 Conclusion

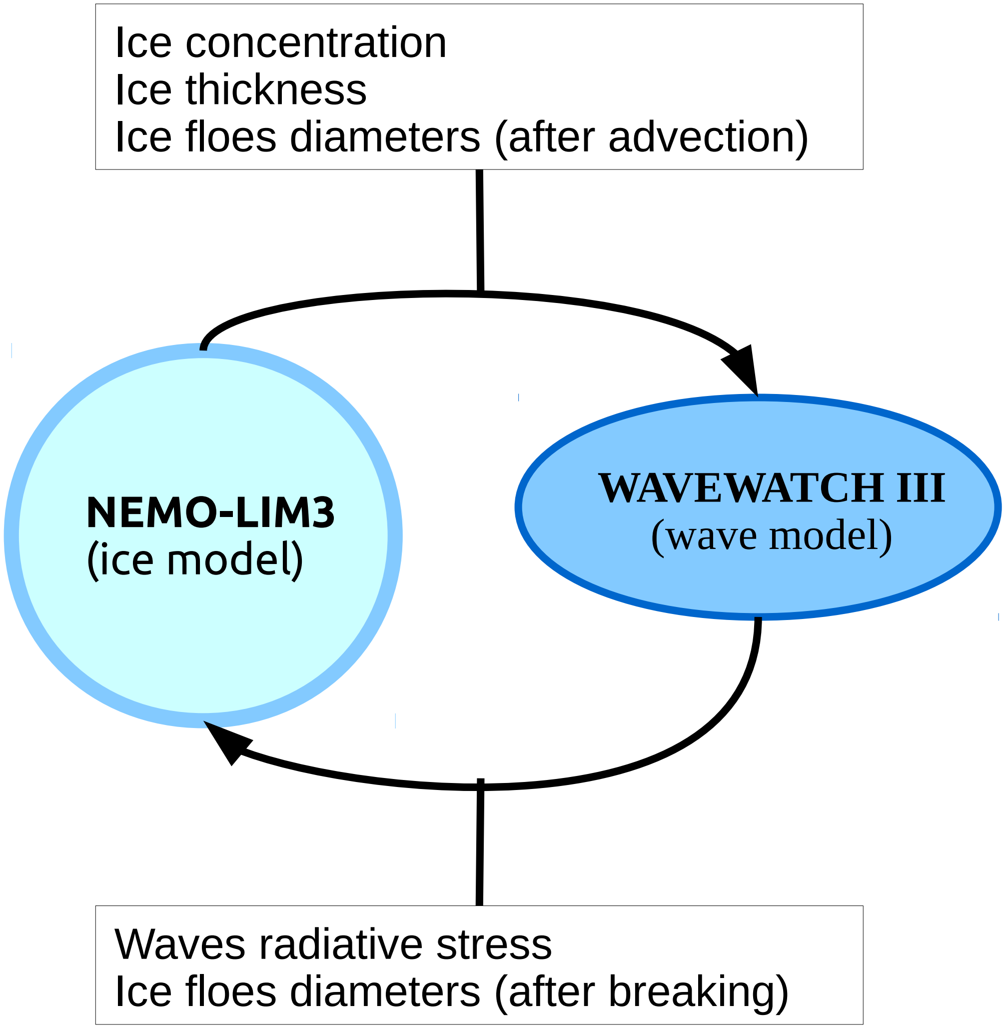
Talk plan:

With contributions and help from Clément Rousset, Verena Haid, Claude Talandier, Camille Lique, Xavier Couvelard, Martin Van Coppenole...

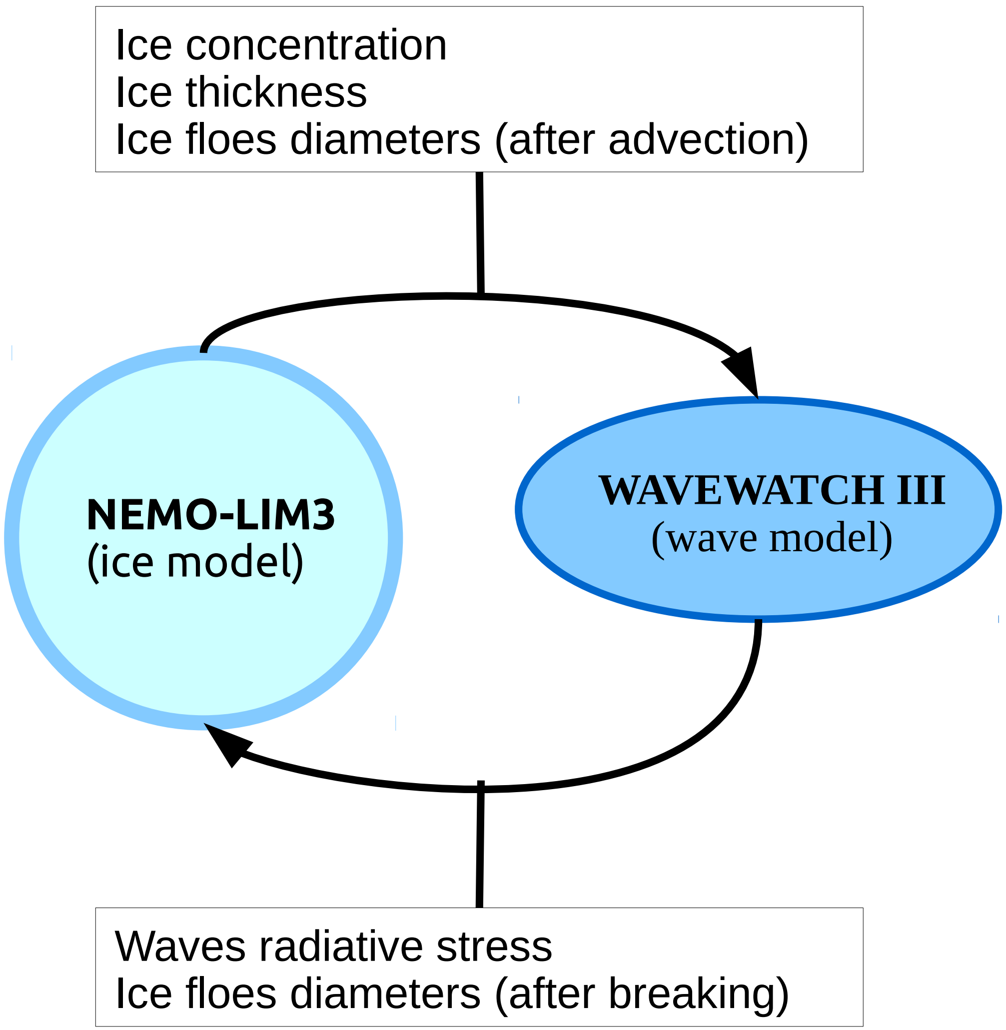
#3 WW3 / NEMO LIM3 coupling (Work in progress)

- **Principle**
- **Simplified geometry tests with SAS**
- **Runs on CREG025**

Coupling


Ice concentration
Ice thickness
Ice floes diameters (after advection)
NEMO-LIM3
(ice model)
WAVEWATCH III
(wave model)
Waves radiative stress
Ice floes diameters (after breaking)

Coupling



For WAVEWATCH III :

MIZ properties :

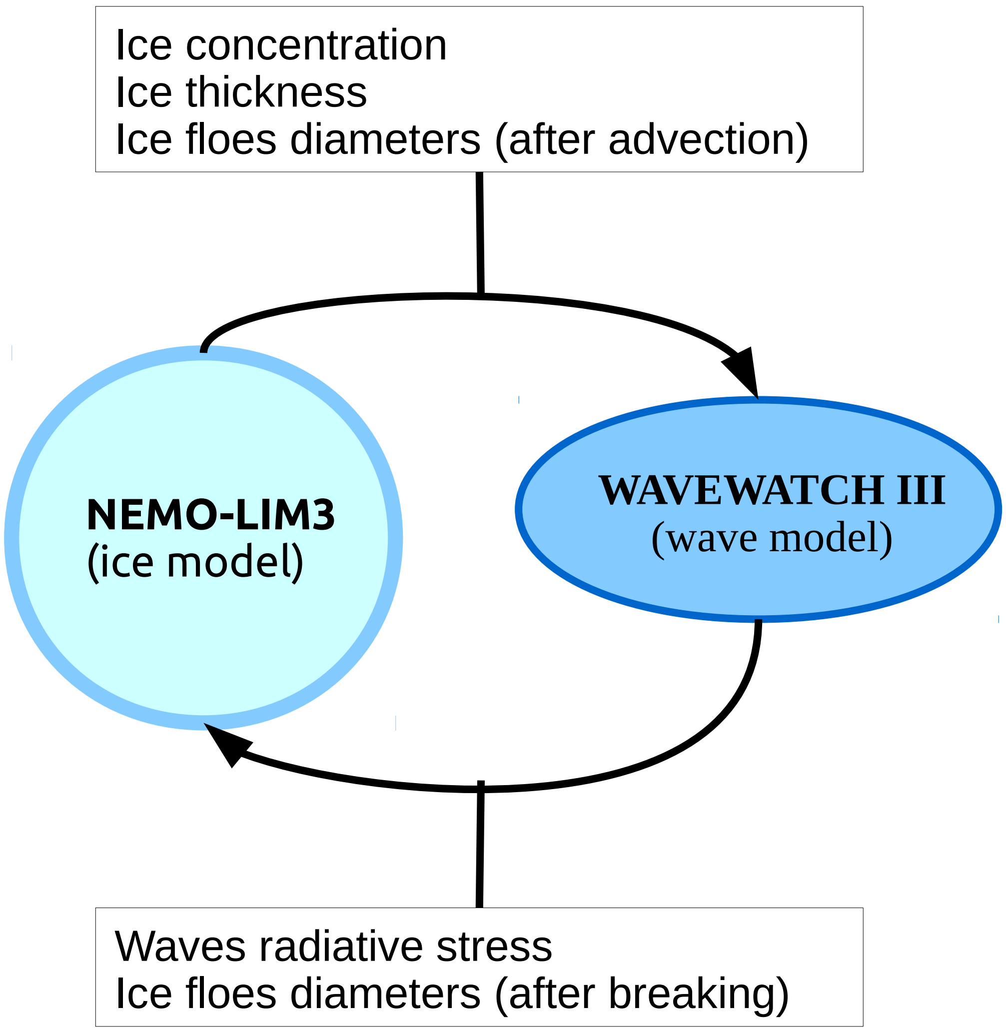
- **Ice concentration**
- **Ice thickness**
- **Ice rheology**
- **Floe size distribution**

Forcings (satellites, sea ice models...)

Constants parameters

Depends on the sea state

Coupling



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Coupled LIM3

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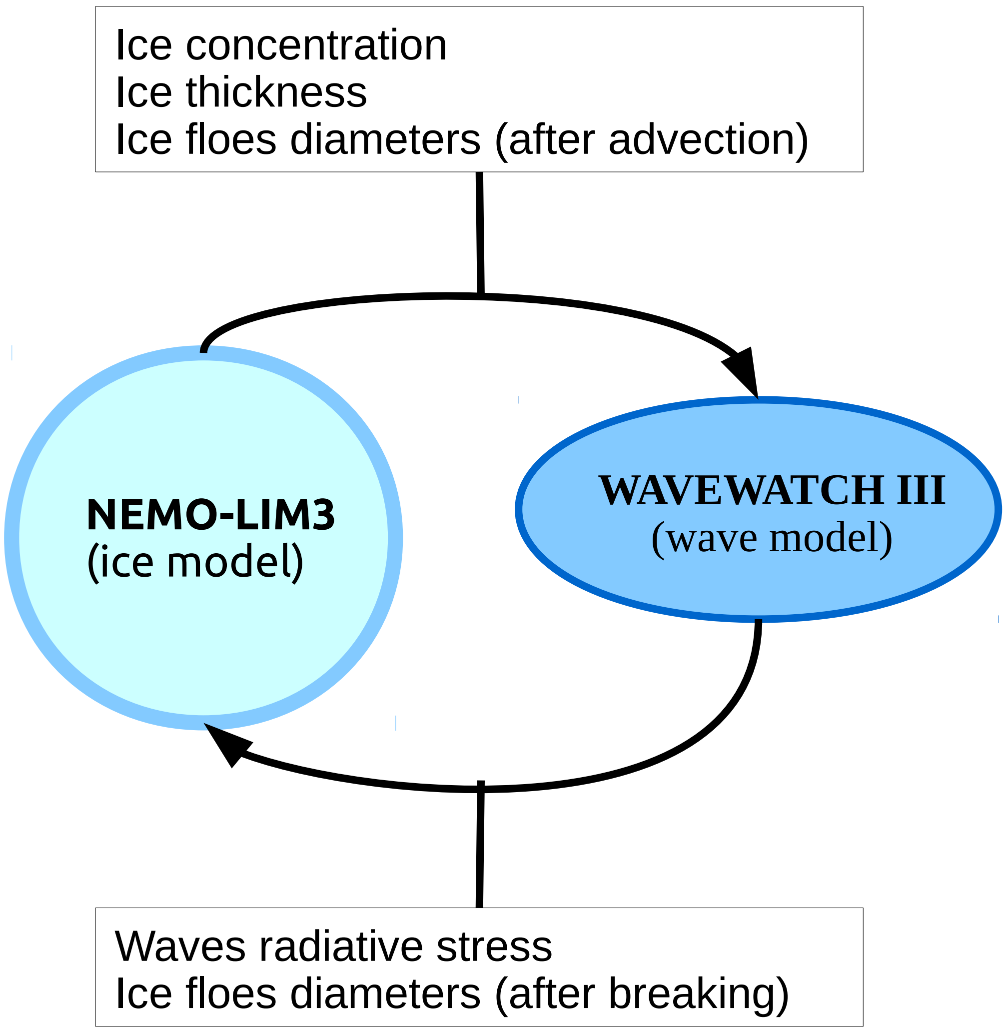
Coupling



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~~Forcings (satellites, sea ice models...)~~ **Coupled LIM3**

Constants parameters

Depends on the sea state **+ advection**

Coupling

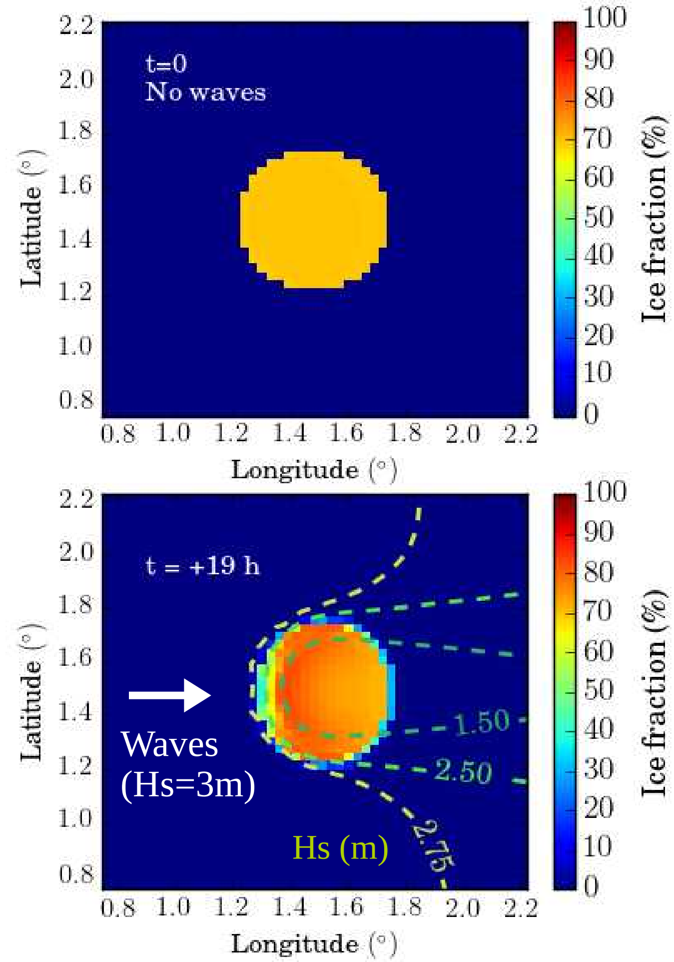
Simplified geometry with SAS

Wave radiative stress illustration :

Wave height decreases

Loss of wave momentum in the wave direction of prop.

Stress from waves to the ice, in the wave direction of propagation

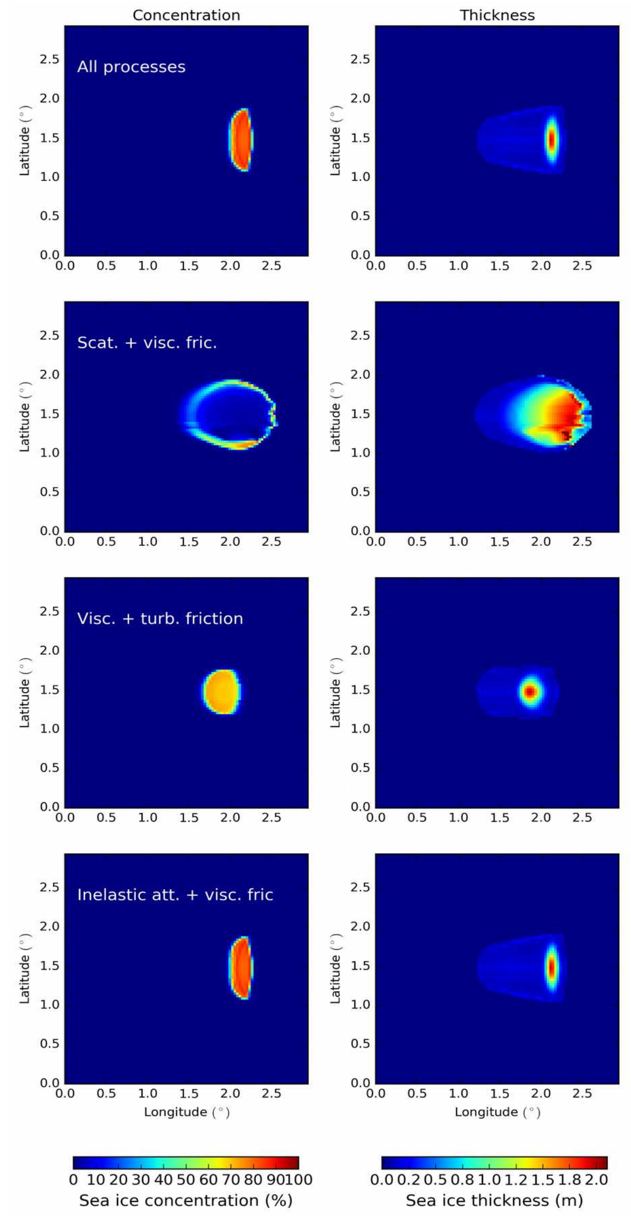


Coupling

Simplified geometry with SAS

Wave radiative stress illustration :

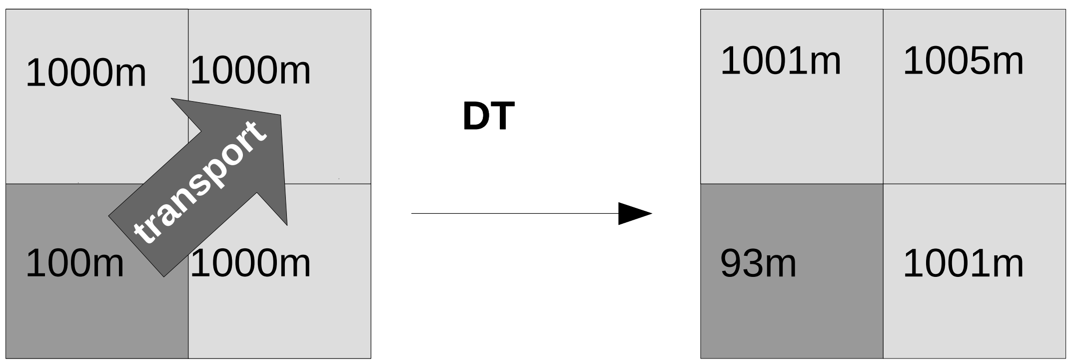
Strong impact of the attenuation processes included.



Current work : coupling with LIM3 (in short)

Floes advection

- Not that easy… You don't take some floe size from one point to give it to another point



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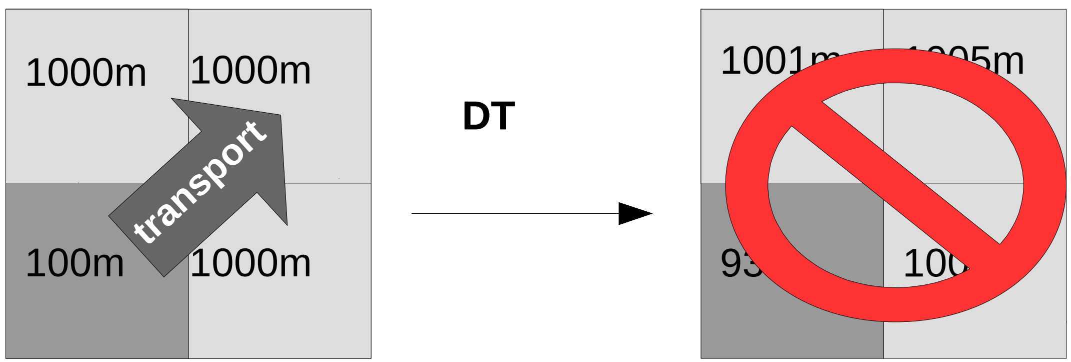
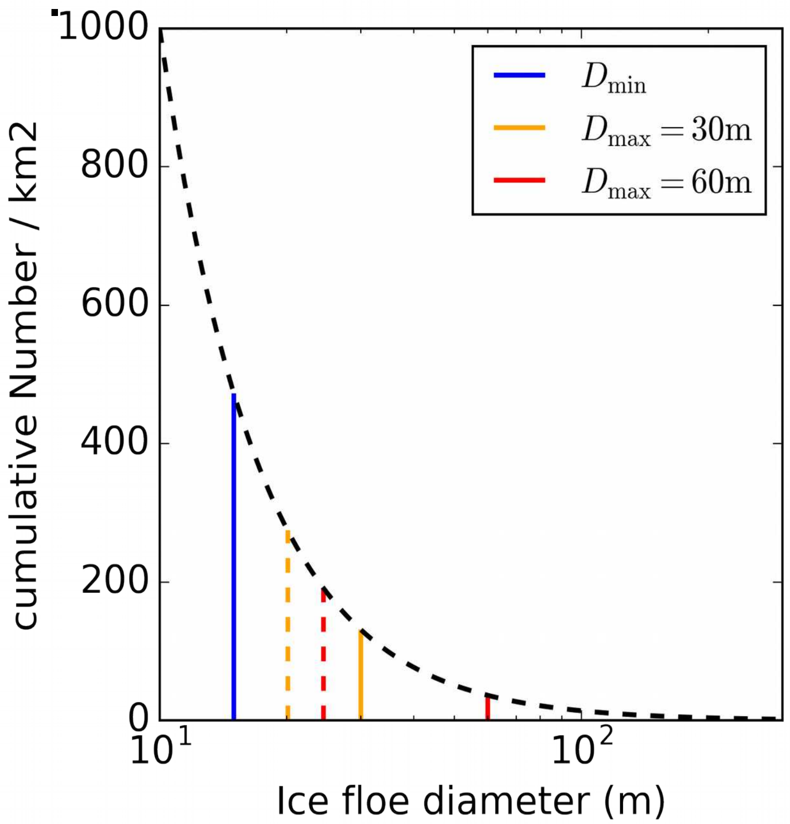


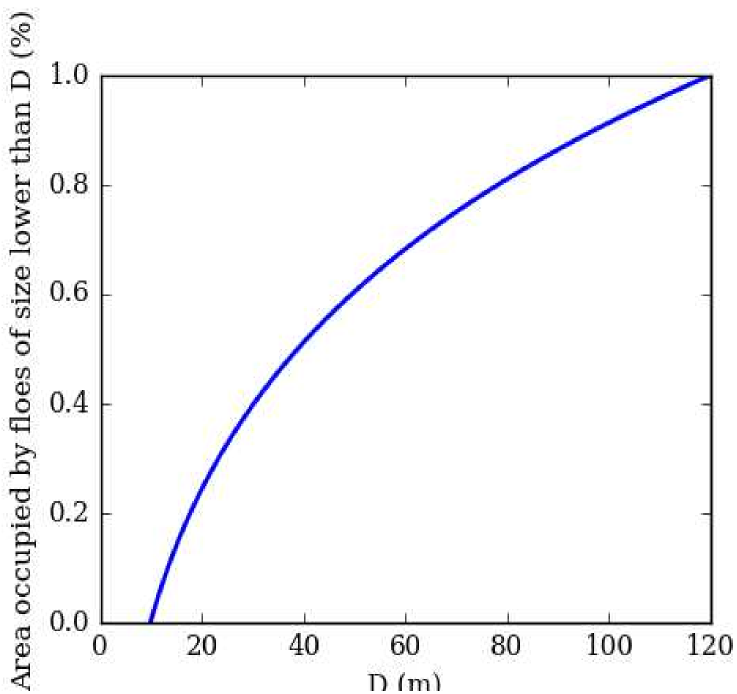
- Zhang et al. 2015, Horvat et al. 2016 → Floes cat.

Current work : coupling with LIM3 (in short)

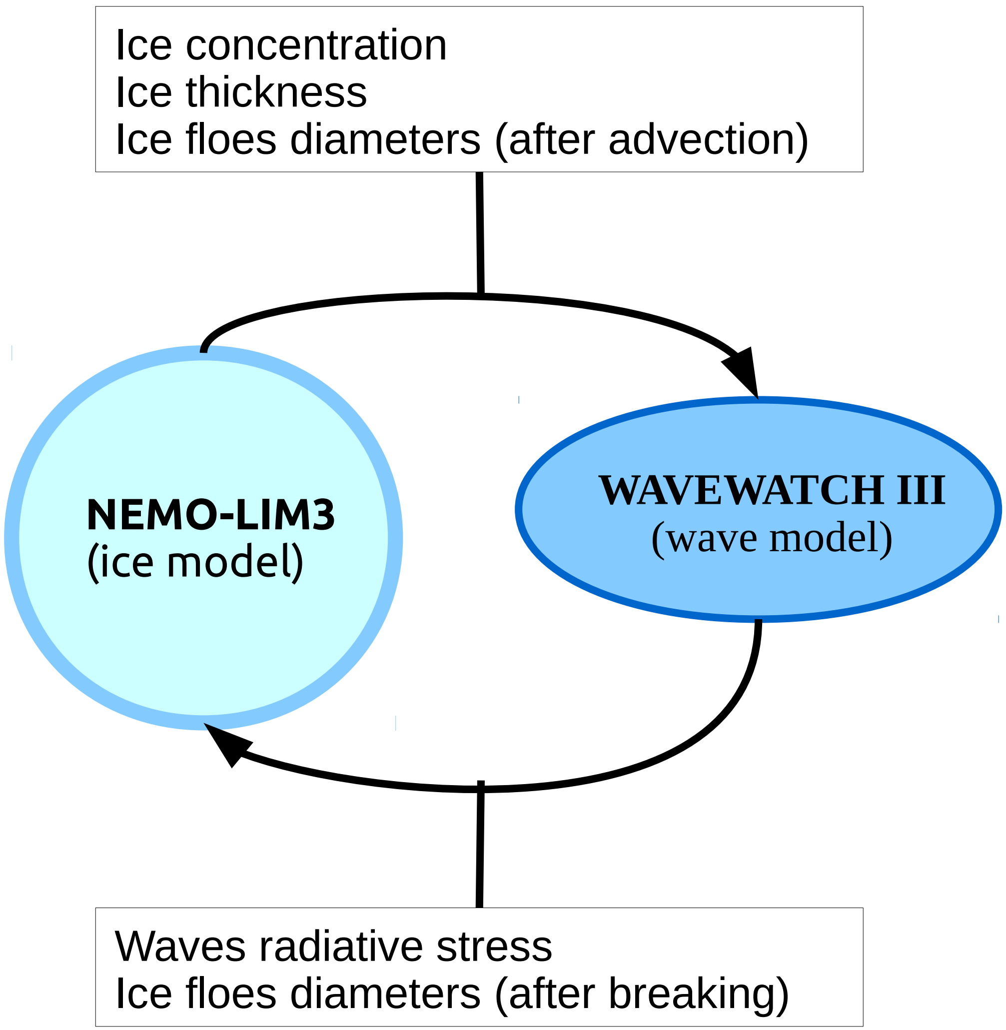
Floes Size Distribution



Floes Area Distribution



Coupling



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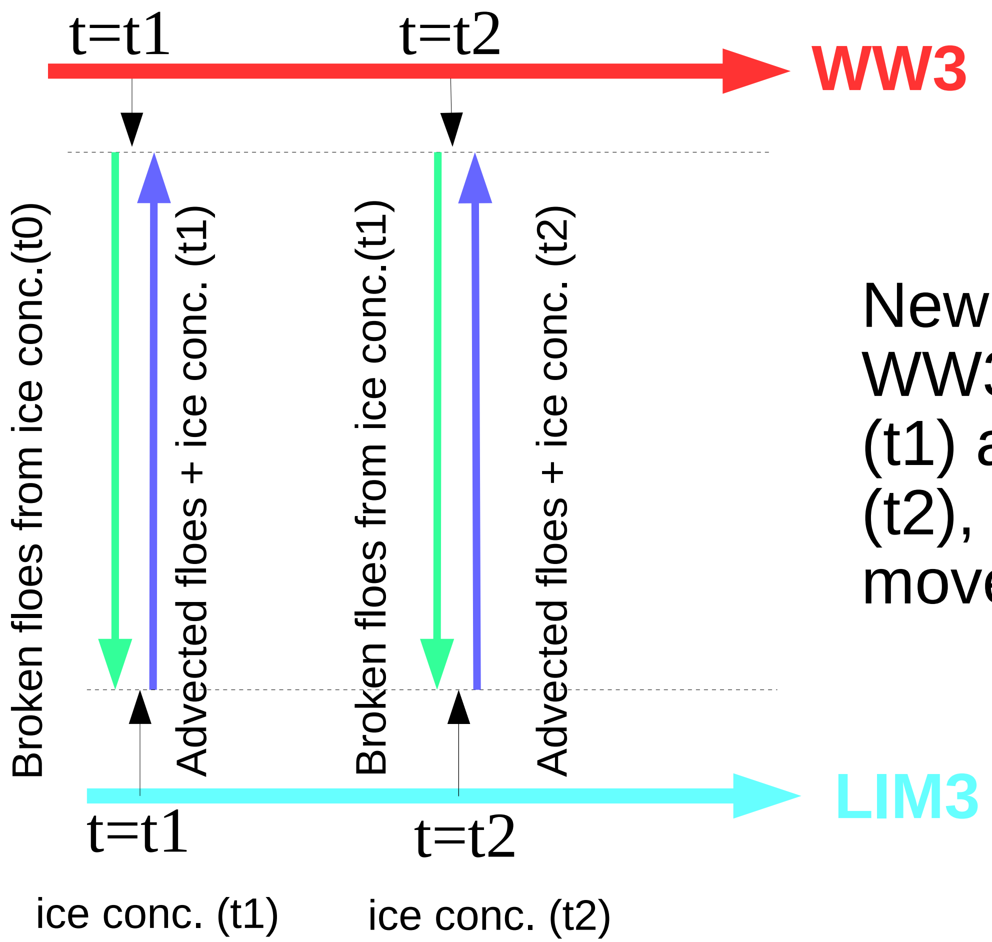
~~Forcings (satellites, sea ice models...)~~ **Coupled LIM3**

Constants parameters

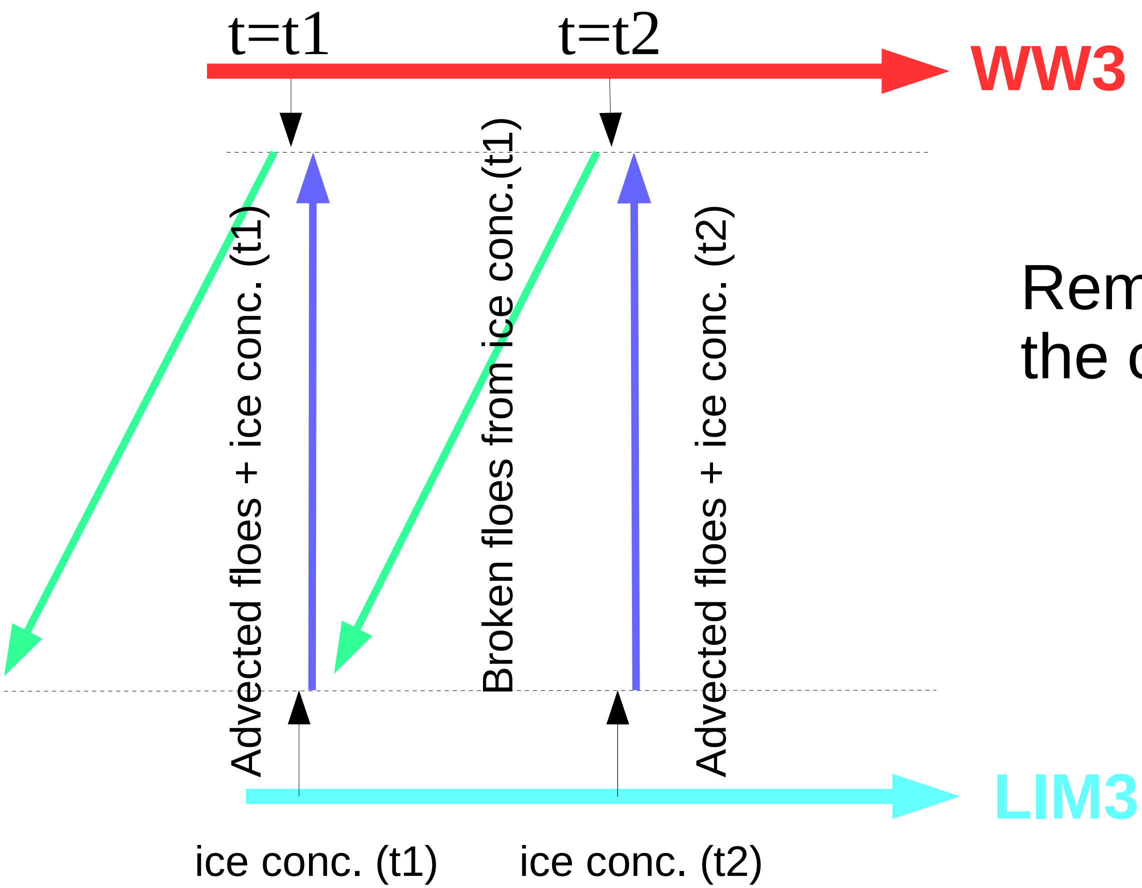
Depends on the sea state **+ advection**

Coupling WW3 with LIM3 (lag)



New FSD is computed by WW3 where the ice is in (t1) and sent to LIM3 in (t2), whereas the ice moved...

Coupling WW3 with LIM3 (lag)

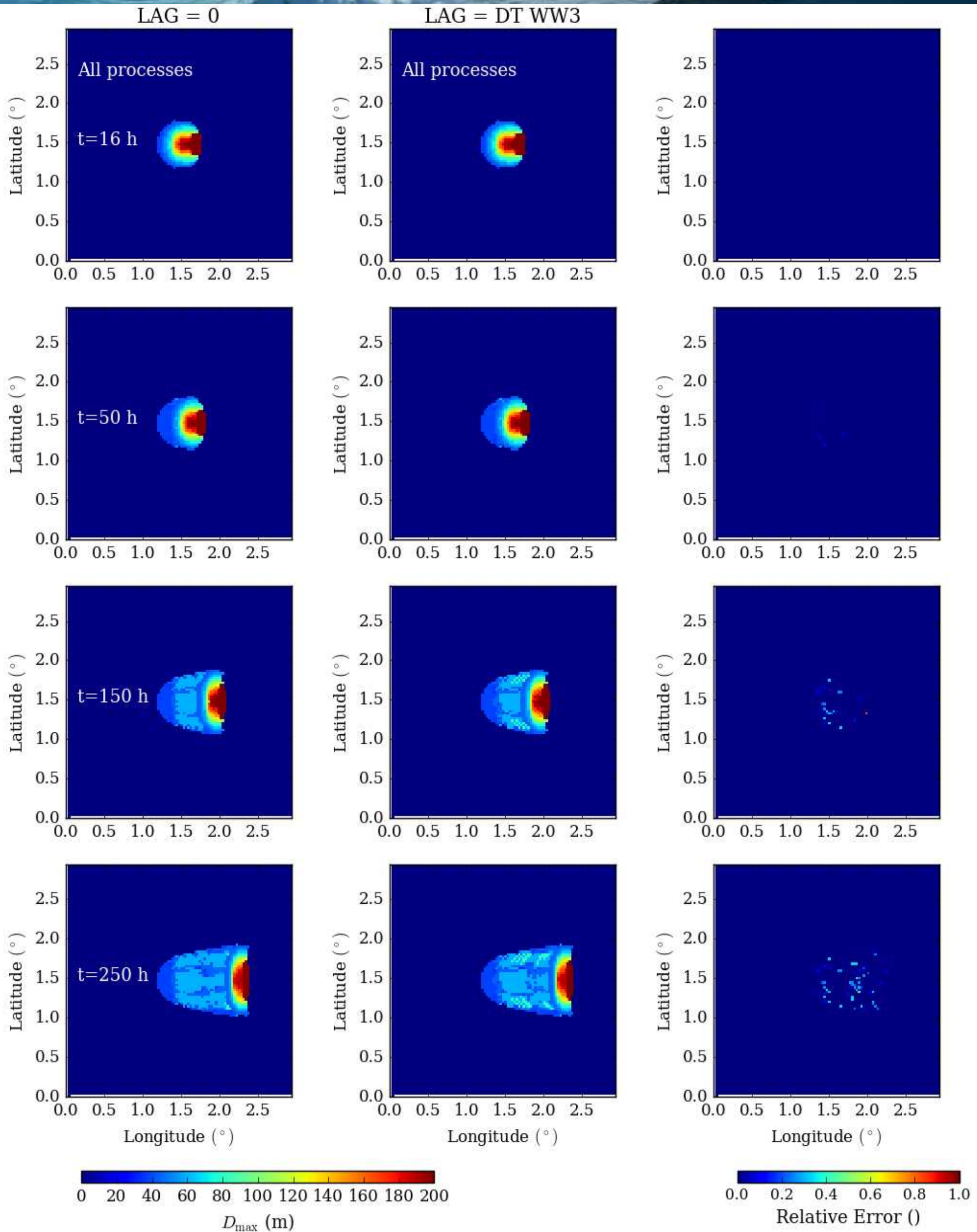


Removing the lag makes the coupling asynchronous

Coupling WW3 with LIM3 (lag)

The difference remains quite limited…

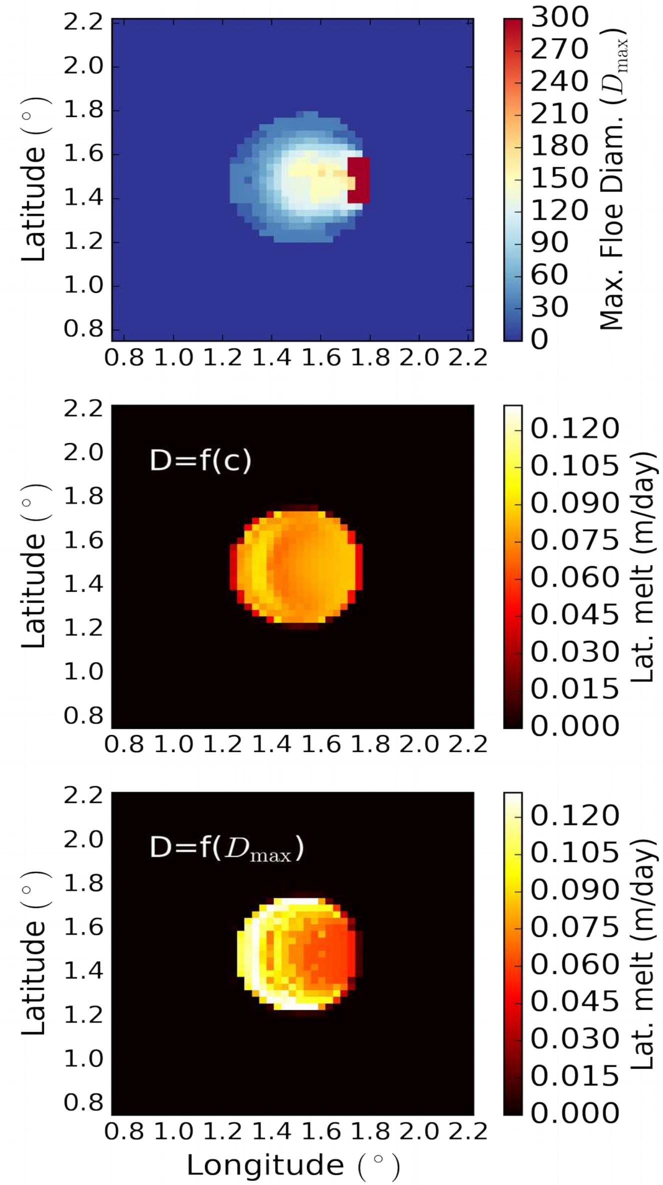
Better keep a synchronous coupling



Lateral melt

New FSD explicitly known (as it is assumed that it follows a power law)

Computation of D average for each categories of floes



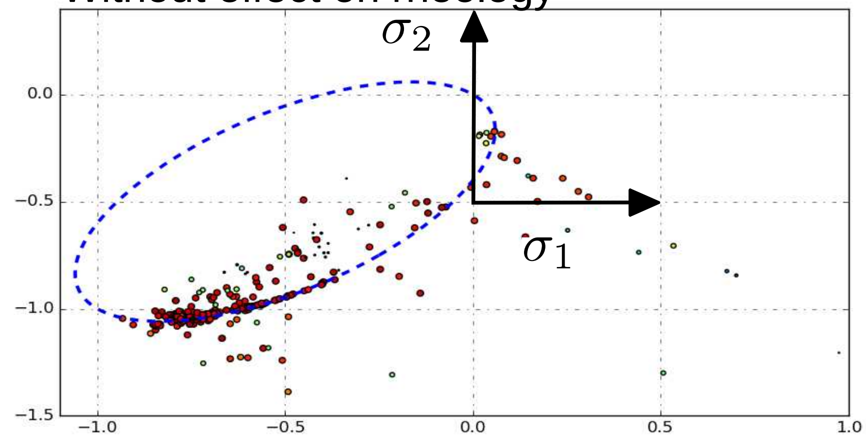
Different pattern from *Lupkes et al. (2012)*

CREG025 :

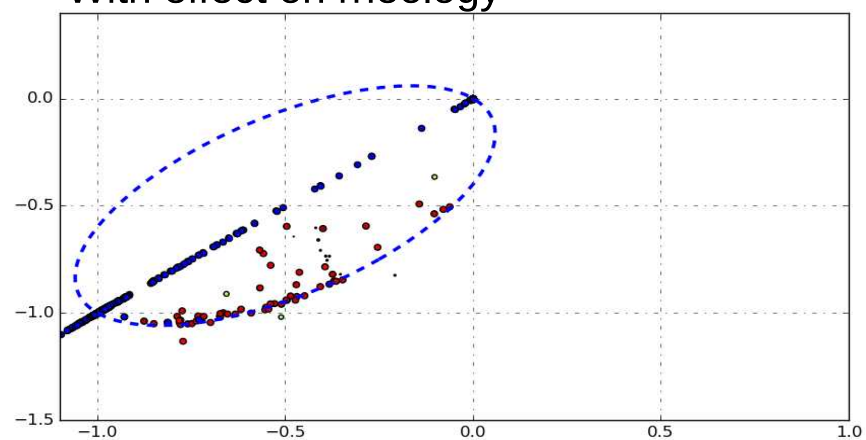
Impact on rheology ?

Assumption : If the ice is broken, the resistance to shear and divergence is removed.

Without effect on rheology



With effect on rheology



Blue points are points where the ice is broken

A work in progress...

Technically : clean the code, put parameters in namelists… Understand why UM adv. scheme fails ?

Test **sensitivity** to parameters (lat melt), floe size redistribution…

Analyze the results (find a proper study case)

Thank you for your attention

This not sea ice but it's my picture

(Thank you Camille)

Questions ?

SUMMARY

Scattering

#1 Depends **strongly** on frequency and thickness

#2 Increase of the **spread**

#3 Increase of the **wave height at the ice edge**

#4 Very efficient to attenuate short waves

#5 Requires to be combined with dissip. proc.

SUMMARY

Total friction term

#1 Depends on **frequency** (but less than other processes) and **not much on thickness**

#2 Exponential attenuation (just like scattering)

Turbulent part

Most of the contribution

Efficient provided that **wave height is still large**

Viscous part

Very weak

SUMMARY

Flexure

#1 Depends very much on **frequency, ice thickness** (but also energy of activation)

#2 **Strongest attenuation** for short waves, and for long waves in thick ice

---

Inelastic dissipation

Non linear with strong attenuation at the **ice edge** (if the ice is not broken)

Efficient provided that **wave height is still large**

Anelastic attenuation

Linear, shows a max. floe size that increases **regularly**

Wave propagation in ice covered sea

The relation of dispersion (deep water)

$$\sigma = (gk + Eh^3k^5 12(1-\nu^2)\rho_w)/(1 + \frac{\rho_{ice} hk}{\rho_w})$$

#1 The **waves** are **faster/longer**

#2 The **thicker** the **ice**, the **stronger** the effect

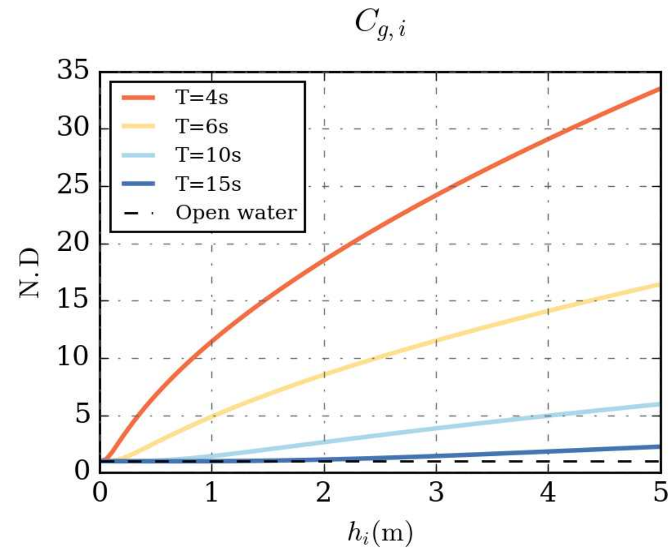
#3 The **shorter** the **waves**, the **stronger** the effect

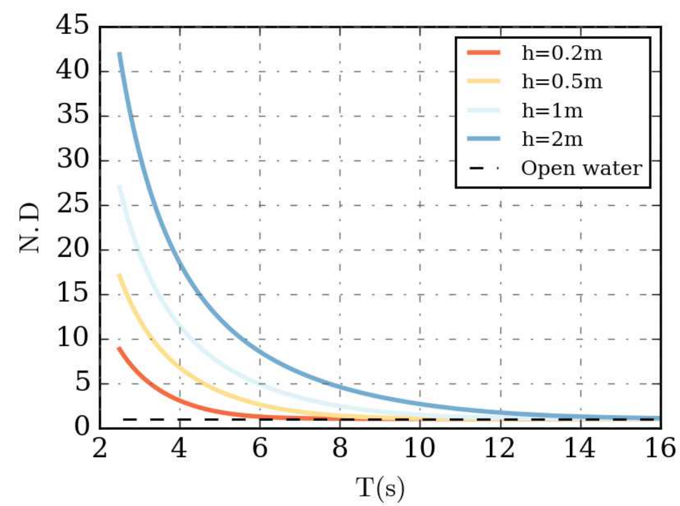
Wadhams (1973)

How do we use it in WW3 ?

Only in S_{ice} (attenuation & breaking)

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{\mathbf{x}} N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial \theta}\dot{\theta}N = \frac{S}{\sigma}$$





Waves attenuation in ice

Flexure (Wadhams, 1973)

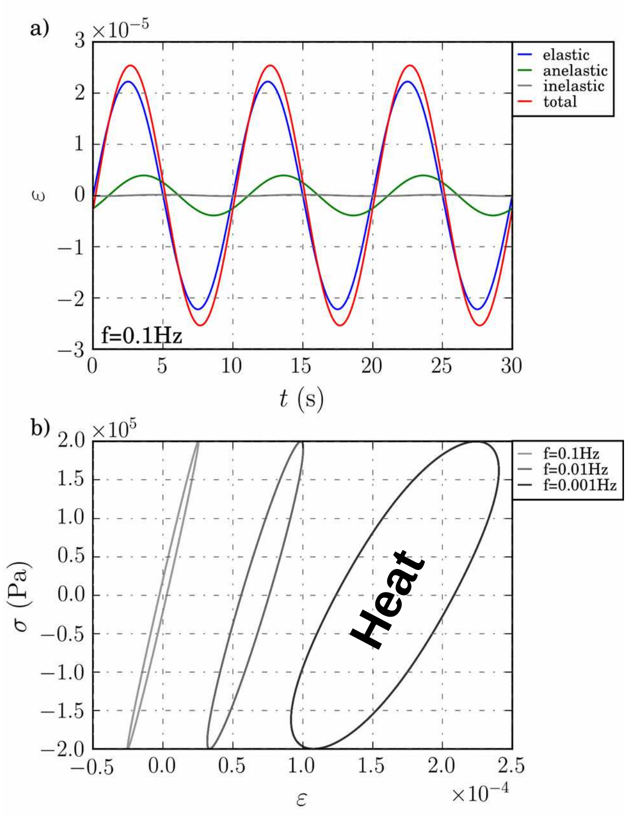
Hypothesis : Ice is visco-elastic
Physically : during loading, micro-craks appear an propagate in sea ice, internal friction.

ANELASTIC	INELASTIC
Delayed elasticity	Creep
LINEAR	**NON LINEAR**
Expected	*Not expected but...*

(Cole, 1995)

Once ice is broken, floes act as **rigid bodies**

We take the same parameters than in Cole (1995), for ice at -5°C



Current work : coupling with LIM3 (in short)

LIM 3 is an ice model, part of NEMO

- Ice is divided into different categories depending on thickness.
- advection due to winds and ocean currents
- Ice rheology with internal stress, but without tensile stress
- Various thermodynamic effects

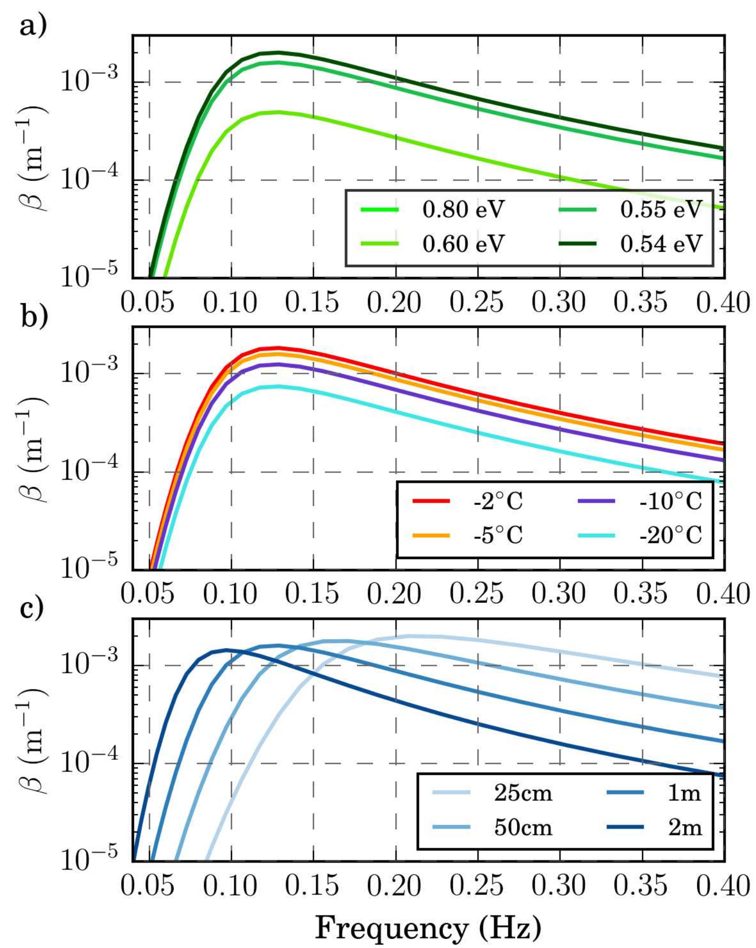
Waves attenuation in ice

Flexure (Wadhams, 1973)

Hypothesis : Ice is visco-elastic

Dependency on ice temperature, activation energy, ice thickness…

We take the same parameters than in Cole (1995), for ice at -5°C



Waves attenuation in ice

Viscous and turbulent dissipation

Liu and Mollo-Cristensen (1989)

Adding molecular viscosity in a linearised Navier-Stockes equation :

$$\alpha_v = -k\sqrt{\nu_m \sigma/2}/(1+k\frac{h\rho_{ice}}{\rho})$$

Viscous layer

Liu et al. (1991)

$$\alpha_t = -k\sqrt{\nu_{eddy} \sigma/2}/(1+k\frac{h\rho_{ice}}{\rho})$$

turbulent layer : $\nu_{eddy} \simeq 10^5 \times \nu_m$

Stopa et al. (2016)

$$\alpha_v = -k\sqrt{\nu_m \sigma/2}/(1+k\frac{h\rho_{ice}}{\rho})$$

$f_e(a_{orb}/z_0)$ is a dissipation factor used for bottom friction

$$\alpha = (1-w)c_v\alpha_v + wc_t\alpha_t$$

$$w = w(Re) \qquad c_v, c_t$$

Depends on Reynolds number